Design Change Report
9th Annual Intelligent Ground Vehicle Competition

"The Beast"

2001 *Beast* Design Team

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18 May 2001

I. Introduction

The development of the University of Detroit Mercy's entry into the 9th Intelligent Ground Vehicle Competition (IGVC), *The Beast*, is presented in this document. *The Beast* is a redesigned version of a 1999 IGVC competition entry entitled *WHY2K?* and is intended to participate solely in the Vehicle Performance Competition. Accordingly, this is a Design Change Report that primarily discusses the design modifications undertaken in the light of past experience. The new Autonomous Ground Vehicle (AGV) incorporates considerable enhancements to the vehicle base as well as significant improvements to the electrical power distribution, steering and speed control, vision, obstacle detection, and navigation systems. A more detailed description of design enhancements is provided in Section II.

The Beast is an AGV that is based on an electrical wheelchair platform. It uses a single color camera and a sonar sensor array to obtain information about its environment. Using this information, image analysis and a fuzzy logic-based navigation strategy are implemented in a 'C' environment running on a PC. The resultant motion commands are executed by a dedicated HC12 embedded controller. An SDRC I-DEAS rendering of the vehicle is shown in Figure 1.

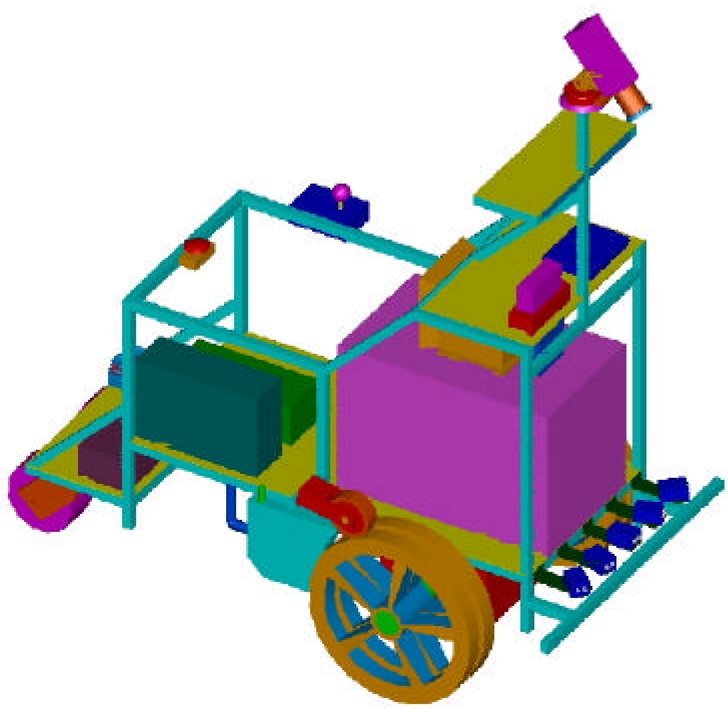

Figure 1: I-DEAS rendering of AGV

Figure 2 displays the overall subsystem block diagram used during the development of *the Beast*.

