University of Detroit Mercy Presents

THOR PRO

IGVC 2009 – Design Report

Team Members:

Jun Chen

Maen Hammod

Modar Horani

Mohammed Horani

Preethi Venkat

Raymond Slowik

Shih-Chieh Liao

Yasser Alnounou

Yazan Aljeroudi

Faculty Advisors:

Dr. Mohan Krishnan

Dr. Mark Paulik

Dr. Chaomin Luo

Consultants:

Kevin Barry

Cheng-Lung Lee

Bryan Thomas

Utayba Mohammad

Faculty Advisor Statement:

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

Dr. Krishnan/ Dr. Paulik/ Dr. Luo ______________________________

1. Introduction

The University of Detroit Mercy's entry for the 2009 IGVC is **THOR PRO**, an articulated vehicle which is based on the same platform that placed first overall in the 2008 IGVC. The fact that there has been no major breakdown in its mechanical or electrical/electronic systems since vehicle induction last year, despite substantial use in research projects and in preparation for this year's competition, is a testimony to its exceptional reliability, an outcome of the rigorous design methodology adopted. While the chassis is the same, significant innovative enhancements both in the hardware and software areas have been made to the vehicle, as addressed later in the report.

2. Design Process

2.1. Design Methodology

Designing an entry for an annual performance-based competition, such as the IGVC, is an exercise in continuous improvement based on the lessons learnt from the previous years, and good documentation practices which facilitate transfer of knowledge.

Shortly after the 2008 IGVC ended, a team meeting was held to reflect on our strengths and weaknesses as well as the innovative aspects of the vehicles of other competitors; an itemized list was generated which served as the springboard for the next cycle of development. For example, it was noticed that on rougher ground the vehicle had a "bouncy" behavior; this led to the replacement of its hard foam-filled tires with new semi-liquid-filled tires which provide increased damping for a more stable ride.

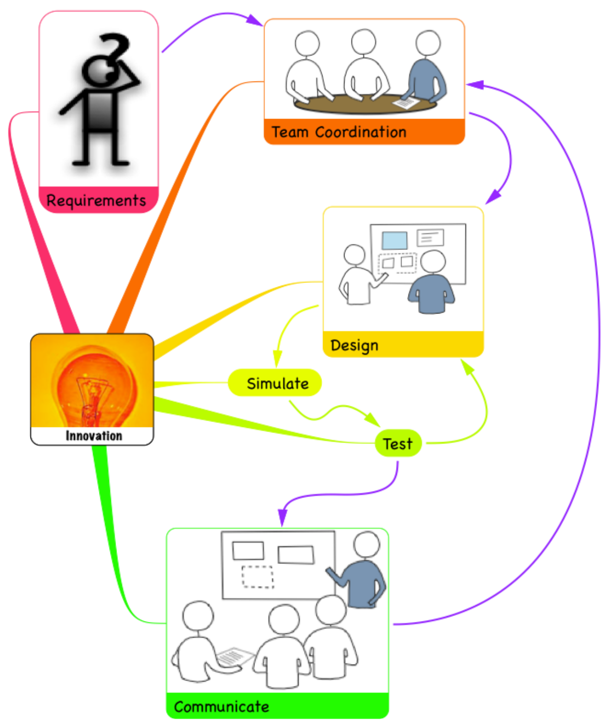

Figure 1: Iterative Design Process Adopted

The team concurrently conducted mechanical, electrical, and software design and implementation tasks. Facilitating an iterative design process was a meeting and reporting structure shown in Figure 1, which ensured that all of the mechanical, electrical/electronic, and software systems would integrate seamlessly with each other. This process, which worked very well for us in 2008, consisted of three components: a) weekly design oral review meetings with faculty advisors to provide task updates, identify problems and formulate solution strategies, b) weekly (as well as on a ad-hoc needs basis) sub-team meetings to discuss specific design and implementation issues, and c) weekly lab periods to execute the design strategies with full team attendance to implement the concurrent design philosophy.

2.2. Team Organization

The composition and organization of the 2009 IGVC team, made up entirely of ECE graduate students, is shown in Figure 2. The team has devoted approximately 2000 hours towards the development of this year's vehicle. In addition to the faculty advisors, a consultant team of student IGVC "veterans", who had participated in earlier competitions, was constituted as a knowledge resource.

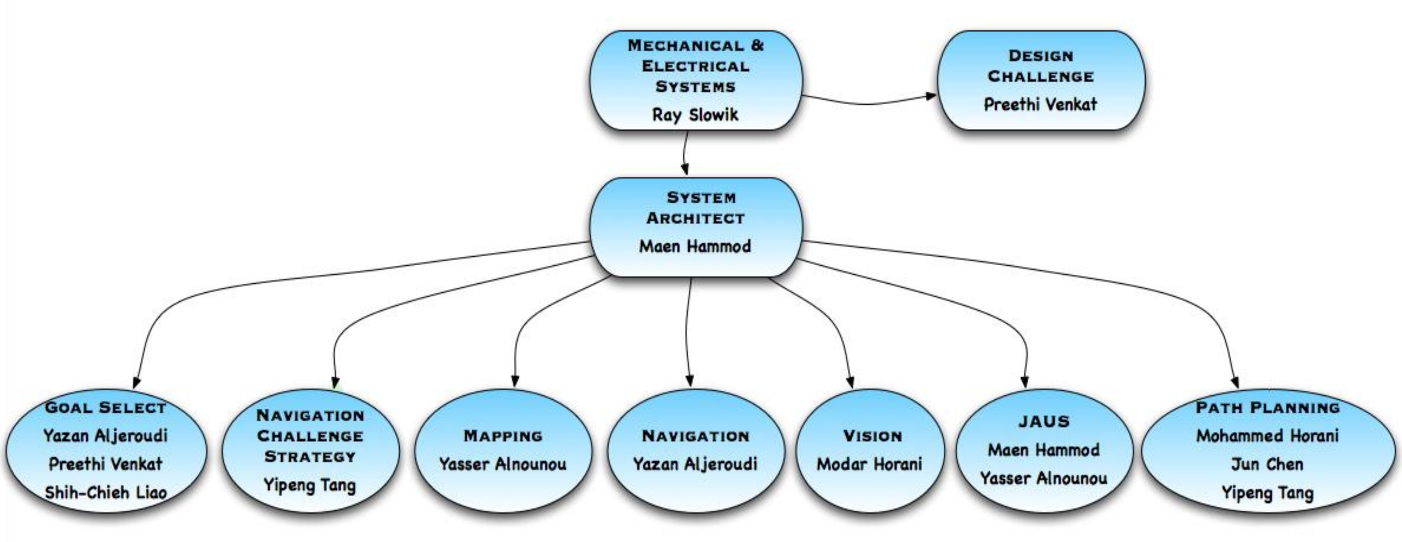

Figure 2: Team Organization

2.3 Vehicle Cost

The cost breakdown for the development of this vehicle is provided in Table 1.

