The University of Detroit Mercy
Presents

THOR

A Newly-Designed Vehicle for The 2006 Intelligent Ground Vehicle Competition

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Faculty Advisor Statement:
We certify that the engineering design in this vehicle undertaken by the student team, consisting of both undergraduate and graduate students, is significant and qualifies for course credits in senior design and in the Master's program respectively.

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1 Introduction

The University of Detroit Mercy (UDM) autonomous vehicle team is presenting Thor as the 2006 entry into the IGVC competition. Named after the Norse god of thunder, Thor is a brand-new vehicle designed to compete in both the Autonomous and Navigation Challenge competitions as well as in the demonstration JAUS event.

The IGVC being a competition, the design/mission statement is quite straightforward: *Design and build the most competitive vehicle within the scope of a short time and a limited budget and accounting for the abilities and expertise of the team members*. That mission statement guided the design and development of the vehicle, its electronic sub-systems and software algorithms.

2 Design Process

The team set out to build an all-new vehicle for this year's competition. Despite a decent performance last year (sixth place in autonomous challenge), the team felt that there were significant fundamental drawbacks that were associated with the old vehicle that could not be remedied.

The team used a design process common to competitions where the targets for the vehicle performance are set by benchmarking the competition. Besides specific targets, the benchmarking will yield general traits that can be emulated (e.g. 2006 DARPA challenge validated the successful model of a professionally retrofitted vehicle coupled with state of the art software).

2.1 Design Methodology

Guided by the aforementioned mission statement, the team set out to determine what attributes and characteristics constitute a "competitive vehicle". Careful and objective benchmarking was done on the competitive entries of the last several years, where available vehicle performance data were related to any distinguishable design traits. Furthermore, the team drew on the extensive competition experience of senior

Vehicle subsystem	Competitive characteristics
Mechanical systems	1. Stable, sure-footed architecture with flexible and easy to control steering mechanism. 2. Simple and reliable drive train with ample power and large diameter, low rolling resistance wheels.
Electrical systems	1. Compact, modular, clean and easy to diagnose circuits. 2. Reliable, compact and lightweight power source. 3. Good telemetry and vision systems.
Software strategy	1. Parallel state of the art navigation algorithms tailored to the individual events. 2. Multiple image processing techniques providing statistical confidence indicators. 3. Incorporation of sophisticated heuristics into decision making.

Table 1: Traits of a competitive IGVC vehicle

team members and faculty, to fill-in the entire competitive map. It is obvious that such a map will be dominated by the winning Virginia Tech entries of the last few years (especially Gemini and Polaris), as well as entries fielded by Hosei University and the University of Colorado. Table 1 shows the competitive "picture" that emerged.

The team conducted the mechanical, electrical and software design and implementation concurrently. The team held weekly Friday afternoon design meetings in order to ensure that all these components will eventually integrate successfully. Iterative refinements of each sub-system/component design were driven by feedback gathered at these weekly meetings. Figure 1 depicts our iterative design process.

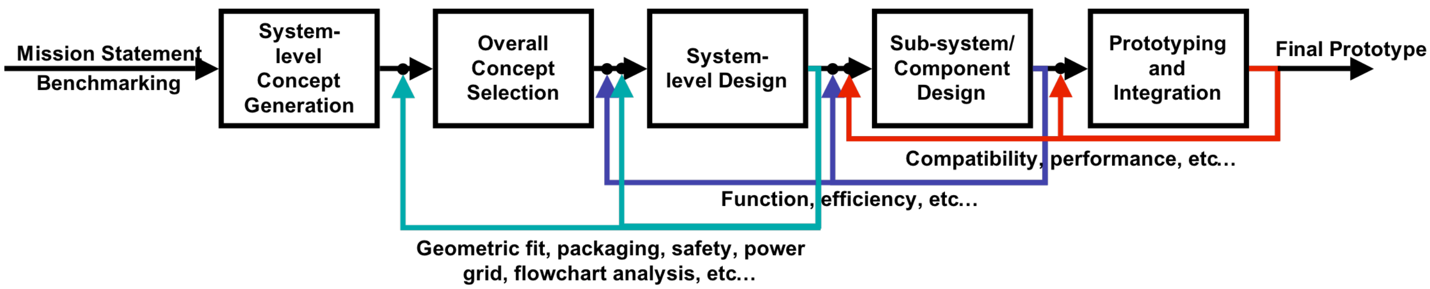


Figure 1: Iterative design process followed

2.2 Team Organization

The team consists of five electrical and computer engineering (ECE) graduate students, three ECE undergraduates and one graduate mechanical engineering student. The chart in Figure 2 below shows the structure of the design team as well as the assigned responsibilities. The UDM design team has devoted approximately 2300 hours to the development of the THOR autonomous ground vehicle.

3 Design Innovations

Mirroring the make-up of the team, which is made-up of mostly electrical engineering students, the vehicle embodies a number of design innovations in electrical hardware and software. Three major electrical subsystems were custom designed and fabricated on Printed Circuit Boards (see Section 5 for a full discussion, and the Appendix for photographs). The first is an advanced power monitoring, regulation, and control subsystem. It utilizes high-efficiency software controlled switching regulators, and a series of Hall Effect current sensors, all of which are continually monitored by THOR's real-time (RT) controller subsystem (the second PCB design). The implementation of the RT control unit was part of a system wide focus on reliable, distributed/parallel hardware and software design. Wherever feasible, multiple low-cost easily available subsystems were chosen over more powerful and specialized hardware. The third PCB-based electrical subsystem is a wireless Remote Monitoring and Control (REMOCO) system that provides emergency-stop, full vehicle remote control, and real-time information on the status of the vehicle. The REMOCO is also compatible with the Joint Architecture for Unmanned Systems (JAUS) messaging architecture.

As for the software, there are salient features in both image processing and navigation algorithms. IP and Navigation strategies both utilize multiple parallel algorithms that are either selected by a behavioral-based Arbiter driven by fused sensor data (Navigation), or statistically combined to provide confidence measures that assist inference and decision processes (IP). Additionally, a sophisticated simulation environment (see Section 6.2.3) was developed to enable testing and fine-tuning of the navigation algorithms.