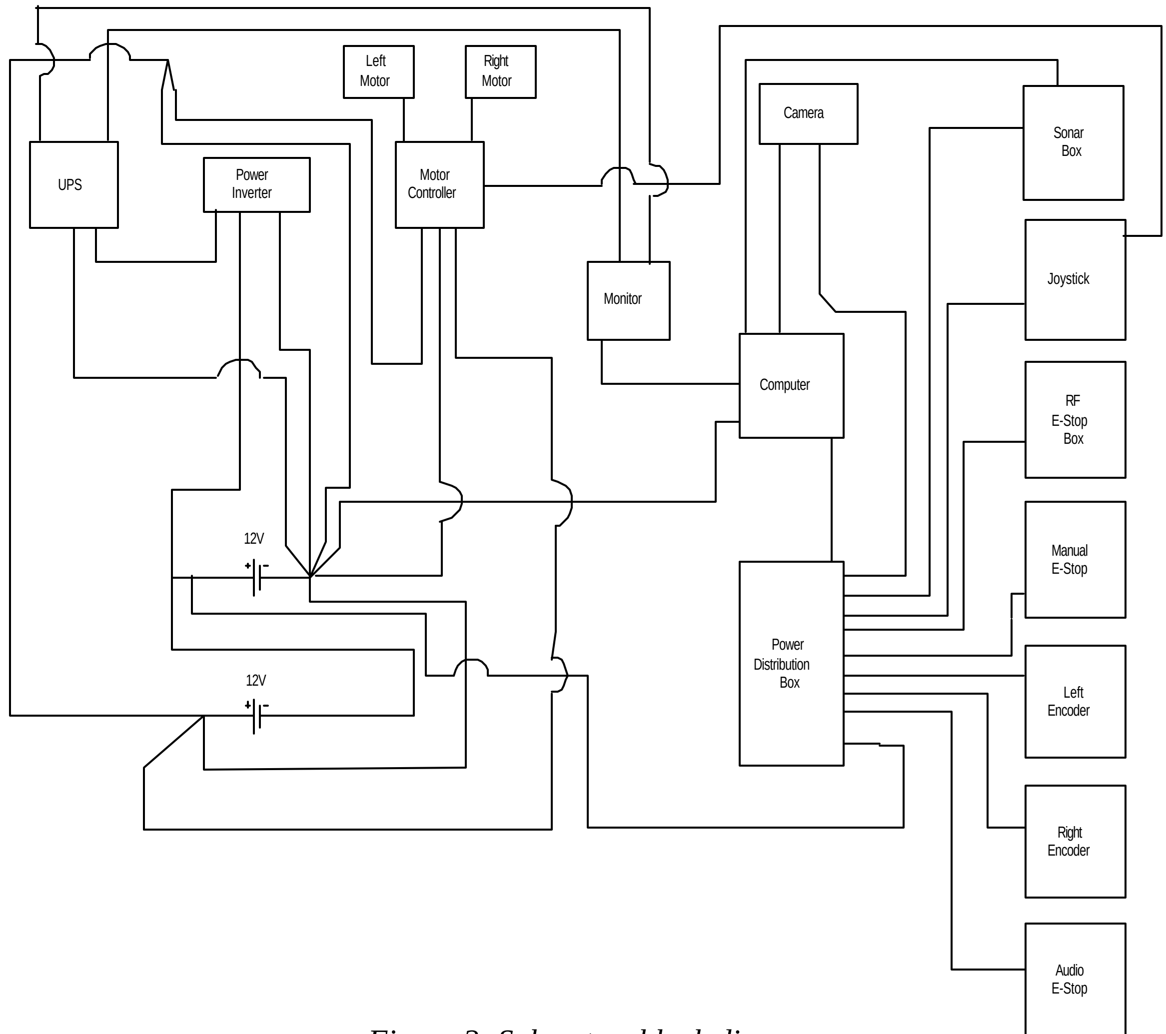

Figure 2: Subsystem block diagram

A. Team Organization

The six-person design team (names listed on cover page) was comprised of undergraduate electrical engineers in their senior year. They were supervised by two faculty members, Drs. Mohan Krishnan and Mark J. Paulik, and consulted with a Doctoral student, Mr. Stamat Stamatov, on some aspects of the design. The project was carried out in the context of a 2-course Electrical Engineering Capstone Design sequence running from January through to August. Based on the performance of the vehicle in the competition, improvements will be implemented in the June-August period.

II. Modifications to 1999 Competition Entry

A vast number of changes distinguish *The Beast* from its predecessors. Numerous design changes combine to make *The Beast* a more advanced AGV. These changes are individually discussed in the remaining sections of the report.

A. Platform

Based on earlier competition experience several characteristics of the platform were modified. The previous vehicle had difficulty turning. The rear castor wheels would become mired in the soft turf. Then, when a turn command was given, the vehicle would continue forward with no immediate response. The vehicle controller would compensate by continually increasing the drive current until the necessary amount of force was generated. Unfortunately, at this point, the vehicle would swing very rapidly and overshoot the intended turn. This overcompensation was a highly nonlinear control problem that suggested some significant platform alterations. These modifications included replacing the rear caster tires with larger flotation tires, shortening the overall chassis length, and altering the drive pulley ratio.

