Adam - an IGVC Robot

Developed by the Bob Jones University Department of Physics and Engineering, 2004-2005

Adam, minus his skin

Team Leader:

Donald Congdon

Team Members:

Andrew Alleman
Brett Castelloe
Tim Hughes
John Mark Jacosalem
David Phillips

Team Advisor:

Dr. Bill Lovegrove

Introduction

The ability to design, implement, test, and refine are the qualities of a successful engineer. Consequently, the capstone of an engineering curriculum typically involves a design project that will put to the test the previous three years of education. The capstone course, *ELE-406 Embedded Systems*, used the IGVC competition as the basis for this year's capstone design project.

The team followed the design process articulated in the course textbook, *The Engineering Design Process* by Ertas and Jones. This process includes 1) recognition of need, (2) conceptualization, (3) feasibility assessment, (4) assignment of organizational responsibilities, (5) preliminary design, and (6) detailed design with iterative feedback leading to redesign as necessary.

Recognition of need

Entrance into the Intelligent Ground Vehicle Competition was the assigned task for our team and therefore automatically created the need. Since the IGVC explores several realistic robotics scenarios, the artificial need created by the competition mirrors the real-world needs of the autonomous robotics problems being explored by industry and academia today. Note that fulfilling the instructor's educational objectives and competing in the IGVC are two different and sometimes contradictory goals, a factor which influenced major design decisions as discussed below.

Conceptualization

The design process began with the team's developing a better understanding of the competition by researching past competitions and designs. Aspects of the design such as chassis structure and sensor usability were carefully examined. Observation of common pitfalls and problems identified some of the issues that the team would need to address or avoid. The best and most successful ideas influenced our design choices and helped us cull out weaker ones. For example, one past team described the limitations of its black-and-white camera, leading us to select a color camera, despite its higher complexity and cost.

Lastly, we noted teams' actual performances in both the autonomous and navigation challenges and compared them to the theoretical expectations expressed in their design reports. Through this comparison we hoped to detect significant disparities between attractive theoretical ideas and their practical implementation.

Feasibility assessment

After much research of "what to do" and "what not to do," the team analyzed the viability of the project. Design requirements for the IGVC as well as budget costs acted as natural constraints on design decisions. Competition rules required minimum and maximum dimensions, safety precautions, and speed limits. These limits guided some of the design decisions while budgetary constraints eliminated expensive sensors and complex chassis designs. Some of these feasibility concerns are described in the design details which follow.

Assignment of organizational responsibilities

With the big picture of the design process in view, each team member focused his attention on a specific section of the project. While a project of this scale requires members to become "experts" in specific facets of the design, the team also needed to work as a whole. Team members therefore had to retain an overall picture of the project as well as a general understanding of each member's specialty.

Team members	Primary area of responsibility
Andrew Alleman (Sr)	Chassis, compass
Brett Castelloe (Sr) Tim Hughes (Sr)	Video, software
David Phillips (Sr)	Power system and e-stop
John Mark Jacosalem (Sr)	GPS, chassis
Donald Congdon (post-grad)	Project management

Figure 1—Team Organization

An online discussion forum and a project web site facilitated design team communication and project documentation. An estimated 800 man-hours of student labor was expended on this project by these team members.

Preliminary design

Figure 2 illustrates the preliminary block diagram of the electronics and control system. Major design decisions as well as the mechanical structure's basic parameters are detailed below.

Chassis: Our team consists entirely of EE students with little or no ME experience and minimal machine shop facilities. Consequently, the major factor in chassis design is simplicity in design and construction. For this reason we elected to use off-the-shelf components that require only basic tools for customization. The strength of the T-slot frame was verified from manufacturer-provided data to have negligible deflection at the intended loads and appears to represent a safety factor in excess of ten. Large safety factors are wise when students with limited mechanical experience are doing the designing.