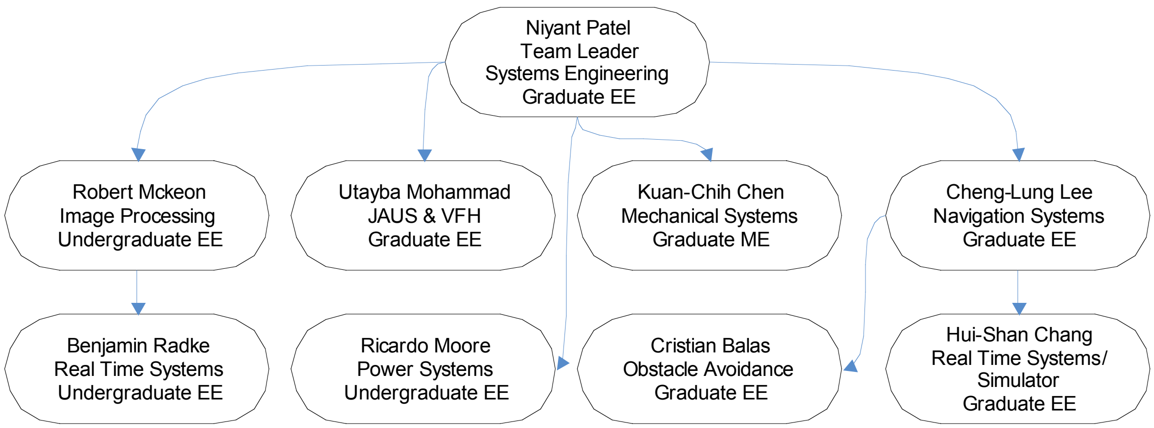


Figure 2: Design team organizational chart

4 Mechanical Systems Design

The mechanical systems on a vehicle of this sort are concerned primarily with how the vehicle is held together and moves (chassis) and how power is generated and how it is transferred to the ground (drive train). Also of note is the geometric placement of components for proper weight distribution and easy access. Throughout the mechanical systems design, extensive use was made of the Catia® computer aided design and automation tool.

4.1 Chassis

UDM fielded two entries last year; one with conventional steering and the other with an omni-directional all wheel drive/steer configuration. The limitation of the former and the complexity of the latter led the team early-on to determine that tank-type steering is critical to success in this competition. The team felt that tank-type steering is the happy medium between easiest control and maximum maneuverability. The two possibilities that emerged were a three-wheeled configuration (two drive wheels in front and a caster-wheel in the back) and the four-wheeled two-body articulated design with the two-degree of freedom hitch similar to Virginia Tech's Gemini. After many spirited discussions, the decision was made in favor of the two-body articulated design (see Figure 3) for the principal reason that it allows the vehicle to “look around” without any sideways motion that could result in sideswiping obstacles.

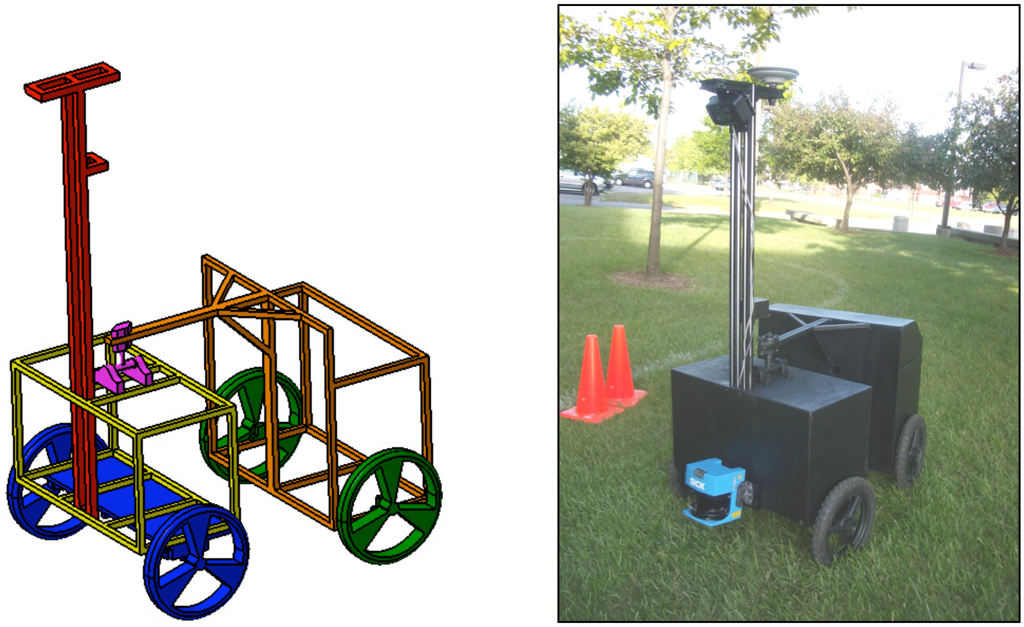


Figure 3: Design rendering and photo of finished vehicle

The chassis is made as a welded construction of thin-walled steel tubing and covered with a fiberglass shell. The rear wheels are free-wheeling while the front ones are driven. The vehicle is 32 inches wide, 31 inches tall (minus the camera mast) and 40 inches long (combined length minus LADAR) and weighs in at just under 225 lbs when fully loaded.

4.2 Drive Train

In accordance with the competitive plan determined by the team, simplicity and reliability guided the design of the drive train (shown in Figure 4). It consists of two ½ horsepower, 24V brushless DC motors with built-in 10:1 gearboxes connected via a 2.18:1 chain reducer to a driveshaft. The power was transferred to the ground via pneumatic 2 inch wide and 14 inch diameter wheels. The entire drive train is mounted on a single ½ inch thick Aluminum plate that in turn is mounted to the bottom of the chassis.

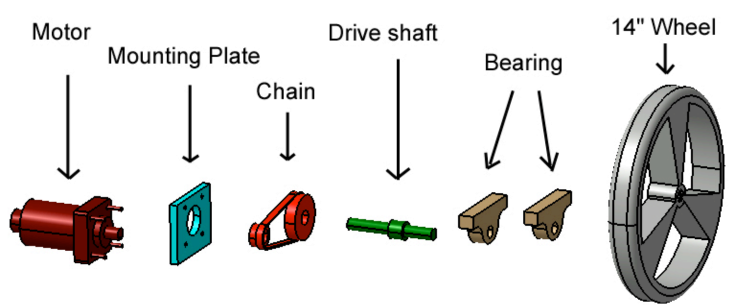


Figure 4: Drive train components in assembly sequence

5 Electrical and Electronic Systems

A considerable effort was devoted to the design and organization of the electrical and electronic systems for THOR. Given the number of electrical drive and electronic sensor and computational subsystems that are present on the vehicle, it is not surprising that these are primarily responsible for overall reliability and durability. The criteria that directed the design were taken from both the competition guidelines and our previous experience at the IGVC. Emphasis was placed on reliability, safety, modularity, built-in diagnostics and power efficiency. An overview of the major THOR electrical/electronic systems is provided in Figure 5.