Description	Retail Cost	Team Cost	Comments
Frame/Body	$586	$586	Some volunteer work was involved
Drive Train	$3,944	$3,944	Purchased new
Front Wheels (4)	$600	$0	Donated by Invacare
Batteries (4) & Charger	$349	$200	Purchased
Power PCB	$172	$172	Designed in-house
Remote PCB	$304	$104	Transceiver donated by Aerocomm
Camera, Lens, Adapter	$937	$898	Used from previous vehicle
LADAR (2)	$11,000	$11,000	Purchased
DGPS and Antenna	$6,000	$6,000	Used from previous vehicle
Digital Compass	$1,096	$0	Donated by PNI Corporation
MacBook computers (3)	$3,902	$3,902	Purchased
Total	**$28,890**	**$26,806**	**Savings of $2,084**

Table 1: Cost Breakdown

3. Design Innovations

A number of significant innovations have been incorporated in **THOR PRO** since the last competition. These are listed below and discussed in greater detail later on in various parts of the report. While these discussions are distributed, for ease of identification an innovation icon (a light bulb) is used to indicate when innovations are being discussed in this document.

- **3D Scanning LADAR**: A 2nd LADAR unit is used to assemble a 3D image of obstacles using stepped planar scans. This information when projected onto a 2D environmental map reveals obstacles above and below the scan plane of the 1st fixed LADAR. It is useful in avoiding obstacles such as the inclined sawhorse (sawhorse with one leg removed), a feature of the 2007 IGVC course.

- **Vector Polar Histogram (VPH+) Algorithm:** A new navigation algorithm that is superior to the commonly used VFH algorithm and its derivatives (VFH+, VFH*) when navigating in a cluttered environment has been implemented.

- **Enhanced image processing techniques: THOR PRO** has a new, augmented Image Processing suite which employs enhanced techniques based on morphological processing to improve lane line structure identification in the presence of significant amounts of noise, and incorporates adaptive thresholding strategies to enable stable vision operation even under changing ambient illumination.

4. Vehicle Configuration

4.1 Mechanical Systems:

Our vehicle is an articulated platform with a differential drive front end and a freewheeling trailer (cover photo). The degree-of-freedom afforded by the 2-body design enables the vehicle to maneuver better in cluttered environments as compared to other vehicle configurations. The center of gravity is low and laterally symmetric and the associated 60:40 weight distribution between the front and rear bodies contributes to drive traction and vehicle stability. The geometric placement of subsystems for proper weight distribution, ease of accessibility, and the efficient use of space is an important aspect of design.

4.1.1. Chassis & Drive Train:

THOR PRO'S chassis (cover photo) is a welded backbone of heavy gauge aluminum covered with thin aluminum side panels. The mast is made up of extruded aluminum bars specified to reduce camera vibration. The vehicle is 28 inches wide, 72 inches tall (including the camera mast), and 39 inches long (not including the LADAR), and weighs approximately 375 pounds when fully loaded. The use of right-angle gearboxes in the drive train narrows the vehicle. This, along with the articulated property permits it to be more easily driven through a standard doorway. The overall vehicle layout achieves an approximate 60:40 weight distribution (front to rear). Placing 60% of the total gross vehicle weight in the front body is necessary to generate sufficient traction. **THOR PRO'S** modular drive train comprises two 3/4-HP Quicksilver 34HC-2 motors, coupled to 10:1 planetary 90 degree gear heads, which are connected to two 14-in. wheels using Lovejoy couplings.

4.2. Electrical and Electronics Systems

4.2.1. Power Distribution System

THOR PRO derives its power from 4 Powersonic gel-sealed batteries of which two are rated for 35 Ah and two for 18 Ah. Under normal operating conditions these batteries will allow the vehicle to be operated for about 5 hours.

A 480W DC battery charger positioned inside the vehicle can be powered from the AC mains to fully recharge the batteries in approximately 2.5 hours.

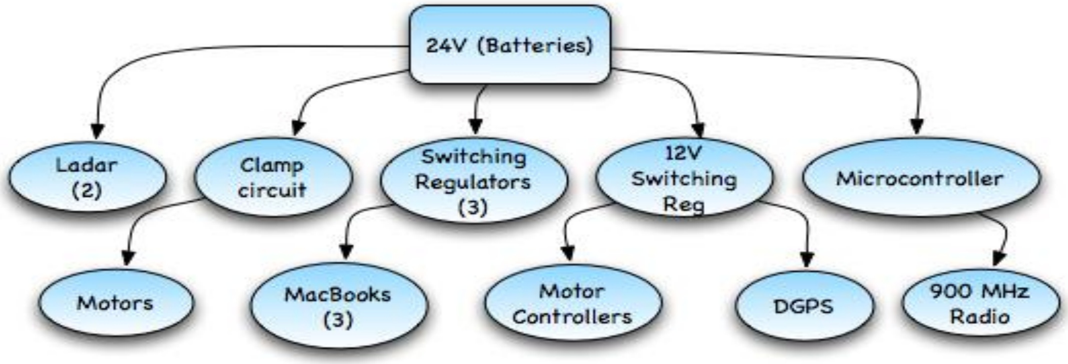

Figure 3: Power Distribution System

The power necessary to properly operate the vehicle and its electrical/electronic sub-systems is distributed via a custom-designed printed circuit board (PCB) to implement the power distribution scheme shown in Figure 3. To help ensure that **THOR PRO** is safe, reliable, durable, and easily serviceable, several special features have been incorporated into the power distribution system. The PCB is designed such that high power components are isolated from lower power components. Fuses are strategically positioned on the PCB to prevent electrical damage due to unexpected current surges. The incorporation of high efficiency switching regulators provides stable outputs with low ripple. In addition, these regulators have been designed to protect the PCB from low battery voltage levels, short circuiting, and overheating, thereby extending the life cycle of the circuitry. A clamper circuit is connected to the motor power supply to absorb the motor's back EMF. The status of the power box is conveyed via a series of panel-mounted light emitting diodes (LEDs). Finally, vehicle-wide systems integration is addressed by the use of a real-time current and voltage monitoring system that sends status information from the power box to the main laptop through a USB connection. Thus, if a problem occurs, its source can be located quickly and diagnosed.