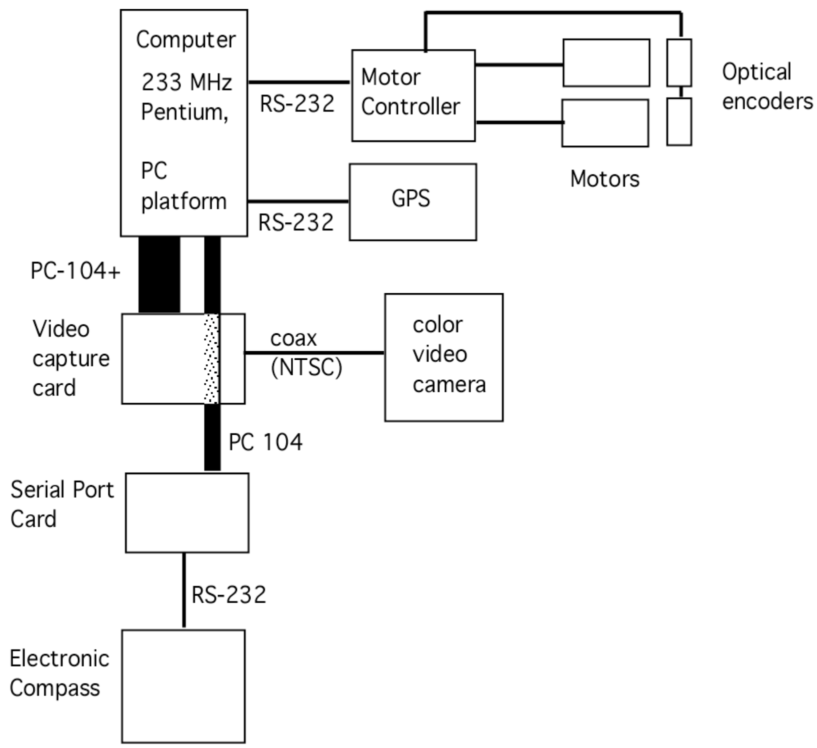


Figure 2—Preliminary Design Block Diagram

Drivetrain: Again, limited ME expertise dictated that we borrow expertise from an experienced vendor. Motors, gearboxes, and wheels were selected from NPC Robotics, a leading supplier of rugged parts for Battle Bots competitions. Preliminary design calculations suggested that 1 HP motors with reduction gearboxes would be adequate with the predicted vehicle weight for the target speed of 5 mph at the specified 15% grade.

Batteries: The selected motors operate on 24V, requiring two 12V batteries in series. A third 12V battery was chosen to power the on-board electronics and to electrically separate the drivetrain from most of the control system. Battery size is a tradeoff between weight and run time. See the performance predictions for details.

Motor controller: We chose a serially interfaced controller based upon NPC Robotics' recommendations as it has seen wide success in Battle Bots and matches our motor specifications. It also supports both open and closed-loop feedback and can therefore be used with motor shaft encoders to achieve precision speed control.

Processor: Although many teams use a commercial office-grade notebook computer to control their robot, our instructor specified that the processor should be industrial grade. This choice would provide a more realistic view of design in an industrial setting. A standard notebook computer presents serious reliability issues in the IGVC environment with its heavy vibration, temperature variations, airborne dust, and potential precipitation. We wanted an industrial-grade processor supplied by an ISO-9001 certified company, one specifically designed for a moderately harsh environment.

The need for real time RGB image processing mandated a Pentium-class processor. Such a system would have the capacity to run a variety of operating systems ranging from simple ones like MS-DOS to more sophisticated ones like Linux and commercial real time systems.

Since most industrial-grade expansion boards use the PC-104 (embedded ISA) and PC-104+ (embedded PCI) form factors, our processor board would have to support this expansion standard.