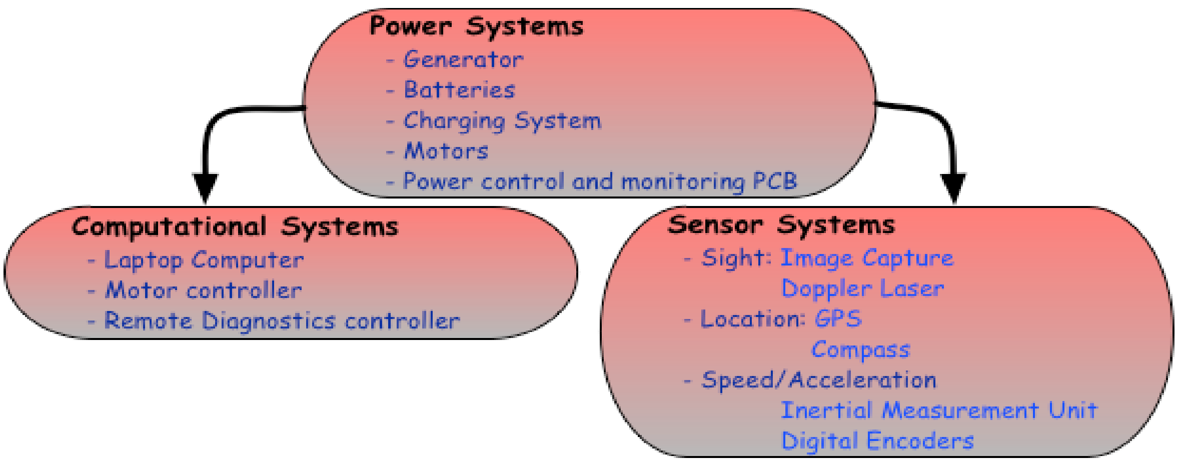


Figure 5 Electrical and electronic system overview

5.1 Power Systems

Batteries, Generator, Charger: THOR derives its primary power from two Powersonic gel-sealed 21Ah batteries. During normal operation the battery system is continuously recharged by a 1000W Yamaha generator which powers a 480W DC battery charger system. THOR is also equipped with a waterproof external AC power receptacle and automatic relay-based power source switching to allow for trouble free and safe system recharging. THOR may also be operated on battery power alone in which case the run time is approximately 1.5 hours. This hybrid power system allows continuous outdoor AGV testing for about 10 hours.

Power Control and Monitoring PCB: To ensure reliable and safe operation, the 24V system power is conditioned, regulated, monitored, and distributed by a custom-built, 4x7 inch, power management printed circuit board (see Appendix). To minimize power losses, high-efficiency LM2675 switching regulators are used to generate the vehicle's 3.3V, 5V, and 12V sources. Each regulator provides up to 1A of current, is reverse polarity protected, and runs at 85% efficiency. The individually fused power outlets are regulated with less than 1% of ripple and are continuously monitored using Hall Effect current sensors. Each system's voltage level as current flows is tracked by THOR's main computer and wirelessly linked to the Remote Monitoring Control Unit (REMOCO) for display. This allows accurate prediction of vehicle runtime as well as verification of the functionality of the independent power systems. Each switching regulator can also be controlled via software commands from the PC. This permits one to shut down power systems during debugging or to reset individual systems by forcing a power cycle.

Motors: Vehicle propulsion is provided by two brushless DC motors (Section 4.2) which feature built-in power electronics and digital Pulse Width Modulation control. The built-in electronics make operation convenient but are not a vehicle requirement. The drive system was designed to be simple, reliable, and compatible with a wide variety of low-cost Commercial Off The Shelf (COTS) hardware (motors and H-Bridge drivers). Figure 6 provides a graphical overview of the interconnection of the principal systems.

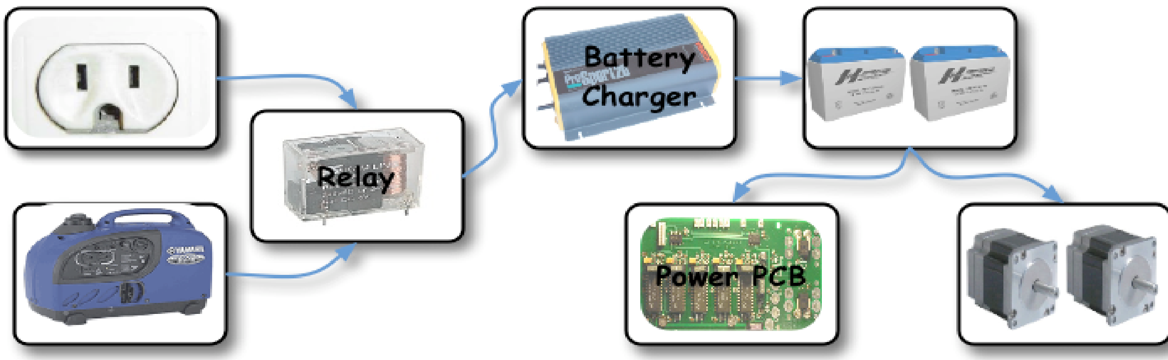


Figure 6 : Power systems overview

5.2 Computational Systems

The wide range of computational tasks necessary to operate an AGV includes image processing, telemetry, navigation, vehicle motion control, sensor management and I/O, and wireless communication. While a single, specialized, high-performance real-time system, could undertake these tasks, a more cost effective and robust approach based on multiple standard-performance systems was adopted for THOR. The data processing and control system was designed to be both distributed and parallel and comprises an HP laptop (3 GHz, 1GB Ram, Win XP Pro) and two Freescale HS12 microcontrollers (24MHz, 12K Ram, 256K Flash, SwiftX Forth). One HS12 system is configured as a real-time controller devoted to vehicle motion control, power monitoring, and wireless communication tasks, whereas the other is used to implement the REMOCO unit.

Real-Time Controller: In order to effectively implement vehicle motion control and handle high-speed sensor I/O for an AGV, a real-time (RT) system is necessary. Rather than purchase a costly general purpose RT-controller directly code-compatible with Matlab/Simulink or LabView, THOR's design team chose to design a dedicated PCB-based system board which would integrate efficient power regulation, wireless communication, vehicle power systems diagnostics, and an RT-controller on a single compact and easily serviceable board (see Appendix). A number of companies make well-designed microcontroller boards that can be socketed as a daughter-board on a larger PCB. In particular, Technological Arts (Toronto, Canada) produces a wide variety of proven designs, and THOR utilizes the Adapt9S12DP256. The use of a daughter-board configuration for THOR's RT-processor makes the overall system easy and cost effective to diagnose and maintain. THOR's main processor is programmed in Swiftx-FORTH and uses multitasking to simultaneously undertake the following:

1. Measure vehicle motion (via encoder input),
2. Provide Pulse Width Modulated (PWM) outputs to control motor speed,
3. Monitor all of the Power System PCB's voltage and current sensor information,
4. Read real-time data from the THOR's Inertial Measurement Unit (IMU),
5. Communicate to the REMOCO over the Aerocomm wireless serial tranceiver link, and
6. Share information with the main laptop computer system.

E-Stop & Remote Monitoring and Control Unit: Wireless E-Stop was implemented as part of the much more full-featured Remote Monitoring and Control (REMOCO) system which was conceived as a real-time user interface between THOR and its operator. An embedded Freescale HS12 microcontroller was used to provide the REMOCO with a broad range of capabilities. A user can interrogate the AGV and display data on a 20 x 4 character LCD screen. Current speed, GPS position, sensor outputs, power consumption, and expected run time are a small subset of the many inquiries the user can make over the wireless serial link. Critical information on individual component power consumption, low fuel levels, and malfunctioning subsystems can be accessed using REMOCO. Furthermore, the protocol interface between the REMOCO and the vehicle is a subset of JAUS, allowing the system to be easily converted into a complete JAUS compliant design.

A printed circuit board design was created (see Appendix) to provide a reliable and compact implementation. It incorporates an embedded Freescale HS12 microcontroller, a high-efficiency switching regulator, integrated joystick, and an Aerocomm serial and general I/O RF transceiver makes it possible to communicate over a range that can exceed 3 miles (line of site).