The original rear caster tires included with the wheelchair were 8” by 2” knobby tires. These were exchanged for 9” by 4” smooth tires. The new caster wheels have two features that will improve vehicle performance. The new smooth tires will reduce the friction on the rear wheels, which only serve as balance points. They also have a larger surface area than the originals. This modification helps to evenly distribute the mass of the AGV, especially on the soft ground of the competition course, and significantly reduces the force necessary to turn the vehicle. The vehicle chassis was shortened to reduce wheelbase and alter weight distribution. These changes reduce the weight on the rear caster wheels and the torque necessary to turn the vehicle.

The final platform innovation is the increased size of the drive pulleys. The original 10-inch plastic pulleys were replaced with 14.25-inch steel pulleys. The attendant increase in torque of about 40% enabled the vehicle to negotiate inclines and turns much better than in the previous year. At the same time this change limits the top speed to about 4.5 mph, which fits in nicely with the 5-mph speed limit required by the competition.

B. Electrical/Electronic Hardware

Multiple improvements have been made to *the Beast's* electrical hardware systems. These improvements include: (1) the creation of a centralized power distribution box; (2) the incorporation of an industrial PC case; (3) the inclusion of two remote e-stop systems; (4) the use of optical encoders and the preprocessing of these signals with an FPGA chip; (5) the incorporation of a dedicated embedded control for motion control; and (6) the introduction of indicator and diagnostic lights.

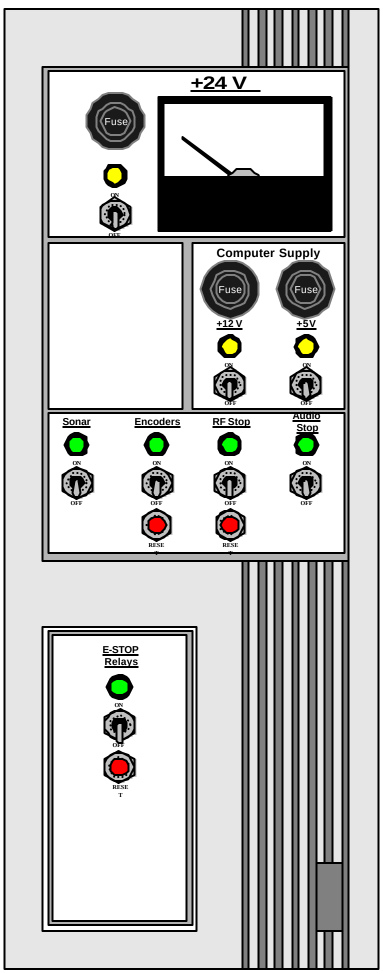

Figure 3: Power distribution box

The centralized power distribution box is a great improvement over the individual reset and power switches found at various locations on the earlier vehicle. The power distribution box incorporates a series of fuses that protect individual subsystems from current overloads. Another feature is the multiple displays that monitor battery condition. An uninterruptible power supply (UPS) has been incorporated to provide clean AC power to the PC and this is a vast improvement over the simple power inverter used earlier. An image of the power distribution box has been included as Figure 3.

A PC mounted on an AGV does not operate in a benign environment. At the very least it may experience high temperatures (operation in June sun), precipitating component failure. This year a new server-class case equipped with four ventilator fans was adapted to provide the maximum possible cooling.

The mechanical encoders used in the previous year suffered from 'contact bounce' problems. These encoders have been replaced by optical encoders immune to this problem. Additionally, these encoder signals are now preprocessed by an Altera FPGA chip, which scales the pulse rate and determines direction and count, before sending them to a Motorola HC12 embedded controller. The use of this design provides flexibility in signal preprocessing.

One of the major innovations of *the Beast* over its predecessors is the incorporation of an embedded controller to carry out speed and steering control. In the previous design, vehicle control was implemented from within a Windows-based ‘C’ environment on a PC. Because of the delays resulting from the operating system overheads, a uniform sampling rate could not be ensured, thus making it difficult to establish real-time control. The multitasking features in the WIN-NT OS proved to be too unstable for effective use. To correct this problem the vehicle now incorporates a Motorola 68HC12 microcontroller programmed using the Forth language. This processor is responsible for monitoring the position feedback from the wheel encoders, establishing speed and steering control via a digital control algorithm, while also providing the stimulus and processing the responses from the sonar obstacle detection sensors. The use of such a distributed processing configuration enables the AGV to function in real-time.