Sensors: Budget constraints precluded the use of any sensors costing more than $1000 and therefore eliminated exotic sensing systems such as laser rangefinders or radar. Resolution limitations and the past problems that other teams have experienced with ultrasonic, infrared, and other similar sensors decided us against these approaches. Furthermore, examination of past competitions convinced us that complex sensor systems rarely perform well. We therefore decided to attempt the competition with vision, a compass, a GPS, and closed-loop motor feedback. Certainly humans accomplish similar tasks with vision alone. We are encouraged in the approach by the success of the DAD vehicle in the first DARPA Grand Challenge. The DAD vehicle relied on stereo vision as its primary sensor input. Our vision system is much less sophisticated but nevertheless we believe that a vision-only approach is highly appropriate and capable. Of course we will take advantage of a compass and GPS as well, as did the DAD vehicle.

Video Capture: Three design constraints limited the choice of video input system: 1) real-time capture at 15 fps using a PC-104+ interface, 2) multiple input channels so stereo vision could be explored at a later date, and 3) driver support for a variety of common operating systems. We planned to supply our image with an ordinary security-type color video camera transmitting standard NTSC video.

Compass: Although the GPS can provide compass-like information (i.e. headings), it requires motion to supply this information. We therefore decided to add a serially interfaced, electronic compass to simplify obtaining basic bearing information.

GPS: Differential GPS is beyond our budget. However, WASS-enabled commercial receivers are inexpensive, accurate, and widely available. We decided to use a serially interfaced GPS receiver for easy interfacing to a variety of operating systems and software development tools.

CAD study: Before any parts were put together on the robot, we prepared a 3-D CAD study using Delmia/Catia to help visualize the physical characteristics of the robot. Besides the help in visualizing the design concept, the 3-D CAD drawing will also help in physics simulations of the robot.

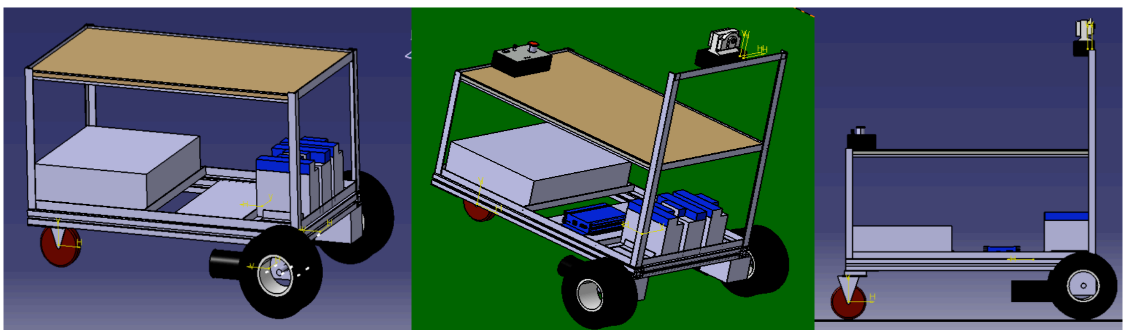


Figure 3—Catia Studies

Performance Predictions

An estimated 125 lb (56.9 N) vehicle on a 15% slope: represents a normal force of 121 lb and a tangent force 29.2 lb (130 N). Adding a rolling resistance (coefficient 0.06) of 33.5 Newtons results in a required total driving force of 164 Newtons. To achieve a target speed 5 mph (2.24 m/s) requires 367 watts (164N x 2.24 m/s) of power. Assuming a drivetrain efficiency of 0.8, the top speed requires 459 watts. Two 1-hp motors (1492 watts) have significant excess drive capability, allowing for extra rolling resistance or for obstacles to be overcome.

The needed 459 watts will require 19.1 amps at 24 Volts (9.6 amps per motor). Max RPM of the drive wheels is 235 rpm (with the 15.46:1 geartrain the maximum motor rpm is 3633 rpm). With ten-inch diameter wheels, 235 rpm corresponds to 7 mph top speed. Motor torque and rpm seem to be more than adequate to meet the IGVC requirements. The motor controller, with built-in closed loop feedback, will be used to limit the top speed to 5 mph.

Batteries are rated at 18 Ah, providing almost one hour of constant drive time at the typical maximum load. In typical testing, running on flat hard ground requires only 94 watts or 4 amps, providing 4.5 hours of constant run time.