5.3 Sensor Systems

The sensors used by THOR are a digital camera, a LADAR (Laser Detection and Ranging) unit, a DGPS (Differential Global Positioning System), and a digital compass/IMU. The signals from these sensors are available through standard interfaces that are easily read into either a laptop or microcontroller. Weatherproof

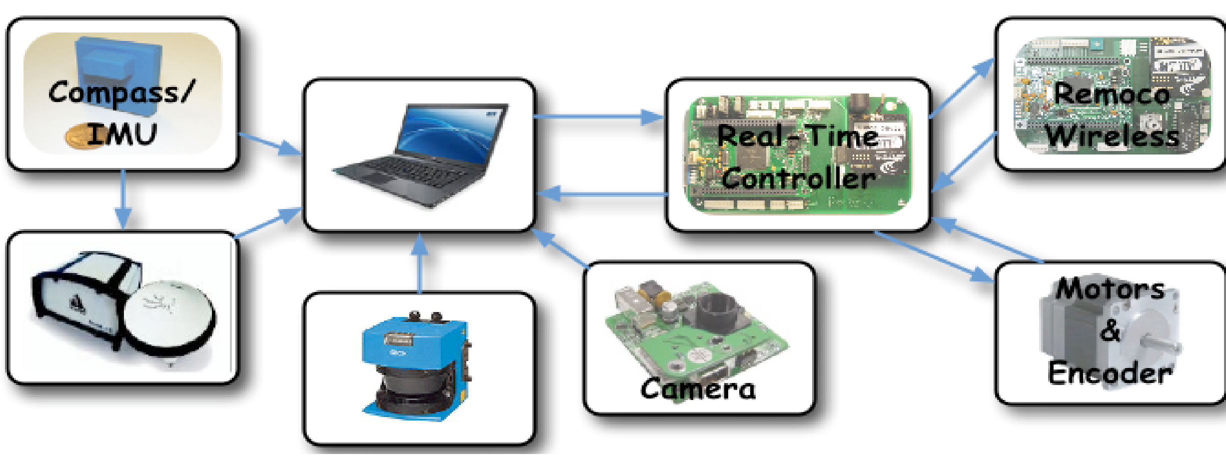


Figure 7: Sensor and computational system interconnections

enclosures were built for the camera and compass while the other units come fully protected. Figure 7 presents an overview of the sensor and computational systems interconnections.

Camera: A low-cost Fire-i board camera from Unibrain was selected with a native resolution of 640 by 320 pixels, a 80.95^0 horizontal viewing angle, and uncompressed VGA picture acquisition at 30 fps. The camera input is used for lane and obstacle detection and provided data to the laptop using the firewire protocol, which eliminates the need for a frame grabber.

LADAR: THOR uses the LMS-200 LADAR unit from Sick to detect obstacles. This unit is capable of collecting data over a 180^0 degree field of view at a resolution of either 0.5^0 or 1^0 as far out as 80 meter with a distance error of ±15 mm. It has a refresh rate of 75 Hz. With the choice of the 0.5^0 resolution mode, the data is transferred at 500 kBaud. To use the full capability of the LMS, a high speed serial interface card for PC communication was designed and built. The LADAR mounting arrangement has been designed to enable easy adjustment of level and orientation; this is critical to enable it to be mounted such that it looks over a ramp or other undulating terrain.

DGPS: A Novatel Propak-LBplus GPS system is mounted at the top of THOR's mast. This system provides a position accuracy of 1.5 meters CEP (Circular Error Probability) with a data rate of 20 Hz. This accuracy is further refined by using Omnistar HP differential correction down to 0.1 meters CEP. This unit also accepts external inputs from an Inertial Measurement Unit (up to 3 axis gyros and 3 axis accelerometers). This unit is used in the navigation challenge.

Compass: A Sparton SP3003D digital compass and IMU, is mounted halfway up Thor's mast, and provides 3-axis tilt-compensated bearing, tilt and roll data with 0.3^0 accuracy and 0.1^0 resolution at a 10 Hz refresh rate. Furthermore, the IMU data is compatible with THOR's Novatel DGPS unit which internally combines the IMU and GPS data to provide stable coordinate information during temporary GPS outage. This unit enables vehicle heading to be established in the navigation challenge as well as vehicle inclination status (ramp, hill etc.) which improves system reliability and perfomance.

6 Computational Intelligence

The most critical aspects of vehicle performance are the algorithms designed for vision and navigation. These were developed using MATLAB® & Simulink® and are described in the following sections. All system software was designed in a modular fashion by different programmers on the team. Careful attention was given to the input and output interfaces for each module so that software integration was a seamless process.

6.1 Vision

The fundamental requirement of the image processing system (IPS) is to provide lane, terrain, and obstacle information to the vehicle navigation software subsystems. The course to be traversed in the competition consists of a lane demarcated by painted white and yellow lines on grass with the possibility of one or other of the two lines being deliberately left out over segments of the course. The course also consists of other challenging artifacts such as a sandpit, a ramp, potholes, colored tarps that alter the color composition of scenes, and obstacles created by the placement of orange and white construction barrels, traffic cones, saw-horses, buckets etc.

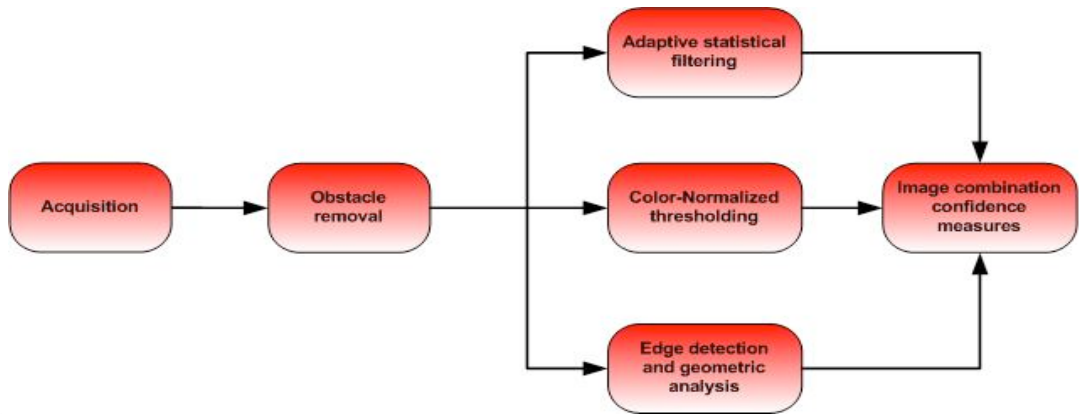


Figure 8: Image processing strategy overview

The vision strategy implemented for THOR is based on parallel analysis, in that it processes images with four distinct algorithms (see Figure 8). Individual results are combined to generate both a set of lane coordinates as well as a confidence measure. These are then fed into a parallel behaviorial-programming based navigation program. This unique approach has been designed to take advantage of the individual strengths of region-based, derivative-based, and morphological image processing techniques. Furthermore, the use of confidence measures dovetails with the application of powerful fuzzy inference techniques which are incorporated in the navigation code.