4.2.2. Sensor System

THOR PRO incorporates five sensors into its compact design: a camera, two LADAR units, a DGPS, and a digital compass. It is extremely important to ensure the continual operation of these devices under the anticipated conditions of operation. Each sensor is mounted in a waterproof case and secured to the vehicle in such a manner that it is not affected by normal vehicle motion. At the same time, the mounting arrangements for each sensor subsystem are designed to facilitate

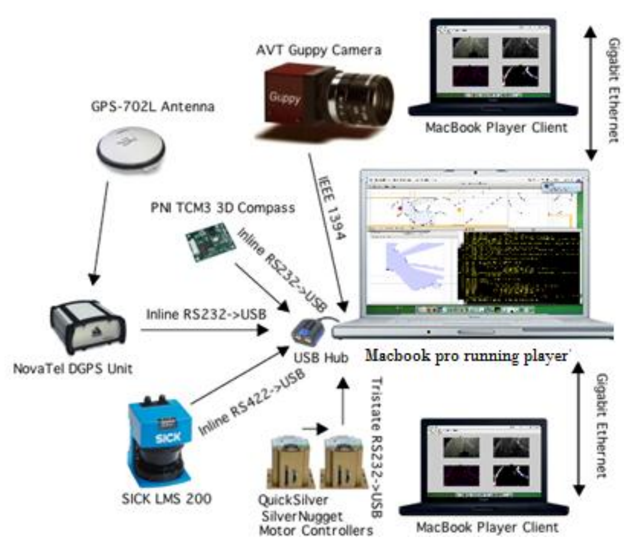

Figure 4: System Communication

their easy removal and replacement if it becomes necessary. The following is a brief description of the sensors that are used by **Thor Pro** as shown in Figure 4.

Camera**:** The AVT Guppy F-033C 1/3” CCD camera was selected as the vision sensor for this vehicle. This camera uses the IIDC IEEE 1394 protocol to relay images, which is ideal for machine vision applications, because the frames are uncompressed and various options such as region of interest and lookup tables can be set and executed in hardware. Also, the camera’s progressive scanning and high frame rates minimize motion blurring. The CS-Mount design enables the camera to accept a very wide angle low distortion lens which provides a 125° field-of-view which makes navigation heuristics easier to implement.

Fixed LADAR: A SICK LMS200 LADAR unit was employed for the purposes of obstacle detection. The unit is capable of collecting data over a 180° field-of-view with 0.5° resolution and a range of 8m. **Thor Pro** uses a 75Hz scanning rate which, at this resolution, requires a 500Kbps data connection. To accomplish this, an RS422-to-USB adapter was constructed to connect the LADAR to the computer.

3D Scanning LADAR: The 3D Scanning LADAR is also a SICK LMS200. It is continuously nodded vertically through a selectable range of displacement using a Quick Silver Motor/Controller arrangement (as in cover page). The output data from the LADAR is associated with a time stamp and a vertical angular position recorded at the start of each scan using an encoder. The output is map-able to a 2D map of the environment through simple projection. Objects that are detected above the height of the vehicle are isolated and removed from the 2D map. Ground returns are handled by controlling the downward tilt of the scanning LADAR and then using the return distance to assess importance. Low angle returns that are below the fixed 2D LADAR plane can be heuristically differentiated into actual obstructions or ramps/inclinations, based on comparison with the fixed 2D LADAR returns. The improved definition in the obstacle avoidance map allows for the inclusion of saw horses and other vertically asymmetric obstructions that would have normally been missed by the fixed plane LADAR. The regular 2D LADAR remains part of the sensor suite as a partly redundant device due to the rapid frame rate achievable with its use as a fixed scan device; it is conceivable in the future that can operate the vehicle with just the scanning 3D LADAR.

DGPS**:** To obtain positioning data in the Navigation Challenge, Novatel’s ProPak-LBplus DGPS system was selected. The DGPS antenna is mounted to the top of the vehicle’s mast while the receiver is securely positioned inside the chassis. Using Omnistar HP’s DGPS system, the signal is corrected to the extent of ± 0.1m accuracy. This system provides data at a rate of 20Hz, which is adequate for **Thor Pro’s** expected speed and desired performance.

Digital compass**:** A PNI TCM3 digital compass was integrated into the vehicle to help determine vehicle heading. This compass provides a heading accuracy of 0.5° and updates at 20 Hz, which again is sufficient for the vehicle’s speed and desired performance.

4.2.3. Remote Control & E-Stop Systems

Although **Thor Pro** must be capable of autonomous navigation in competition, incorporation of a remote control facilitates manual operation of the vehicle. The remote control, which can operate in one of two modes (PC or RC), is made up of a custom designed PCB housed within a durable Futaba remote control shell. When the remote control is set to operate in PC mode, it transfers control of the motors to the computer (retaining E-stop control). If placed in RC mode, the operator can manually drive the vehicle.

The transceivers that are used in **Thor Pro's** design are Aerocomm AC4490-200A transceivers. Although the vehicle is only required to be controlled from a maximum distance of 50ft, with the implementation of the aforementioned transceivers, the vehicle is capable of being controlled from nearly a mile away. A twist-to-release remote E-Stop button is integrated into the remote control unit. As an added measure of security and immunity to interference, we transmit encrypted data over a spread spectrum wireless link for two-way communication between the vehicle and remote.