For the electronics, the estimated current draw is 3A. The 18 Ah battery should then provide a run time of more than 5 hours. Battery life for the electronics is designed to be longer than that needed for the motors because it is expected that during testing there will be significant periods of time when the control electronics will be running but the robot will not be moving. We targeted four-hour testing times between recharges, and both battery packs are predicted to provide this.

We plan to run the software at a 1/15 second frame rate in reactive mode, providing a reaction time of 0.067 seconds. At 5 mph, the robot moves approximately 0.3 meters between frames. The camera views several meters ahead, providing adequate time to respond to obstacles even at full speed. Deliberative mode is expected to require a much slower frame rate, and so we plan to operate at speeds much slower than 5 mph in deliberative mode.

Detailed design

Frame and Chassis: The robot's lower frame is comprised of extruded aluminum T-slot material supplied by 80/20, Inc. Rigid T-slot extrusions provide strength and ease of assembly. Strategically, lighter aluminum angle brackets are used for the upper frame for stability and to minimize cost and weight (Figure 4). A piece of aluminum sheet metal mounts the batteries and motor controller. A salvaged electronics case houses the sensitive electronics (Figure 5). Custom motor mounting plates complete the mechanical design.

Figure 4—Chassis Design

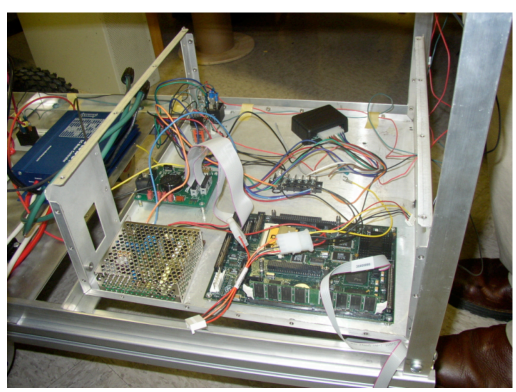


Figure 5—Electronics Enclosure

Padding and rubber grommets were used to prevent vibration problems with the heavier components such as the three batteries which are padded by half-inch foam. Also, rubber grommets are used for mounting components such as the electronics box and the motor controller to reduce vibration.

Electrical System: The electrical system is composed of the motors and motor controller, batteries and power supplies, emergency stop system, single board computer, and the sensors (GPS receiver, compass, and video camera). All of these components are integrated into an embedded system designed to meet the conditions of the IGVC. The single board computer coordinates the electrical components for the tasks specified by the controlling software.

Motors: Modified wheelchair motors with attached gearboxes (NPC-R82) from NPC Robotics drive the robot. The motors are front-mounted as they would be on a wheelchair. This positioning keeps the weight of the motor shaft near the middle of the robot frame and helps prevent the robot from tipping forward. A rear-mounted free-wheeling caster supplies back support and accommodates easy maneuverability.

Motor Controller: For compatibility and ease of interface, the motor controller (NPC-AX2550) also comes from NPC Robotics. This controller digitally manages motor speed using PWM techniques and supports closed-loop feedback through optical shaft encoders. The controller communicates with a host computer via an RS232 serial interface.

Batteries and Power supplies: Three 12V gel-cell batteries (PS12180) are used to power the robot. Two of the batteries are connected in series to supply 24V to the motors, the motor controller, and a simple +12V linear regulator that powers the video camera and hard disk drive. The remaining 12V battery powers all other electronics (single board computer, GPS, compass, and video capture board) via a high-efficiency +5V DC-DC converter. Batteries are located far forward to shift weight onto the larger front drive wheels. We anticipate about a 70/30 weight distribution.

Emergency Stop System: The emergency stop system is comprised of circuitry that stops the motors 1) at the push of a conspicuous red button located on the top of the robot at the IGVC-specified height, 2) by a wireless key, or 3) by deliberate switching off or accidental failure of the 12V supply. The system is designed to fail in a safe state and will always halt the motors. The motor controller provides built-in e-stop capability to brake the motors.