The initial algorithm applied to an image serves to reduce size, identify, map, and remove obstacles (barrels, cones, pot-holes etc.) from the image frame. This is accomplished by the application of color-based segmentation, combined with geometric and region measures. One purpose of this step is of course to locate potential obstacles. However, a less obvious benefit is substantial improvement in line/curve identification and mapping algorithm performance due to the absence of large obstructions along lane edges.

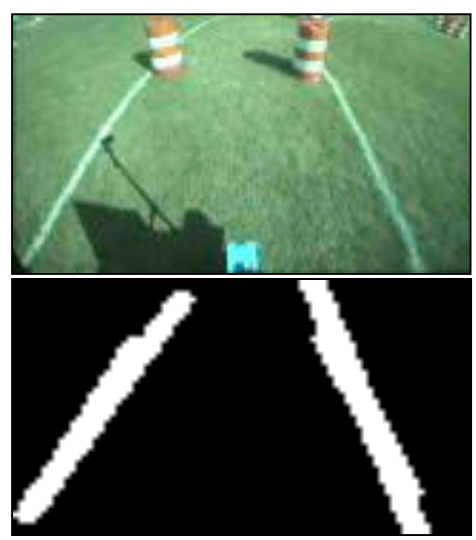


Figure 9: Original and final processed images

The obstacle-reduced image is processed by three separate and parallel IP algorithms. The first, implements a color-based row/column-adaptive statistical filter to establish an intensity floor. This eliminates illumination and hue gradients and highlights line areas. Following this, cumulative row and column pixel aggregation projections are used in conjunction with an intensity histogram and apriori knowledge about lane thickness and separation to determine a global threshold. The constants identified are dependent on lane quality and image noise. Next, a connectivity filter is applied to the rows to reduce salt and pepper noise. Finally a quadrant-based Hough transform is applied to collect pixels most likely associated with lane lines.

The second IP algorithm adaptively normalizes each color plane using local means and combines them using a single color map thus altering contrast to favor white and yellow lines. A sparse binary image is extracted from this “grayscale” result by selecting row and column maximums (with a mean-based floor threshold). Again, a quadrant-based Hough transform is applied to collect pixels most likely associated with lane lines.

The third IP technique applied utilizes the contrast-enhanced image from the algorithm above, but applies a Sobel edge detector followed by morphological dilation and erosion and a geometric characteristic filter to yield long continuous line segments. Once again this processing path is completed by the application of the Hough transform.

The three results are then combined and a majority-voting confidence measure generated (see Figure 9). Perspective correction insures the accuracy of the location of mapped obstacles and lanes. The application of the Hough Transform in each of the above algorithms serves to make the lane identification results insensitve to breaks in the lines (openings or dashes). Intermediate image results can be found in the Appendix.

6.2 Navigation

The vehicle needs to be navigated in two different competition paradigms – the autonomous and navigation challenges – that have different demands. For instance, vision is essential for the former whereas GPS waypoint-based goals are used in the latter. Currently two separate algorithms based on different philosophies have been developed for the two needs, but the possibility of crossover usage is being investigated. The algorithm developed for the autonomous challenge is well suited to the development of sophisticated heuristics and the fusing of a broad range of sensor data. The navigation challenge algorithm on the other hand is ideally suited for shortest path calculation and the circumnavigation of obstacles.

6.2.1 Navigation for Autonomous Challenge

A behavior-based programming architecture is used to implement vehicle navigation. The overall objective is to optimally fuse goal-following behavior as determined by the vision algorithms and obstacle-avoidance behavior as (predominantly) determined by the LADAR to provide a composite steering angle to the motion controller. Only obstacles within 4 meters in front of the vehicle are considered as being relevant. The structure of the adopted strategy is shown in Figure 10.

Essentially a series of parallel algorithms is executed, each of which employs simple calculations or heuristics to determine a vehicle heading. Environment sensors and situation-based confidence measures are used to select a dominant behavior by subsuming other commands via the use of an Arbiter program. Inputs include compass heading, e-stop/remote control, lane, barrel, and pothole positions from image processing,

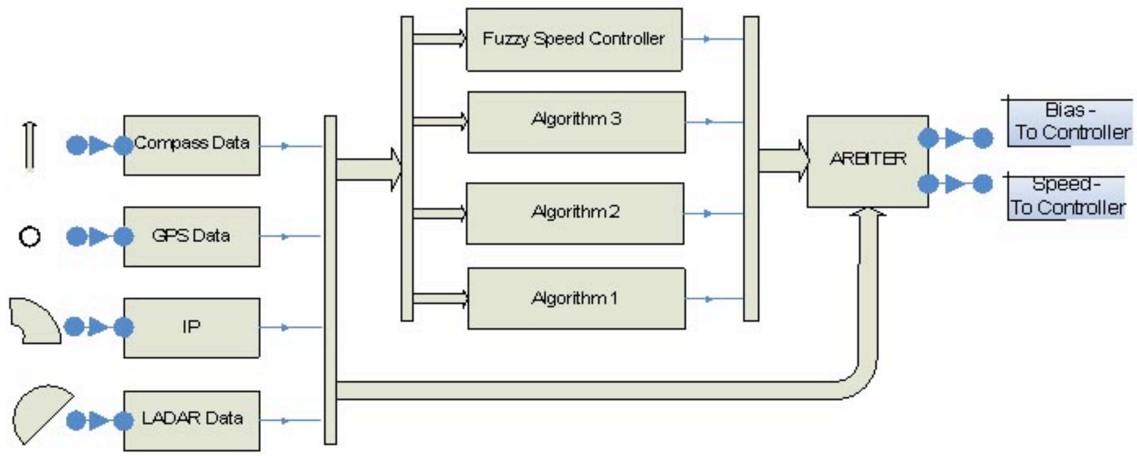


Figure 10: Arbitrated parallel navigation strategy

general obstacle locations from the LADAR, and DGPS path history. Most inputs are accompanied by a statistically or heuristically determined confidence measure. For example when there is high confidence in the quality of the lane and obstacle location inputs from the vision algorithm (as indicated by confidence measures), Algorithm 1 determines the composite steering angle with minimal input from the fuzzy inference system (FIS). When the vision results are less certain, Algorithm 2 is selected. It invokes fuzzy inference techniques to combine the IP and LADAR inputs to establish the resulting steering angle. Similarly, Algorithm 3 comes into play when sensors indicate that the vehicle has navigated into a trap. It invokes a ballistic behavior which uses the ability provided by the zero turning radius of THOR to turn around and exit the trap with the help of a stored local map.

One other facet of THOR's navigatio.n strategy is the incorporation of fuzzy speed control that enables THOR to set its speed in accordance with the confidence associated with its sensor inputs and the general clutter of its surroundings. A major advantage of the modular and parallel structure of this navigation strategy is that it facilitates continuous enhancement through incorporation of additional algorithms to handle other difficult navigation situations without significant rewriting of earlier code. Other behaviors can be easily added and administered via the Arbiter, and the computational load can easily be distributed among multiple processors.