A great deal of effort has been spent developing the two new remote emergency stop (e-stop) systems. They both utilize the vehicle’s integral regenerative braking system to bring it to a quick and complete stop when an e-stop relay transfers control from the computer to the vehicle’s self-centering joystick. The two remote e-stop systems are based on RF and audio signals respectively. The RF-based system utilizes a commercial Siemens automotive remote keyless entry module. In previous years it was noticed that the Electromagnetic Interference (EMI) at the competition site inhibited reliable and consistent operation of RF-based devices. Consequently, it was decided to incorporate a second remote e-stop system, based on audio activation, as a backup provision. A "turkey call" device originally designed as a hunting lure was employed as the audio source. It possesses unique spectral content and was preferred to a conventional whistle because of the consistency of the sound source. A microphone mounted on the vehicle chassis receives the sound, which is then processed by frequency selective circuitry. If the expected signal is present in sufficient strength, the relay that switches control to the joystick is activated.

The final hardware additions are the indicator lights. To comply with new competition requirements, two strobe lights are mounted in the front of the vehicle, one red and one blue. These lights will indicate when the vehicle detects an obstacle or a pothole. One light is controlled by the detection of obstacles by the sonar sensor array, while the other is controlled by the identification of potholes by the vision software module. Additionally, an array of cluster lights is used for diagnostic troubleshooting. These lights are controlled from the computer through a National Instruments digital input/output card.

C. System Sensors and Software

Every system sensor and software module has undergone major revisions since the previous competition entry. The image acquisition and processing system, obstacle avoidance system, and navigation and heuristic strategies, have all been significantly improved.

Vision Systems

WHY2K, the previous AGV entry, used a 3-camera configuration consisting of a forward-looking narrow viewing angle color video camera and two Internet cameras for side views. The latter exhibited color consistency problems, which made color-based thresholding unviable, whereas the center camera's field of view made lane boundaries invisible at any point closer than 12' from the vehicle. Additionally, the motorized intensity compensation system (automatic level control) was unable to effectively adjust for the extreme dynamic range of outdoor lighting conditions. The three cameras were replaced by a single precision color camera with a 110° wide angle lens mounted at the front of the vehicle, seen in Figure 4. This new camera exhibits excellent color consistency and has a field of view encompassing a 25' width at 7' from the vehicle; this feature allows the lane boundaries to be fully visible immediately in front of the vehicle, even if it is left or right justified within the lane. The camera's field of vision is illustrated in Figure 5. Also new is the National Instruments PCI-1411 image acquisition card, which can perform real-time conversion from Red-Green-Blue (RGB) to Hue-Saturation-Luminescence (HSL) image representation, which contributes to an enhanced frame processing rate. The vision algorithm used earlier utilized a gradient-based edge detection technique on the intensity image plane only. Presently this