Single Board Computer: The robot is controlled by an Ampro LittleBoard P5V PC-104 single board computer which comes equipped with an Intel Mobile Tillamook Pentium 266 CPU and 256MB of memory. The LittleBoard computer has a daughterboard that provides PS/2 keyboard and mouse input connectors and two USB ports. On the LittleBoard itself are two RS232 serial ports, a parallel port, two IDE interfaces, a Compact Flash slot, VGA video output, and a floppy controller.

The factors that led to the choice of the LittleBoard included its +5V-only power requirements, its low-power Pentium processor, support for LINUX, rugged PC-104 expansion slots, solid state (i.e. non-rotating) media support, conventional PC-type I/O, and certification for a wide range of temperature, shock, and vibration conditions (MIL-STD 202F).

Auxiliary navigation (GPS and compass): A serially interfaced Garmin GPS-18 receiver (WAAS enabled) determines current position and destination coordinates. A serially interfaced PNI TCM2 3-axis digital compass gives bearings to supplement GPS navigation. The GPS is accurate to 3m.

Video (camera and video capture board): A NTSC color video camera and an RTD Embedded Technologies CM7326ER PC-104 video capture board are used for imaging and obstacle detection. The video capture board handles both the PAL and NTSC video standards with variable frame rates and capture resolutions. It also supports multiple video channels leaving open the possibility of stereo vision in the future. A hue-based obstacle detection system is crucially dependent upon accurate color information in the video signal. To prevent problems due to color shift in the signal (due to environmental conditions, camera inaccuracies, video capture card inaccuracies, or otherwise), we provide the camera with a "known white" target in the image, an approach used by NASA to guarantee accurate color corrections on images from planetary explorers.

Software: The preliminary design called for embedded Linux as the operating system of choice. We chose the Ampro processor board in part because it came with an embedded Linux support kit (TimeSys Linux).

A primary consideration in the software design is simplicity. This is primarily an EE team with limited programming experience. This is also the first ever IGVC vehicle from Bob Jones University. Given the well-known difficulties in software development, particularly embedded system software development, we believe that we should adopt modest software goals. A simple software system fully developed and functioning is preferable to an elaborate and sophisticated design that is unimplementable given the personnel and time constraints of this project. Recent research in autonomous vehicles provides some guidance here, as discussed further below, leading us to believe that a relatively simple algorithm can nevertheless perform well under expected IGVC conditions.

The navigation algorithm is made highly tunable via an extensive configuration file, allowing easy optimization to match the actual contest course without programming changes.

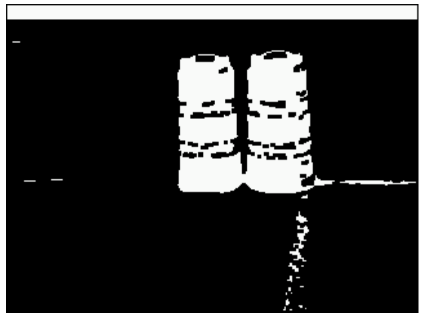
Algorithms

Autonomous challenge: Two main approaches are used in autonomous navigation: *reactive* and *deliberative*. Reactive approaches are very fast but are known to fail in complex environments. Deliberative approaches handle a much wider arrangement of environments but require intensive computation, difficult to do in real time.

Our solution, based in part on observations about how humans drive, is to use a combination of both. When the path ahead is largely clear and there is an obvious path with only peripheral obstacles, we drive fast in simple reactive mode. When our quick and simple image analysis fails to reveal a clear and obvious path, we slow down and drop into deliberative mode.

Reactive mode: Our reactive mode is based on avoidance of orange, yellow, and white color hues. These colors are identified pixel by pixel, a smoothing algorithm is applied to reduce noise, and then a trapezoid of free space is computed at the bottom center of the screen (this trapezoid of free space represents the presumed free path ahead). The robot steers towards the center of the trapezoid. The chief limitation of this algorithm is the possibility of driving through gaps in the lines, a possibility that we minimize by a built-in preference toward the center of the free space and by the trapezoid free-space approach which naturally extends lines parallel to the direction of motion. Properly marked potholes are naturally avoided. A dead-end will drop the robot out of reactive mode into deliberative mode, which will then be responsible for recovering from the dead-end.