6.2.2 Navigation for Navigation Challenge

Navigation for this challenge was implemented using the data from the GPS, LADAR, compass, and encoders. The compass reading reveals the current vehicle heading. The latitude and longitude coordinates of the current vehicle position (from the DGPS) and the next waypoint are converted to a conventional polar representation, and a target vehicle heading is established. This heading does not however take obstacles into account. In order therefore, to effectively navigate to the waypoint, the Vector Field Histogram (VFH) algorithm is used to establish a modified steering direction that accounts for obstacles.

The VFH algorithm is based on the creation of a local polar map of obstacles in front of the vehicle derived from the LADAR data. A modified vehicle heading is then established as the minimum of a cost function that is influenced by the target direction amongst other factors. The cost function is evaluated over all openings that are big enough to accommodate the vehicle as determined from the local map. The VFH algorithm also enables vehicle speed to be determined based on the obstacle clutter and the change in vehicle direction to be executed. Figure 11 presents an overview of the algorithm flow. Since the LADAR can only scan a 180^0 arc in front of it, the vehicle will not see any obstacles once the nose of the vehicle passes them. If these obstacles are close to the vehicle sides, the VFH algorithm (in its basic form) may result in decisions that cause sideswiping of such obstacles when a turn is executed. To avoid this situation a composite local map is first developed piecing together current and previous LADAR data, with the help of compass and GPS data. The compass and GPS data help provide the corrections that enable the past and present LADAR readings to be combined with the correct perspective. The modified VFH algorithm takes this local map and reflects the close obstacles just passed to a corresponding position in front of the vehicle. This forces the vehicle into a softer turn which eliminates sideswiping.

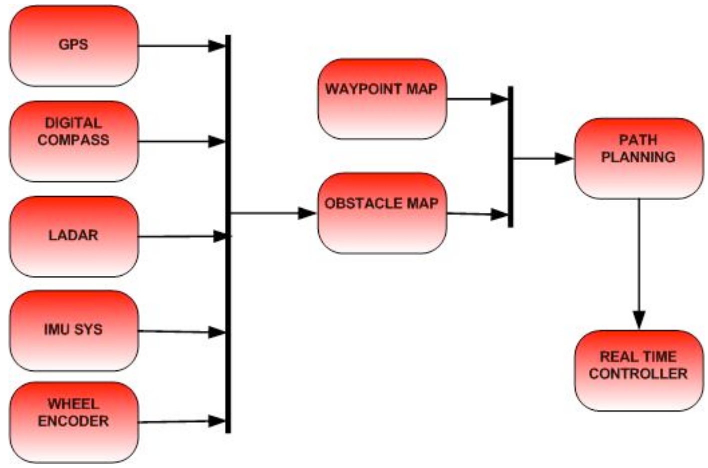


Figure 11: VFH strategy

6.2.3 Simulation

A software simulator was developed to test both navigation algorithms extensively for various obstacle and lane configurations and waypoints. This enabled the autonomous navigation algorithm to be adjusted for optimal path determination (including avoiding common traps) via the incorporation of sophisticated heuristics, while narrowing down the particularly difficult cases that needed special attention. Additionally, the same simulator was instrumental in developing a 360^0 polar map for the VFH algorithm. This facilitated the incorporation of heuristics which insure that THOR properly clears obstacles before resuming a heading to the next waypoint (prevents sideswiping etc.).

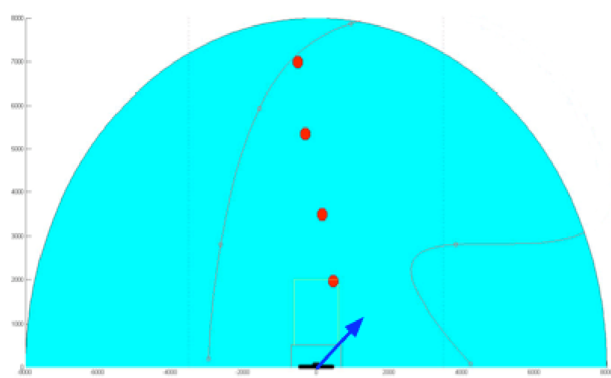


Figure 12: Navigation strategy simulator output

The simulation program was developed using MATLAB® & Simulink®. It was designed for easy manipulation of input data, representation of the information obtained from the LADAR and the Image Processing systems, and integration with the programs used in the Autonomous and Navigation Challenges. As seen in Figure 12, different course situations can be easily considered, by placing lines and obstacles with a simple mouse click. The heading directions returned by the various navigation routines are graphically represented on the same figure.

7 System Integration, Testing & Validation

The process of system integration is very important to getting the overall product to meet the performance objectives. This is especially true for the design of an autonomous vehicle with a complex interaction of mechanical and electrical systems, and software. The weekly design review meetings helped provide the structure for this process.

Construction of the vehicle began in mid February and was completed by mid March. While this effort was going on, several other concurrent developments were taking place. Software code for controlling the drive motors, the remote control unit, and the various electrical systems were developed and tested in a bench top mode and the power systems were designed, built and tested. The vision and navigation algorithms were developed and tested first on static archived images, then by using an earlier competition vehicle on our test courses; an indoor course with lanes defined by paper strips and two outdoor courses to enable testing in an environment as close to the real conditions of the competition as possible. The tuning of the navigation algorithms was particularly facilitated by the software simulator we had developed as described in Section 6.2.3.

When the new chassis was ready, the drive train was assembled, and the vehicle was tested outdoors using the remote control unit (REMOCO) by the end of March. Next the electronic systems were brought on board and integrated. Finally testing of the autonomous vehicle in its competition modes began. We are currently in the process of fine-tuning vehicle performance for competition in the autonomous and navigation challenges.

8 Other Design Issues

8.1 Predicted Performance

Speed: The drive motors have a no-load speed of 3000 rpm. Taking into account the gearing incorporated into the drive train as well as the wheel size, this translates to a maximum speed of 6.6 mph. Actual tests with a fully loaded vehicle yielded a maximum speed of 5.7 mph. Through the use of speed control software this was restricted to 5 mph, in accordance with competition rules.

Ramp climbing ability: Based on the torque output of the drive motors in conjunction with the selected gearing and wheel size, it was predicted that THOR would be able to climb an incline of 15% as required by the competition rules. In actual tests THOR was able to negotiate a gradient of over 30%.

Reaction times: Processing an image, making a navigation decision, and having the vehicle controller relay it to the motors take approximately 40 ms, 15 ms, and 10 ms respectively, for a total cycle time of 65 ms. Assuming that the vehicle is moving at its maximum permitted speed of 5 mph, this translates to roughly 0.5 feet of traversal before refresh, which is more than adequate for safe navigation considering the setup of the course. In the navigation challenge, vision is not used. However, waypoint-based path planning is introduced. The overall measured computation time averaged to 42ms per cycle.