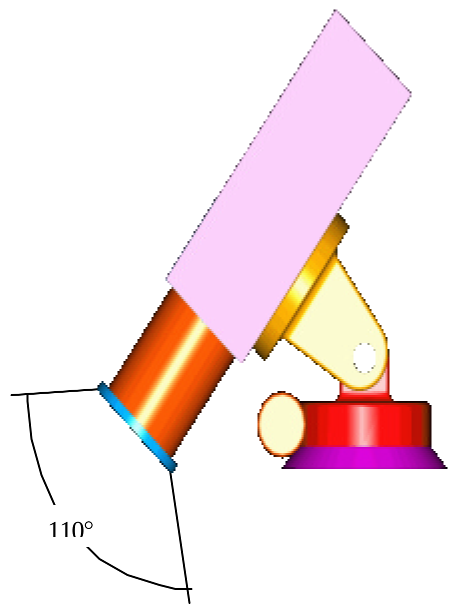

Figure 4 Camera mount

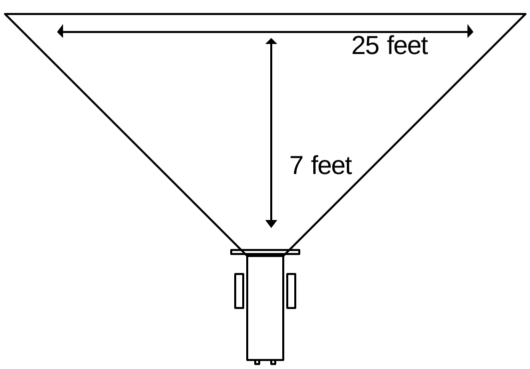

Figure 5: Camera field of vision

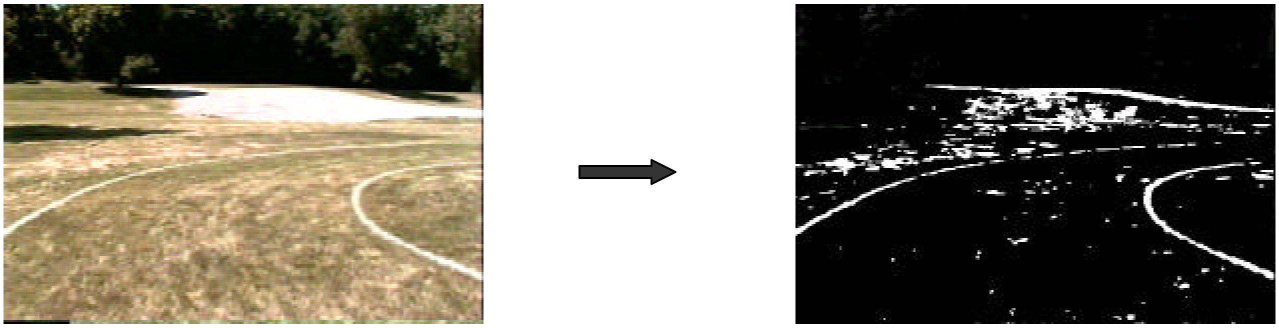

Figure 6(a): Original image *Figure 6(b): Initial color filtering*

technique is applied to all three planes (HSL) and is accompanied by region-based color segmentation, coupled with a Hough transform-based technique used to detect the existence of lines in the image field. The image in Figure 6b shows the changes made to the image in Figure 6a during the initial color filtering. To summarize, the new vision algorithms enable improved confidence in the detection of features in the scene that aid in navigation.

Obstacle Detection Systems

The sonar ranging system incorporated in the previous design utilized Polaroid ultrasonic sensors that were pivoted by two servos to ensure complete coverage. There were significant scanning delays, and the system was blind to objects closer than 2.5'. The new system uses five Devanech ultrasonic sensors, mounted at angles of -60°, -30°, 0°, 30°, and 60° respectively, with respect to the vehicle heading. This configuration allows for a large area of detection while enabling short-range multiple sensor redundancy, as these sensors can "see" from 2" to 9'. This layout provides a field of view > 180^{o}, with no blind spots, which is shown in Figure 7.

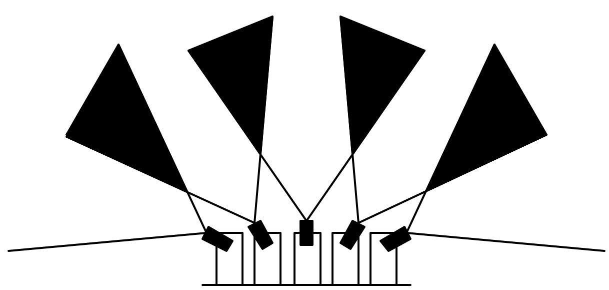

Figure 7: Sonar field of view

Heuristic Strategies

The incorporation of heuristics-based decision making was incorporated in a very rudimentary fashion in *WHY2K*. The current vehicle has a much more sophisticated heuristics module that combines human-like image interpretation with the history of vehicle motion to make informed decisions in uncertain situations. An enhanced history log in which previous command decisions and vehicle responses are charted enables this function.