4.2.4. Electrical and Electronics Communication System

The various electrical and electronics systems were interfaced in the manner illustrated in Figure 4. The AVT Guppy is connected via Firewire (1394B) to the MacBook Pro. The DGPS system is connected to the computer through a USB interface using an inline RS-232-to-USB adapter. The SICK LMS200 LADAR is connected to the computer via a custom inline RS-422-to-USB converter. The PNI TCM3 digital compass uses RS-232 and requires 5V at 20mA for operation. Finally, all the computers are networked via gigabit Ethernet.

4. Development Environment, Processor Architecture, Algorithms, Etc.

Some of the most important features of **Thor Pro** that directly impact its performance are discussed in this section. Certain modules are used only in a particular Challenge; if not self-evident, usage is clarified.

5.1. Software Development Environment

The software development environment used is shown in Figure 5 and consists of two layers. The first is the server layer which is occupied by Player™, an open-source, Unix-based (Linux or Mac OS X) robotic software system that serves as an interface between robotic algorithm implementations and the vehicle systems. Specifically, it provides standard interfaces for a typical set of robotic peripherals (LADAR, cameras, motors, etc.) that can be accessed from the local computer or any other computer over a TCP/IP network. The second layer is the client layer occupied by user programs written in MATLAB®. These layers communicate with Player™ over a TCP socket to acquire data from sensors and send actuator commands, which Player™ then passes on to the vehicle. The writing of efficient wrappers to enable communication between the two layers is what has enabled our program developers to utilize MATLAB®, with its wealth of proven and powerful resources, for algorithm development. The construction of this environment is the single most important development over the past few years of IGVC participation. It provides the stable foundation that facilitates seamless integration of the algorithms of future generations of developers in support of this effort. The pipeline to MATLAB®-based development, a contribution of one of our "IGVC alums" to the Player-Stage™ open source community is particularly useful!

The development environment also permits the use of the Stage™ simulator. Stage™ allows off-vehicle testing and development by simulating a robotic environment complete with the robot, obstacles, LADAR, camera and GPS. Stage™ can be used to quickly test and validate a new algorithm which saves a lot of time compared to direct validation on the vehicle. The availability of Player™-compatible drivers for all of **THOR PRO'S** hardware facilitates robot software development and testing by allowing algorithm code to run unmodified on either the simulator or actual vehicle. A graphical depiction of robot motion within its environment affords a powerful tool to gauge the effectiveness of algorithms; examples of this feature are provided later in the report.

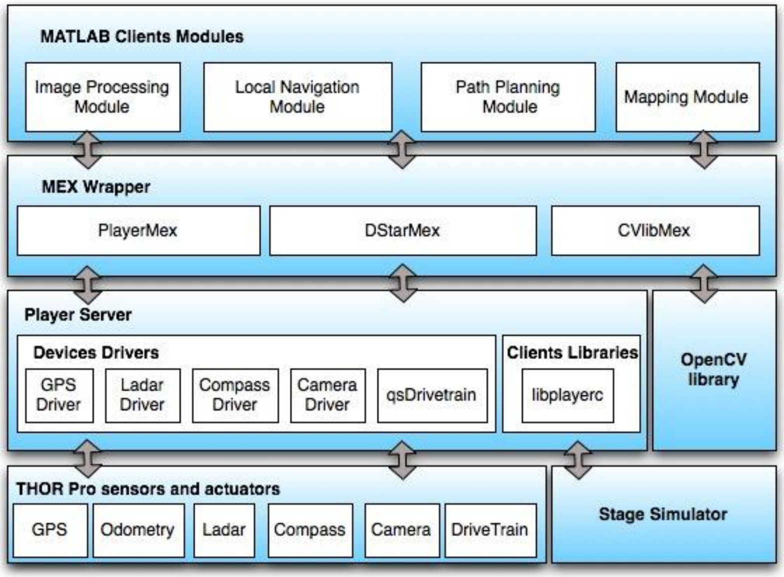

Figure 5: Software Development Environment

5.2. Enhancing the Frame Rate

Sophisticated vision algorithms are central to a successful strategy for the Autonomous Challenge due to the complex obstacle, lane, and terrain features present. If, when implementing these algorithms, the associated computational complexity causes the overall image-frame processing rate to drop too far, the vehicle may not be capable of operating effectively at higher speeds.

In order to favorably address this tradeoff, a multi-pronged strategy to increase the frame rate was adopted. First, **THOR PRO** distributes its computational tasks among three laptop computers (with a total of 6 processor cores). Using Player™ as a server facilitates setting up this distributed computing architecture and provides a wealth of existing open-source code to draw from. The topmost computer (in the three drawer stack), a MacBook Pro, is entirely devoted to running components of the overall vision algorithm. This computer utilizes the MATLAB® parallel processing toolbox to spawn multiple workers which exploit parallelism in several of the IP routines (e.g., contrast enhancement and adaptive thresholding). This enables effective utilization of the multiple processor cores present. A second MacBook Pro is responsible for accepting the data from the vehicle's sensors, implementing heuristics on the vision results, generating a map, and navigating the vehicle. A third MacBook is tasked with goal selection and path planning.

It is also possible to pipeline as well as distribute computations for image processing by assigning elements in the IP algorithm chain to two computers, so that multiple image frames are being processed concurrently. This results in a one-frame delay for motion decisions but can yield a higher overall frame rate, which if high enough causes negligible effects on vehicle dynamics.

The second element of **THOR PRO'S** computation strategy is based on the use of the built-in NVidia® Graphical Processing Unit (GPU) present on MacBook computers to offload the most computationally intensive tasks (e.g., 2D-convolution, morphological processing, etc.). This is accomplished via the use of open-source NVidia® CUDA™ libraries, and the Jacket™ MATLAB® GPU library plug-in by AccelerEyes®.