Battery life: The power requirements of the various vehicle sub-systems are listed in Table 2. The demand from the drive motors obviously has the most influence on overall run time. Additionally this demand varies with the torque output required – the listed value corresponds to the worst-case situation of maximum torque requirement. Using the gasoline generator, THOR can operate for over ten hours (based on fuel capacity). If the generator runs out of fuel, THOR can continue to run for more than 1.5 hours on the 24V onboard battery bank. The laptop's battery allows it to run for about the same time (1.5 hours) without re-charging.

Component	Voltage (V)	Current (A)	Power (W)
Laptop	16	6	96
LADAR	24	0.6	14.4
DGPS	12	0.5	6
Digital Compass	5	0.01	0.05
Firewire Camera	12	0.3	3.6
DC motors (2)	24	14	336
RT-Transceiver	3.3	0.25	0.825
RT-Controller	5	0.25	1.25
Total			458.125

Table 2: Power Consumption Estimates

Distance at which obstacles are detected: While the LADAR unit has a range of about 262 feet (80 meters), only obstacles closer than about 13 feet (4 meters) are taken into account by the software, since this is all that is relevant for immediate navigation. The camera with its additional mounting height is capable of seeing occluded barrels which may define a trap. An ongoing effort is to investigate whether this additional information could be converted into heuristics that aid navigation.

How the vehicle deals with traps and potholes: Both vision and navigation incorporate an extensive set of heuristics designed to prevent driving into the most commonly anticipated traps through effective path planning; these are currently being fine tuned through the use of both specially developed software simulations and the actual creation of various traps on practice courses. If despite this we enter a trap, the zero turning radius of the vehicle will permit extrication. In addition, use of the immediate history of GPS data and compass information enables the vehicle to avoid reversing course after extrication from a trap.

Accuracy of arrival at navigation waypoints: The waypoints at the competition are designated as two meter radius circles centered on the GPS coordinates of the waypoint. The DGPS system used has an accuracy less than 10 cm at a data rate of 20 Hz. The digital compass used to indicate current heading has an accuracy of 0.3^0. These capabilities enable THOR to consistently "touch" the waypoints.

8.2 Safety, Reliability & Durability

These were significant factors in several of our design decisions and have been discussed throughout the document. To recap, the two e-stop systems (manual button and remote) were designed such that the vehicle could be reliably brought to a quick and safe stop when called for. It is important to note that e-stop commands are not processed by the main system computer, but are directly fed to hardware controller that interrupts operation. The vehicle was weatherproofed such that light rain would not result in electrical short circuits. This involved the incorporation of fully waterproof connectors, NEMA enclosures for major subsystems, and a sealed fiberglass body cover. All electrical circuits were carefully fused to prevent electrical damage. Furthermore, individual currents and voltages were monitored in all circuits to enable automatic shut down by the real time controller. The status of individual systems can also be queried from the wireless REMOCO unit. Diagnostic software and LCD&LED indicator systems were developed so faults could be quickly pinpointed and repaired. The exhaust fumes from the gasoline generator were properly vented from the vehicle to prevent buildup. A fire extinguisher is mounted onboard to enable quick action to be taken in case of a fire. A wire harness was used for the safe routing of all electrical wires for power distribution. Also, sealed gel-cell batteries were utilized so as to eliminate potential safety problems associated with leakage.

8.3 Vehicle Cost: Efficient Use of Materials/Power

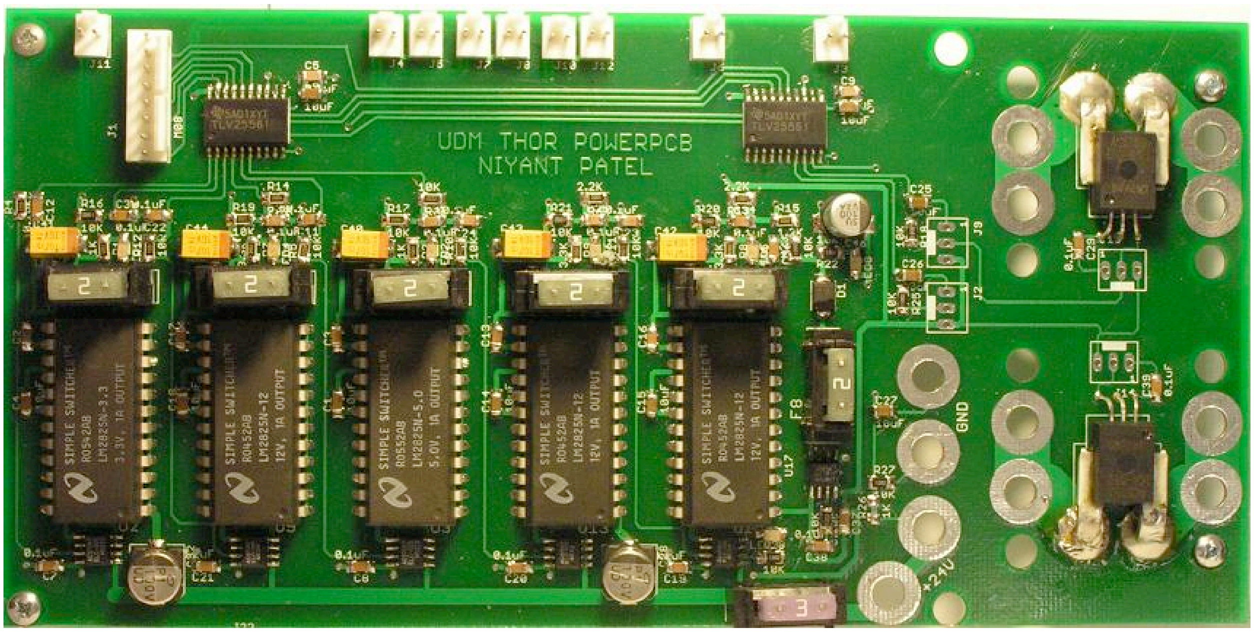
Throughout the design, development and construction of the THOR AGV, the team endeavored to produce a modular, reliable, efficient and low-cost design. For example THOR's drive system permits the use of easily available brushed or brushless DC motors, and the parallel/distributed computational systems are comprised of a 2-year-old laptop and two common microcontrollers, and yet they deliver excellent performance. Also, superb run-times were obtained via the use of efficient switching power regulation throughout. Similarly the chassis, a rigid and effective design, utilizes only standard welded square tubing (salvage grade). These design decisions resulted in a cost effective and efficient design as indicated in the following table.