Navigation Strategy

The navigation module of *WHY2K* used the potential fields method to combine the inputs from the vision and sonar sensors. This has been replaced in *the Beast* by sensor fusion based on a fuzzy logic technique. A fuzzy inference system makes a motion decision that generates a properly contoured path to arrive at the target. It does this by generating a desired average speed and differential speed for the two drive motors of the vehicle (which uses the "tank drive" paradigm). A fuzzy inference system first combines the desired angle provided by the vision module with the forbidden angles from the ultrasonic sensor array to generate a single resultant angle of travel. This angle is then combined with the distance to the target point also provided by the vision module to determine the two speeds mentioned above. This conversion is accomplished through a lookup table that is fine-tuned during testing for optimal vehicle dynamics.

III. Design Issues

A. Design Process

The process began in January with thorough exercise in reverse engineering to understand the features, capabilities and limitations of the inherited autonomous ground vehicle (AGV), in the context of the requirements of the Year 2001 IGVC competition. This study led to the definition of the design requirements for *The Beast*, which were then organized into the logical task groups illustrated in Table 1. The tasks were then broadly distributed amongst the various team members with some overlapping responsibilities in keeping with the principles of concurrent design. The scheduling of common class, laboratory, and team meeting times, along with periodic peer and advisor review sessions provided an excellent framework for project execution to meet established deadlines.

Effective system integration was a singularly important part of this design process as a number of complex subsystems were being separately designed. Wiring and documentation protocols were established early on, and careful revision histories were maintained for all schematics and software. Finally, the scheduled design review meeting structure provided the framework that enabled smooth integration of the individual subsystems into the overall design.

Team Member	Task List
Adnan Al-Kujuk	Test track design and logistical support
Kate Krause	Vision
Vera Loggins	Navigation and embedded control
Jason Twehues	Project documentation and e-stop systems
Miguel Valdovinos	Software integration and heuristic strategies
Wade Warnecke	Hardware including sensors and power distribution

Table 1 – Team Roster and Task Divisions

B. Safety

Safety was a significant factor in many of our design decisions. Redundant remote e-stops ensure the AGV can be halted no matter what the situation. Changing the pulley ratio changed the top speed from 6 mph to 4.8 mph. This alteration also shortened required braking distance. Additionally, a large diode/fuse based reverse battery protection device was installed, and fuses were used on all high current lines. Finally, no-contact (female) connectors were utilized in all cases where live voltages (AC or DC) were present.

C. Reliability and Durability

Many changes have been made to the earlier *WHY2K?* AGV to help ensure high levels of reliability and durability. A wire harness was used to route wires from the power distribution box to the individual subsystems. Keyed, locking, automotive-rated AMP connectors where used throughout the vehicle. A complete diagnostic software suite was designed to verify individual system operation, and diagnostic indicator lights were added to many subsystems to visually indicate operation status. A UPS was added to ensure a clean supply of power to the PC, and a protective plexiglass enclosure was constructed to help shield critical components during inclement weather. Finally, the frame was shortened, and diagonal bracing was added throughout which improved structural rigidity.

D. Predicted Performance

The original OEM wheelchair platform was capable of traveling at a top speed of 6.5 mph while carrying a 250 lb passenger and negotiating an incline of 9^o. The modifications made to the drive pulley system reduced the top speed to 4.5 mph and increased the effective torque by 40%. The new vehicle platform has been tested with a full complement of gear and is easily capable of climbing a 30^o incline at full speed. It should be noted that the weight of the equipment added to make the vehicle autonomous is significantly less than the 250 lb that the original wheelchair was designed to carry, and the current platform is stronger and more rigid.

The dual 12V automotive batteries (configured in series for 24V) provide the vehicle with a conservatively estimated operating time of about 1.5 hours between charging cycles. The total current draw during full speed operation is approximately 61 Amps, and the batteries are rated to provide 92 Amp-hours of power while maintaining 12V. However, when negotiating an actual course, the vehicle rarely operates at full speed, and the average current draw is considerably less (approximately 30-40 Amps).

The sonar sensor suite detects obstacles anywhere from 2" to 9' in front of the vehicle over a 180-degree arc with no blind spots. Obstacles over 6" tall will be successfully detected (adjustable) anywhere in this field. The Image Processing system also identifies obstacles by both color and shape if they lie within 24 feet of the vehicle front, and fall within the 110-degree field of view. The fuzzy navigation system integrates the data from both acquisition systems to determine the optimal vehicle path.