5.3. Mapping, Path Planning and Navigation

Mapping: Mapping is an important capability for autonomous robots that facilitates good decision making. It is particularly beneficial in the Navigation Challenge, since it enables the use of path planning algorithms to determine the optimal route between waypoints. However, even in the Autonomous Challenge, the ability to maintain a global map could be used to enable the robot to partially retrace its path when it thinks it is in a trap. Mapping requires an accurate estimate of the robot pose (X, Y, Yaw) so that precise registration of the local map on the global map can be carried out. A Kalman Filter was implemented to estimate vehicle pose reliably by fusing data from the motor encoders, the DGPS, and the compass. This also allows GPS outages to be managed if they occur. The creation of a global map enables path planning to be used in the Navigation Challenge to optimize travel. In the Autonomous Challenge, a local map containing fused obstacle and lane line information is used for goal setting.

Path Planning: Performance in the Navigation Challenge is considerably enhanced if path planning is utilized. Path planning is carried out using the D*Lite algorithm, which provides the best route between waypoints. D*Lite can work off a partially complete map of the field, and progressively re-plans the optimal route when the map is augmented with new information as the robot explores.

Navigation: For both Challenges, robot navigation is carried out using the VPH+ algorithm. This is a more recent and sophisticated algorithm compared to the hitherto commonly-used VFH family of algorithms, and it exhibits better performance in cluttered environments. It incorporates an obstacle grouping step, which is based on a higher-level interpretation of obstacle clusters, and prevents the robot from venturing into concave obstacle configurations. Figure 6 shows the robot path chosen in the same navigation task with VFH+ and VPH+ respectively, clearly illustrating the superiority of the latter.

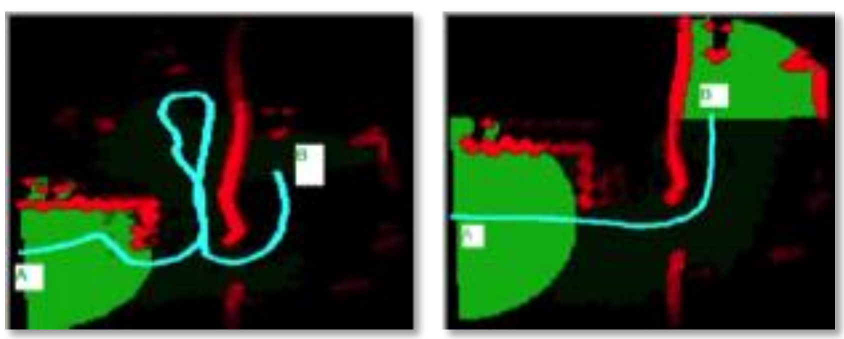

Figure 6: VFH+ and VPH+ Navigation

5.4 Software: Autonomous Challenge

The software for the Autonomous Challenge can be broken into three main parts. Image Processing, Goal Selection, and finally Navigation. All of these tasks run in parallel, taking advantage of the multi-computer/multi-core system architecture.

Thor Pro's novel image processing algorithm can be summarized as follows. It begins by utilizing the color characteristics of the various scene elements to simultaneously enhance lane contrast and produce a gray-scale image. This image is then corrected for lens and perspective distortion and adaptively thresholded to compensate for illumination variations, producing a black and white (BW) result. The BW image is then subjected to morphological and derivative filtering to eliminate noise, extract lane structure, and highlight edges. Next, a 4-quadrant Hough transform and repository-based outlier removal algorithm is applied in order to fit lane edges and produce consistent linked linear segments. These segments are then tracked with multiple Kalman filters to remove jitter and smooth image transitions. In each step of this process, special attention has been paid to computational complexity and possible parallelism. The result (see Figure 7) is a stable, real-time extraction of salient lane features. The following paragraphs provide further detail on the new and innovative elements of this process.

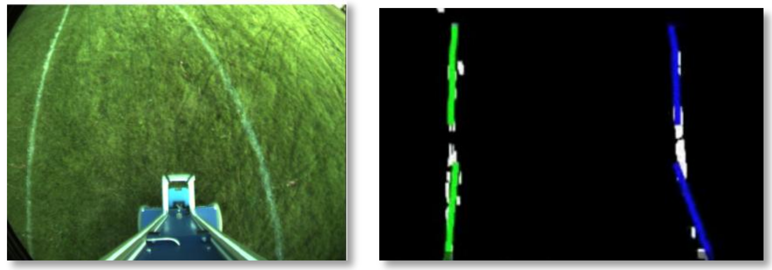

Figure 7: Kalman Stabilized Quad Hough Results

Adaptive Thresholding: Variations in illumination due to the angle of the sun, glare, and irregular reflectivity commonly occur when analyzing outdoor images. It is difficult to effectively threshold an image with a global value in this situation. Thor Pro makes use of an innovative row and column adaptive approach which tracks illumination and contrast variations and develops local thresholds which are still responsive to global changes in illumination (e.g. sun vs. clouds). This approach provides a consistent BW image result that is insensitive to illumination gradients. The input to the adaptive threshold module is a gray scale image where the contrast of the white lanes has been enhanced relative to the background by taking into account a priori information derived from color histogram analysis (see Figure 8).