Item Description	Team Cost	Retail Cost	Comments
NovAtel DGPS + Antenna	$2,700	$6,000	Discounted from Novatel
SICK LMS LADAR	$0	$5,500	Used from Previous Vehicle
Digital Compass	$0	$960	Donation From Sparton
Brushless DC Motors	$0	$1,000	Donation
Quantech PCMCIA to RS232	$0	$275	
Fire-I Camera	$0	$96	Used from Previous Vehicle
Gel Cell Batteries	$70	$70	
Yamaha 1000is Generator	$650	$650	
Frame/ Body	$500	$500	
Skyway 14 in Wheels	$84	$84	
Laptop	$0	$1,200	Used from Previous Vehicle
Pro Sport Battery Charger	$149	$149	
PCBs & components	$500	$500	
Total	$4,153	$16,484	

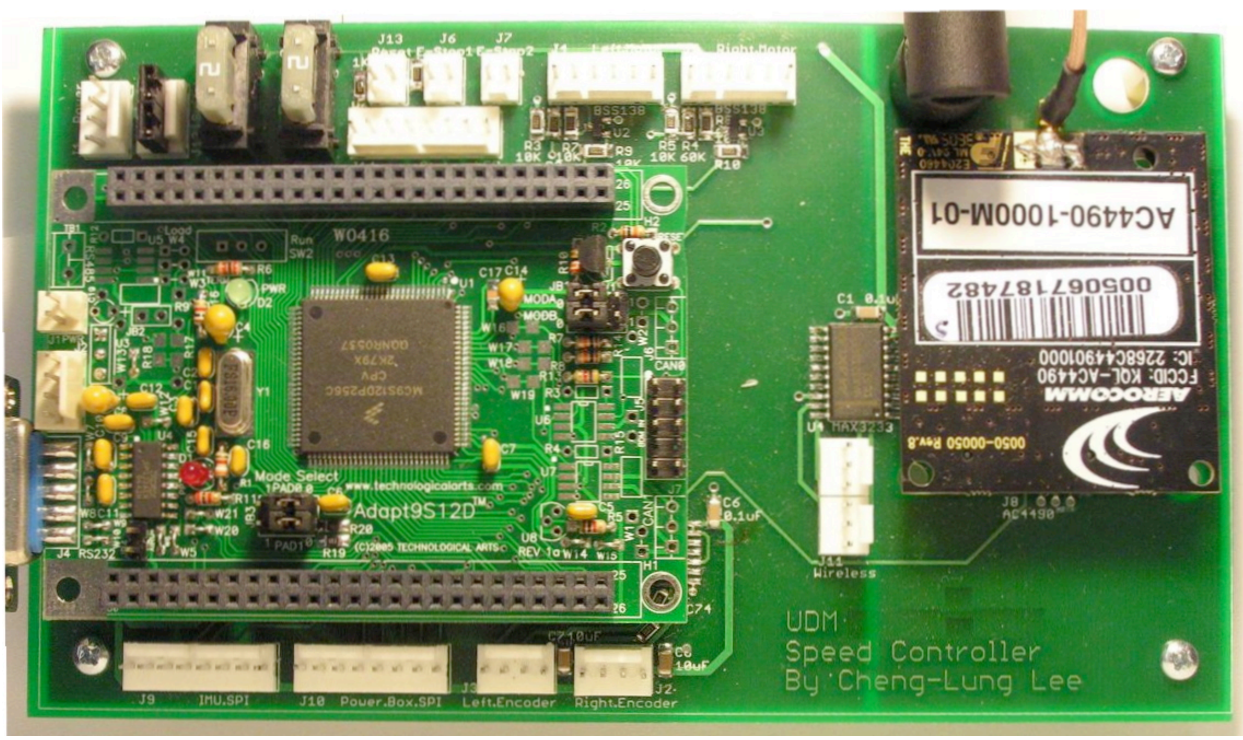
Table 3: Vehicle Component Cost

APPENDIX: Additional Pictures and Figures

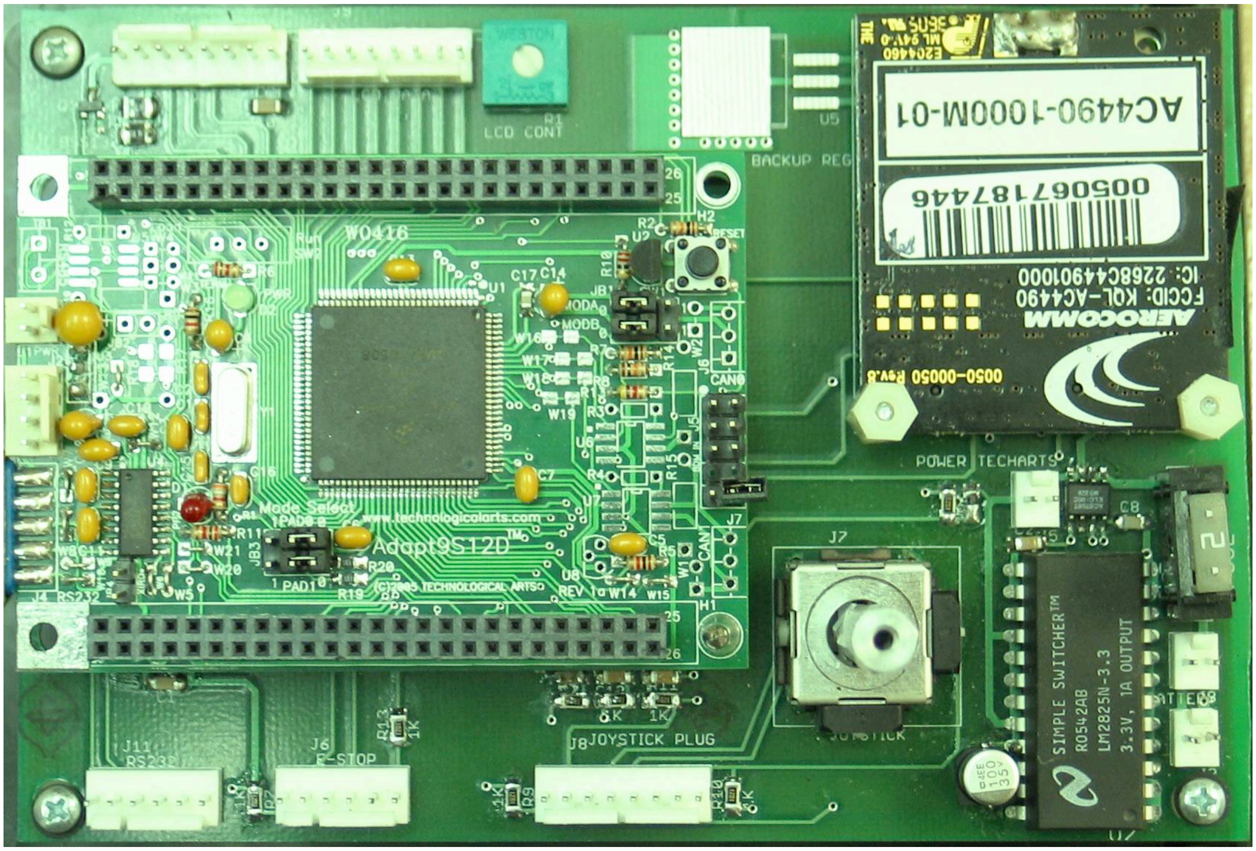
1 Printed Circuit Board Figures



Appendix Figure 1: Power systems regulation and monitoring board



Appendix Figure 2: Real-Time controller



Appendix Figure 3: REMOCO -- Remote Monitoring Controller

2 Image Processing Figures

Appendix Figure 4: Original image

Appendix Figure 5 : Identified barrels

Appendix Figure 6: Adaptive statistical filtering → Binary result

Appendix Figure 7 : Edge detection result

Appendix Figure 8 : Color normalized thresholding result

Appendix Figure 9 : Combined three algorithm Hough Transform results