The use of a dedicated embedded controller for vehicle steering and speed allows for improved reaction times relative to our earlier design. The controller uses a combination of non-linear, open loop predictive control and more traditional proportional integral control. This structure allows the vehicle to quickly overcome starting and turning inertia while smoothly achieving the goal position and velocities. Experimental evaluation has demonstrated that the vehicle can achieve full speed in response to a command in approximately 1.5 seconds, and can turn 90 degrees in approximately 1 second. The sensor acquisition systems are considerably faster. The image processing/acquisition, sonar obstacle detection, and navigation systems can produce final integrated goal decisions at a rate of approximately 14 frames per second. The performance indicated here assumes the use of a 1.2GHz Pentium class windows OS based PC as the main computational engine. The most computationally demanding task is the image processing and interpretation. If a dedicated image array processor were employed decision rates of 30 frames would be possible.

The image processing and interpretation system has been designed to identify traps and avoid them. This is accomplished by examining the field of view at a number of distances in front of the vehicle to anticipate problems (up to 24 feet). If, despite these algorithms, the vehicle finds itself in a dead-end trap, it reverses its course and uses dead-reckoning based on stored motion history and wheel encoders to extricate it. Currently the vehicle will reverse until the image processing system identifies an alternative route forward. Other obstacles such as potholes, buckets, or construction barrels are avoided by choosing an optimal path around them. Barrels are identified easily by their color and their clear ultrasonic signature. Similarly, buckets produce a clear sonar response which when coupled with image processing results allows straightforward identification. Potholes are identified solely by color and size characteristics. If other low-lying debris is on the course (not seen by the ultrasonic system) the current image processing algorithms will attempt to avoid them if there is a clear path of approximately 3 feet width available. If no path is found, the situation will be treated as a dead-end case as indicated above.

With the current hardware *the Beast* is capable of participating in the follow-the-leader competition, but the necessary algorithmic changes have not been implemented this year. The addition of GPS hardware should allow participation in the GPS-based navigation competitions in the future as well.

E. Problems and Solutions

The most vexing hardware problem was the lack of consistent documentation detailing electrical connections all over the vehicle (from the earlier *WHY2K?* platform). Much time was spent determining pin-outs and separating power connections from signal wires. Rigorous guidelines have been implemented to prevent this from recurring in the future. Other hardware problems were related to EMI and ground loops. The use of shielded cables, line buffers, and consistent central grounding structures ameliorated these effects.

The most prevalent software problems involved the typical coding errors that required methodical debugging efforts. The frequency of these was reduced somewhat by establishing coding standard practice guidelines early on in the design process.

The most challenging problems encountered in the design and production of this vehicle centered on the development of effective algorithms to interpret the vehicle environment. These included the low-level image processing routines, the higher-level heuristic-based image interpretation algorithms, and the navigation code. Extensive testing with a test track constructed on campus was very helpful in this process.

F. Cost

The cost of the major component upgrades is shown in Table 2 below. A major component of *the Beast* not noted in the table is the 1700 student-hours invested in this AGV.

Item Description	Vendor	Cost	Purchased	Donated
Sheave – 14.75" (pulley)	Grainger	$121.80		X
10"x4" caster tire and assembly	Exmark	$1,800.00	X	
Mark III Controller	Wheelchairparts.com	$683.00		X
Mark III Controller	Invacare	$683.00	X	
HC12 E.V.B.	Motorola	$105.00		X
AMP circular plastic connectors	Amp	$600.00	X	
Plexi-glass	AIM	$102.00		X
Sonar part #SRF04	Devantech	$125.00		X
Encoder part #92-Q064-00-00	Oak-Grigsby	$120.00	X	
Camera w/accessories	Panasonic	$800.00		X
Computer	Yeong Yang	$1,600.00		X
E-stop materials	Active Electronics	$80.00		X
Strobe lights	Gails Street Lighting	$100.00		X
Miscellaneous hardware	Ace Hardware	$230.00		X
Totals:		$7,149.80	$3,203.00	$3,946.80

Table 2 - Cost