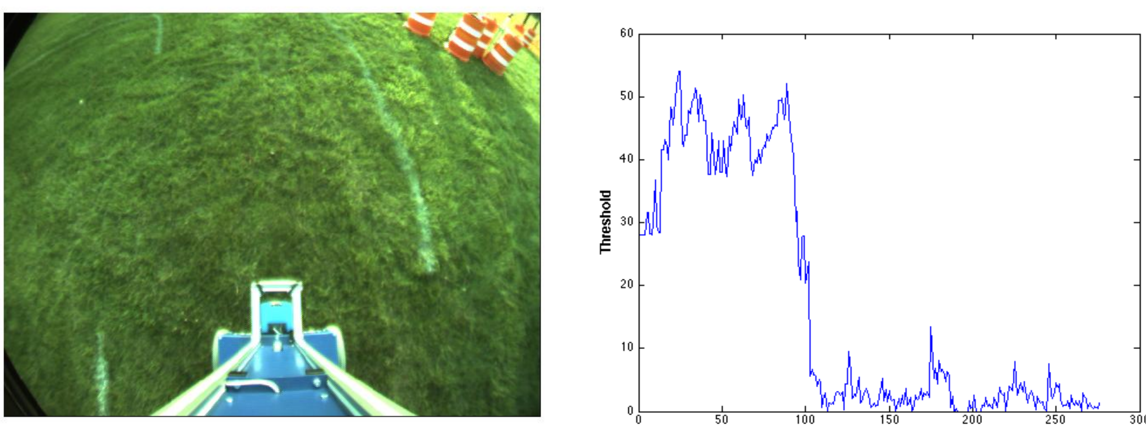

Figure 8: Adaptive Thresholding

Morphological Filtering: The BW image resulting from the adaptive thresholding operation is still likely to consist of sparse, pixel-based lines combined with multiple “noise” artifacts arising from grass-blade reflections, light colored dead grass patches, bare ground regions etc. These are addressed by a multi-step filtering process whose central element is a novel morphological filtering operation. The challenge at this point is to both agglomerate the individual lane pixels and attenuate noise. By designing a morphological structuring element (strel) which joins pixels which are organized in elongated regions with predictable width characteristics, lane pixels can be joined by a dilation/erosion operation while leaving unorganized noise elements unattached. An elongated diamond-shaped strel was developed to meet these requirements. Figure 9 below illustrates a representative morphological sequence. Figure 9(a) depicts an adaptively thresholded image. Notice that the lanes comprise many individual pixels with substantial numbers of small gaps. Figure 9(b) illustrates the effect of morphological dilation with the diamond strel. In this case it is clear that lane pixels have been added to make “solid” structures. The application of a subsequent erosion with the same strel reduces the noise to its original state while leaving the lane pixels nicely agglomerated (Figure 9(c)). The final morphological operation is designed to help filter out as much of the remaining noise as possible without damaging the extracted structures of the lane lines. The use of a simple 3x3 square structuring element and an erosion operation provides excellent results as illustrated in Figure 9(d).

After this set of filtering operations, the lane elements are nicely structured and it remains to identify a minimal set of pixels to submit to a Hough transform operation. Since the Hough transform is computationally intensive, it behooves one to transform as few pixels as possible. A simple derivative filter utilizing a Sobel mask is used to accomplish this. The resulting image is then passed to a 4-Quadrant Hough transform operation that serves to extract line segments for each quadrant.

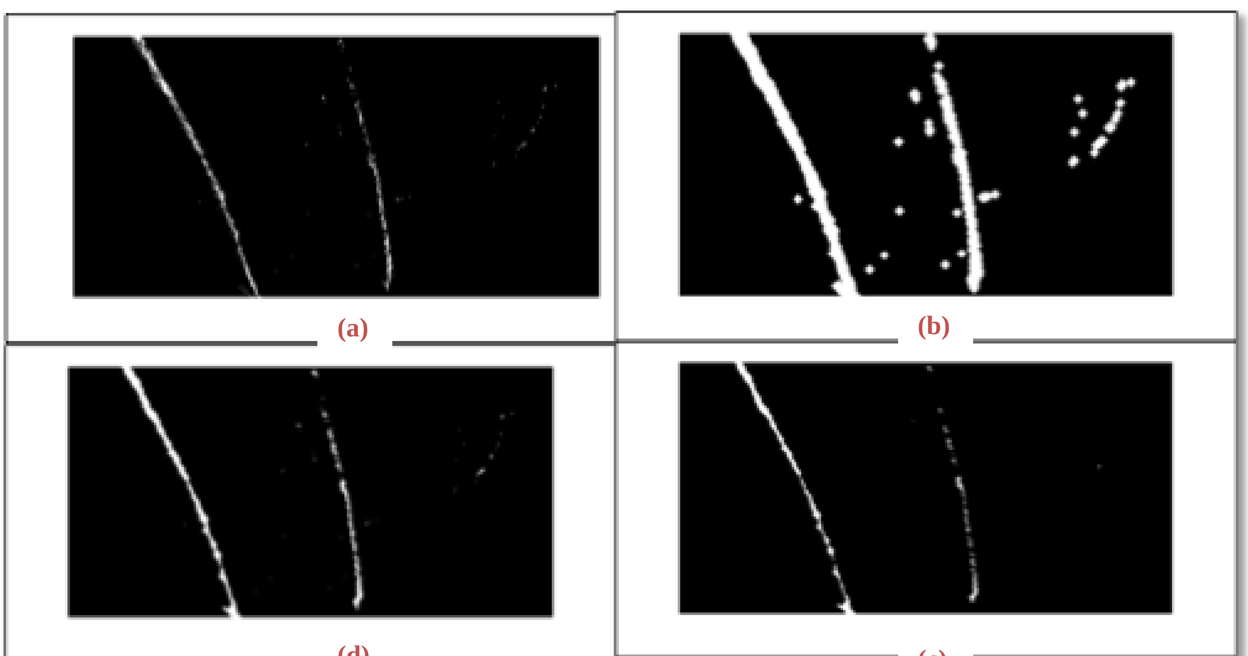

Figure 9: a) Thresholding b) Dilation c) Erosion d) Noise Filtering

Repository-based outlier detection: Despite the extensive structural lane identification and noise filtering undertaken up to this point, it is still possible occasionally to have noise artifacts presented as lane lines. This is particularly true in the case of high-glare poor-contrast image analysis. To improve the stability of the identified lanes, an innovative repository-based outlier detection system was implemented. The system tracks lane-line candidates and requires that a similarity measure be satisfied to be included in the same repository cell. If a line is sufficiently different than preceding samples, a new repository cell is configured and counters are adjusted to track frequency values for all active repository cells. Thresholds are used to determine when it is appropriate to switch the active lane, with hysteresis incorporated to prevent jitters in active lane selection. Separate repositories exist for each of the four image quadrants and Kalman filters are run for all active repository cells to smooth line transitions and reduce image jitter due to robot and camera mast motion. The overall effect generated by this sophisticated system is to remove noise outliers from consideration, as well as dramatically smooth lane segment motion with the image frame used for goal selection and navigation.

Goal Selection: The goal selection algorithm is concerned with determining the "forward" direction. For the Navigation Challenge this is relatively easy, as forward is towards the next waypoint. However, in the autonomous challenge, the forward direction is less easy to determine, since it requires the vehicle to "go around the course". The forward direction then has to be established from the results of the Image Processing algorithms, which, due to the sensitivity to illumination, reflection, etc., are not 100% reliable. Further complicating the situation is the presence of course features such as switchbacks and ramps, which can create apparent traps.