Deliberative mode: The robot stops and looks for free paths in a number of different directions by rotating left and right within a range limited by the previous path and then selects the most-free path. If no paths are free, a dead-end is assumed and the robot will retreat and deliberate a new path.



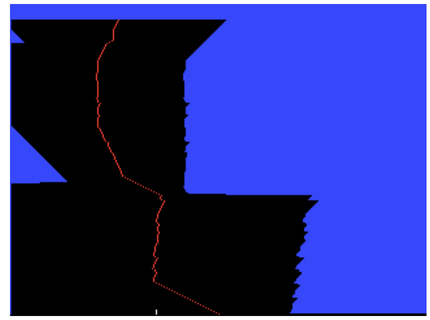


Figure 6 **Figure 7** **Figure 8**

Figure 6 shows a raw image, Figure 7 shows the result of analysis for blocked areas, and Figure 8 shows the free path space and the proposed path from an early version of the deliberative algorithm.

Navigation Challenge: Waypoints are visited in the order they are entered by the operator. The navigation algorithm addresses two conditions: 1) When no obstacles are detected in the immediate path, the robot computes the heading to the next waypoint based on current GPS position, determines the current heading by compass, and then steers in the appropriate direction to achieve that heading. 2) When obstacles are detected, the reactive algorithm from the autonomous challenge is used to steer around them, after which the robot returns to the first algorithm. WASS limitations restrict the accuracy of arrival at waypoints to within 3 feet, confirmed by testing. This is more than sufficient to meet the 2 meter requirements of the contest.

Performance Tests

Near the completion of the basic construction stage, we ran tests to determine speed, performance on 15% ramps, and battery life. These helped the team to know the robot's limitations and also to note the differences between the theoretical design predictions and the actual real-world performance.

Speed tests: In testing, the vehicle reached speeds in excess of 6 mph on level ground on a grass surface and on climbing a 15% grassy incline. Closed loop speed control limits the vehicle to 5 mph in competition and has been shown to be effective for a range of terrain conditions.

Battery life tests: Motor power and therefore battery life varies greatly with terrain. Tests confirm our preliminary predictions of battery life, and we observe more than an hour of run time on level smooth ground. The electronics package draws a mere 1.6 amps when running without a monitor, less than expected due to our highly efficient design. At this rate we have in excess of 8 hours of run time, exceeding our expectations.

Reaction time tests: As of this writing the reactive algorithm is running at 7 Hz, for a reaction time of 0.14 seconds, double the designed reaction time. Although this is adequate for IGVC, we hope to improve this by contest time. The deliberative algorithm currently runs at 2 Hz but stops between decisions so response time is not critical.

Systems integration

Testing revealed that our embedded Linux would not support our video capture driver, and the driver shipped with the board turned out to be an untested demo. The embedded extensions are apparently not open source, thereby limiting our ability to customize or fix bugs. Our technical support experience has been similarly unsatisfactory.

We attempted to use a commercial Linux distribution as a fallback solution. However, we were unable to get the video capture drivers to work under any of several versions that we explored. Discussions with the video capture board manufacturer led to the discovery that the video capture drivers for Linux were not well-supported nor fully tested, and the manufacturer was unable to assist us in making them work.

As a consequence of these discoveries, we decided to abandon Linux despite the approaching project deadline. In order to allow the project to proceed, we chose to use MS-DOS as a stable, simple environment for which a working video capture driver was available. Consequently the current software is running under MS-DOS with a 32-bit extender to allow 32-bit programming. We use the free Open-Watcom C++ compiler and write the code in C++. We purchased a commercial serial communication library (COMMDRV/DOS) to provide high-quality buffered service from our three serial ports.