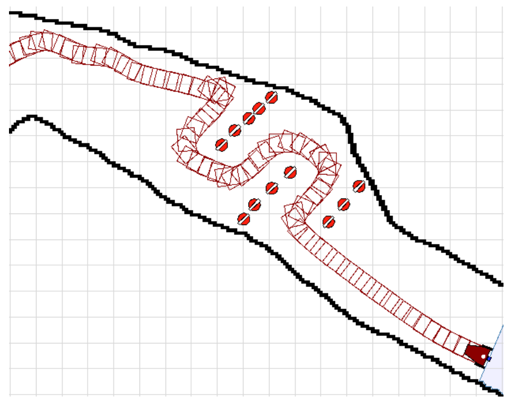

Figure 10: Goal Selection

To deal with this situation, a heuristic layer is created. This layer combines two pieces of information to set the goal direction. The first is a "GPS tail" direction established by GPS coordinates 4 meters apart from the immediate travel history of the robot. The second is the result of the Quad Hough part of the Image Processing algorithm with its built-in level of confidence measure. When the IP results are less reliable, greater reliance is placed on the tail in setting the goal direction and vice versa. This approach contributes to improved navigation of switchbacks and traps. The effectiveness of this algorithm can be seen from the Stage™ simulation of Figure 10 which shows the robot negotiating a switchback smoothly.

5.5. Software: Navigation Challenge

Given the set of waypoints, the robot first needs to determine an optimal route, then plan the best path between pairs of waypoints on the route. What makes the Navigation Challenge interesting is the uncertainty of the starting box and the location of

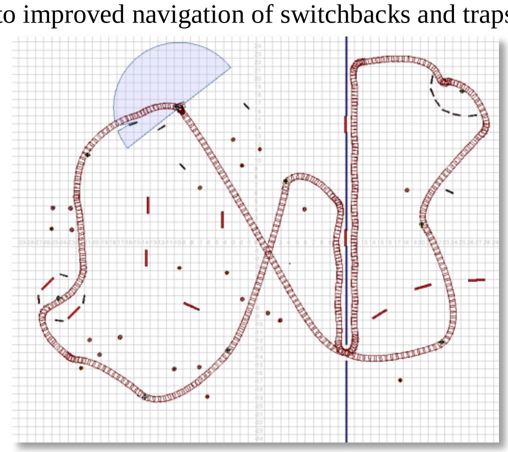

Figure 11: Stage™ Simulation of Nav Run

the gate in the fence separating the two areas. Additionally, one's strategy may or may not involve completing all waypoints on one side of the fence first. For these reasons, a route is planned using a variant of the classic Traveling Salesman Problem (TSP) for a finite number of cities. The strategy also involves the creation and use of "fake" waypoints to make it easier to locate the gate and go through the fence. The D*Lite algorithm then provides an initial path between waypoints for the robot to follow. Actual navigation of the path is accomplished using the VPH+ algorithm. Allowance is made for manual overrides of our TSP-derived solution for the best route over the 3 heats of the Navigation Challenge. A Stage™ simulation of a Navigation Challenge run is shown in Figure 11.

5.6 Software: JAUS Challenge

The goal in this Challenge is to meet the SAE AS-4 AS5669A/AS5710/AS6009 JAUS Standards and to achieve this by creating a JAUS module to link to the Player™ server, which will thus make all the robots supported by Player™ JAUS compatible. Thus **THOR PRO** can migrate quickly while using Player™ devices to providing JAUS compatible services. The general architecture is shown in Figure 12.

After a review of the open source software resources for JAUS (Openjaus, Jaus++, RE2, RI-JAUS, etc.), Jr Middleware was found to be the only one meeting the SAE AS-4 AS-5669A standard. Thus we choose Jr Middleware for **THOR PRO'S** JAUS implementation. Jr Middleware's API acts as an interface between the application and transport layers, providing support for inter-process and network communications, hence making it simpler to use. Jr Middleware is SAE AS-4 AS-5669A compliant which supports run-time discovery, message relay, prioritization, guaranteed delivery, and large packet segmentation.

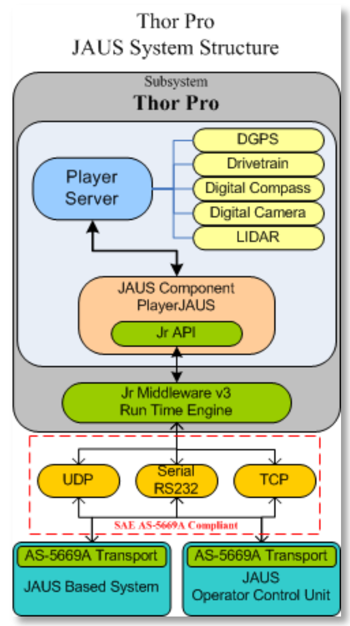

Figure 12: Thor Pro JAUS Structure

Our JAUS system has already been successfully implemented and tested with the JAUS Validation Tool (JVT) in keeping with SAE AS-4 AS5669A/AS5710/AS6009 Standards. The services supported currently in our Player™ JAUS module are: a) Global pose sensor, b) Local pose sensor, c) Primitive driver, and d) Velocity state sensor. When fully tested, the source code we have generated will be released to the general public through our website http://aml.udmercy.edu/AMRL/Welcome.html to support Player™ as a JAUS compatible medium!

5.7 Simulation

As stated earlier, the software development environment was based on Player-Stage™; the features and merits of this choice have been discussed in Section 5.1. Stage™ provides a powerful simulation environment that can be used to develop and test algorithms for the Autonomous and Navigation Challenges in environments similar to those expected in actual competition. A substantial benefit accrues from the use of such a simulation system - the team can construct highly complex situations, test performance, and make necessary corrections much faster than when using the actual vehicle. Figure 10 showed a simulated Navigation Challenge run. Figure 9 showed a simulated

Autonomous Challenge run on a segment of the recreated 2007 IGVC course, while Figure 10 showed a simulated Navigation Challenge run.

6. System Integration

Naturally, this project was divided into subtasks to facilitate development and assignment of tasks to individuals. However, this then requires a systematic process to integrate all the parts into a single, working product. The foundation of this was the design methodology discussed in Section 2.1. But in addition, the software systems architecture first formulated in 2007, with the Player-Stage™ platform at its core, has now been consolidated and solidified to the point where new sensor configurations and algorithmic enhancements created by future generations of developers can be seamlessly integrated. All hardware interaction was accomplished through Player's™ common interface. All the software algorithms that were developed were first tested on the Stage™ simulator. To facilitate actual vehicle testing we designed a couple of courses on campus containing features anticipated on the actual IGVC course for the two performance Challenges. Integration of the mechanical sub-systems has been discussed in detail in last year's report. Since **THOR PRO** is not a new vehicle, that discussion has been omitted from this report.

7. Predicted Performance

7.1. Speed

Given the vehicle's 14-inch wheels and 10:1 gear ratio, **THOR PROS**' motors are capable of theoretically driving the vehicle at 6.6 mph at their power-optimal speed of 1600 rpm. Vehicle testing has yielded results close to this estimate. In accordance with IGVC regulations, however, the maximum speed of the vehicle has been limited to 5 mph by integrating speed control into the vehicle's software.

7.2. Ramp climbing ability

Based upon the rated torque output of the motors, the size of the vehicle's wheels and the selected gearing, calculations and testing have revealed that **THOR PROS** has ample torque to ascend an incline with a gradient of up to 30% (16.7°) without stalling. According to the IGVC rules, the vehicle needs only to be capable of climbing a 15% (8.5^0) incline.

7.3. Reaction times

For the Autonomous Challenge, it takes approximately 100 ms (10 frames per second) to run the system algorithms (based on software timing estimates). At 5 mph, which is the maximum permitted speed, this cycle time translates to a decision being made for approximately every 22cm of travel. In the Navigation Challenge, the algorithms take approximately 25 ms to complete. At the 5 mph speed limit, this cycle time corresponds to a decision being made approximately every 5.6 cm.

7.4. Battery life

Table 2 lists the power consumed by the vehicle components under normal as well as worst-case operating conditions. Using these values, it is expected that the vehicle will be able to run for approximately 5 hours under normal operating conditions and slightly less than 2 hours under the worst-case conditions. These estimates have been borne out experimentally.

Device	Normal Operating Conditions			Worst-Case Conditions		
	Voltage [V]	Current [A]	Power [W]	Voltage [V]	Current [A]	Power [W]
LADAR	48	1.2	29.0	48	1.2	29.0
DGPS	12	0.2	2.0	12	0.2	2.0
Compass (USB)	5	0.02	0.1	5	0.02	0.1
Camera (FireWire)	12	0.17	2.0	12	0.17	2.0
Laptops	16.5	2.1	35.0	16.5	4.8	79.0
Motors/Controllers	24	6	216.0	24	20	552
Total (Watts)			**284**			**665**

Table 2: Component Power Consumption

7.5. Distance at which obstacles are detected

The vehicle's LADAR unit is configured for a range of 8 meters. The camera is set up for a somewhat shorter range to eliminate glare and horizon effects (approximately 5 meters).

7.6. Accuracy of arrival at navigation waypoints

The waypoints at the competition will be designed as concentric 2m and 1m radius circles centered on the GPS coordinates of the waypoints. **THOR PRO'S** DGPS system provides an accuracy of $\pm$ 0.1 meters in DGPS mode, and $\pm$ 0.01 meters in real-time kinematic (RTK) mode. It can be seen that this accuracy is more than sufficient. This has also been demonstrated both via simulation and actual experimentation. Additionally, the use of Kalman-based sensor data integration allows positional accuracy to be maintained even with modest DGPS outages.

8. Safety, Reliability, and Durability

Even though **THOR PRO** is a developmental vehicle, it is important for it to operate in a safe and reliable manner as well as be durable, just like any other product. As pointed out earlier, the durability of its mechanical and electrical/electronic systems has been proven through its flawless operation over more than a year. **THOR PRO** includes several features that not only contribute to its performance, but also increase its safety, reliability, and durability. Three E-Stop systems are implemented to ensure that the vehicle can be stopped safely, quickly, and reliably. These are the soft, hard, and remote E-Stops which are controlled by the microcontroller, the manual mechanical button on the rear of the vehicle, and the remote control, respectively. The vehicle is weatherproofed such that light rain will not cause electrical short circuits. This involves the incorporation of NEMA enclosures for the power distribution system, as well as a shell that surrounds the vehicle chassis and the various components. Also, all computers are housed in a shelving system that is placed inside the vehicle, between the battery charger and the top of the chassis. This efficient use of space serves as a means of protecting the notebooks while still providing easy accessibility. The shelves are lined with cushioning material as well, to protect the notebooks from vibrations resulting from vehicle movement. All electrical circuits are carefully fused to prevent electrical damage. Furthermore, individual currents and voltages are monitored in all circuits. Diagnostic software and LED indicator systems were developed so faults could be quickly identified and repaired. A wire harness is used for the safe routing of all electrical wires for power distribution, and sealed gel-cell batteries are utilized to eliminate potential safety problems associated with chemical leakage.

Thor Pro implements three-levels of "watchdogs" on the motor controllers to prevent unintended vehicle operation. The first watchdog is a hardware watchdog, which prevents vehicle operation in the event of a hardware failure. Every 500ms the computer must send a specific message to the motor controller. If the message is not sent, an E-Stop is triggered. In the event of a hardware failure or computer crash, the message will not be received by the controllers and the vehicle will stop. The second watchdog is a software watchdog, to prevent vehicle operation in the event of a software failure. The motor driver will expect a new velocity command from the software algorithm at least every 2 seconds. If such a command is not received, the driver will halt the motors until a new command is received. The third watchdog monitors smooth wireless data transmission between the remote control and the vehicle. Any failure of the remote control or jamming of the wireless signal will trigger the E-Stop, acting as a hardware watchdog.

9. Conclusion

The UDM team is excited at the potential of **Thor Pro** for this year's IGVC. Its performance in trial runs on the test courses on campus is very promising. We look forward to defending our title!