Our late change of operating systems provided an additional challenge in systems integration. Our GPS interfaced through a USB port, but there is no USB support, at least for serial devices, in DOS. Serial-to-USB converters are common, but USB-to-serial is rare and problematic. Furthermore, both standard serial ports on the PC were already in use with the motor controller and compass. After extensive research, including an attempt to hack the GPS receiver to extract serial data internally and attempts to share a serial port, the decision was made to install a PC-104 serial port expansion card to provide a third serial port and to purchase a serially interfaced GPS. This solution provides a clean and effective interface that is highly successful.

The remainder of the system worked as designed without any major integration issues.

Safety

We implemented a dual e-stop as required by the rules, and tested the vehicle to guarantee the required stopping distances. The motor controller provides integrated e-stop capability and provides the braking necessary to guarantee the minimum stopping distances.

In addition to the required dual e-stop systems, foam bumpers on the front and rear of the robot provide an additional measure of safety for bystanders and obstacles. Main power supplies are fused. Batteries are sealed lead-acid with valve-regulated sealed construction and consequently have limited emissions and may be inverted without danger. The motor controller supports automatic stop in case of command loss. A keyed main power switch prevents bystanders from powering on the robot.

Reliability and Durability

The embedded processor provides a BIOS-level watchdog function for improved software reliability. The motherboard is temperature and vibration tested and reliability rated by the manufacturer. Tires are foam filled for durability. Batteries are sealed for long life. Major components including the processor and batteries are mounted with shock-absorbing materials. Easily-removable, completely-enclosed body panels provide protection from the elements. The motor controller includes both overcurrent and overheating protection.

Efficiency

A high efficiency DC-DC converter provides the main +5V power supply. A high efficiency embedded motherboard includes a low-power Tillamook CPU, no fans, no rotating media, and +5V only power requirements. Unused systems (i.e. the printer and USB ports) are powered down for further power savings. The system runs monitorless except for setup and testing. The motor controller includes high efficiency multiple-MOSFET power output stages and is rated at 120A/channel with no cooling fan. At 3.8 lb, the controller is one of the lightest in its class.

Bill of Materials

Maintaining a minimal cost was one of the major considerations in designing the robot. With our low budget, design was limited to inexpensive components with expensive components being possible only through donation. Creativity was used to stay within the budget and helped the team members learn useful skills in lowering costs without compromising design quality. Figure 8 summarizes the robot's major components and includes corresponding retail and actual prices.

Components	Quantity	Retail Price	Cost to Team
PS12180 18Ah batteries	3	$144	$144
Ampo Littleboard Pv5 single board computer	1	$995	$995
NPC-R82 motors	2	$570	$570
NPC-PH608 wheel hub	2	$40	$40
NPC-AX2550 motor controller	1	$94	$94
NPC-PT444 wheels	2	$495	$495
Garmin GPS-18 receiver	1	$89	$89
PNI-TCM2-20 Digital Compass	1	$699	$0
PC-104 4-port serial board	1	$149	$19
T-slot and angle bracket frame	N/A	$180	$180
Emergency stop system components	N/A	$70	$70
CM7326ER PC/104 video capture card	1	$455	$455
NTSC video camera	1	$15	$15
Misc. electrical components (estimated)	N/A	$100	$100
Total		**$4,096**	**$3,267**

Figure 9—Bill of Materials

Conclusion

As a new vehicle designed and built from scratch by a team of only six students on a limited budget, this vehicle is remarkably capable and is expected to perform well at the IGVC. Although price/performance ratio is not a contest criteria, it is an important real-life consideration. We believe that our vehicle will excel in price/performance compared to our competitors. We consider this design project to have been a great success.

A note regarding the name

Adam was the first human being, and so represents a fitting name for our first IGVC robot. Readers expecting an interpretation as an acronym may prefer the title Adaptive Dynamic Autonomous Machine.

Certification of design work performed by the Bob Jones University design team

I, Dr. Bill Lovegrove, Professor of Electrical Engineering at Bob Jones University, certify that the members of this engineering design have done significant engineering design work on the robot that is equivalent to the work that is awarded credit in a senior design course.

Signed:

Date: