University of Detroit Mercy Presents

THOR PRO

IGVC 2015 – Design Report

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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

Advisor Signature: Mark J. Paulik

Introduction

The University of Detroit Mercy's entry for the 2015 IGVC is Thor Pro, an articulated vehicle that was first introduced in the 2009 IGVC. The chassis, motors and basic power systems return this year with innovations being introduced for the computational systems, power systems, sensor subsystems and algorithms. These significant enhancements in the hardware and software are addressed later in this report.

Design Process

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 to facilitate transfer of knowledge.

At the beginning of the design process, a team meeting was held to determine the improvements we could make on the robot for this year's competition. We used a Quality Function Deployment (QFD) House of Quality design methodology to finalize which areas we would focus on. These areas came down to: power system improvements, such as a new lithium batteries, improved wiring, and smart timed shutdown systems for the onboard computers; software improvements, such as local and global navigation, image processing, mapping, and localization; and updated hardware, such as a GigE camera, three networked embedded computer systems advanced digital compass and Differential GPS.

The team simultaneously conducted mechanical, electrical, and software design and implementation tasks. Facilitating an iterative design process was a meeting and reporting structure, which ensured that all of the mechanical, electrical/electronic, and software systems would integrate seamlessly with each other. This process 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. Several software applications were used to facilitate project management. New this year was the use of multiple social networking based methodologies to permit remote teaming, technical exchange, and event coordination.

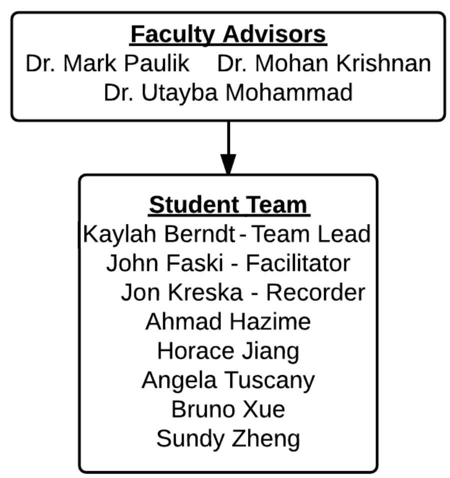

Figure 1. Team Organization.

Team Organization

The composition and organization of the 2015 IGVC team, made up of ECE and Robotics undergraduate students, is shown in Figure 1. The team has devoted approximately 200 scheduled hours and over 200 additional hours towards the development of this year's vehicle. The team, composed entirely of undergraduate seniors, is presented in Table 1 along with their general development area assignments.

Table 1. Member and Section.

Section	Member
Hardware	Johnathan Faski/Ahmad Hazime
Image Processing	Angela Tuscany/Kaylah Berndt
Localization and Mapping	Bai Xue/Hao Jiang
Path Planning	Hengyang Zheng
Navigation	Jonathon Kreska

Vehicle Cost

The cost breakdown for the development of this vehicle is provided in Table 2.

Table 2. Cost Breakdown.

Description	Retail Cost	Team Cost	Comments
Frame/Body	\$586	\$586	Used from previous vehicle
Drive Train	\$3,944	\$3,944	Used from previous vehicle
Wheels (4)	\$600	\$0	Used from previous vehicle
Batteries (4)	\$1,650	\$1650	Purchased
Battery Charger	\$350	\$200	Used from previous vehicle
Power PCB	\$172	\$172	Used from previous vehicle
Remote PCB	\$304	\$104	Used from previous vehicle
Camera and Adapter	\$937	\$898	Purchased
Camera Lens	\$299	\$0	Donated by Theia Technologies
SICK LMS111 Lidar	\$6,700	\$5,175	Borrowed from Univ. Lab
DGPS and Antenna	\$6,000	\$6,000	Borrowed from Univ. Lab
Digital Compass	\$1,350	\$0	Donated by Sparton
MacBook Pro	\$4,000	\$4,000	Purchased
Embedded Computers (2)	\$2,200	\$2,200	Purchased
Router	\$100	\$100	Purchased
Pico-PSU + Case (3)	\$225	\$225	Purchased
Incidentals, Cables, etc.	\$500	\$500	Purchased
Total	**\$29,917**	**\$25,754**	**Savings of \$4,163**

Design Innovations

A number of significant innovations have been incorporated in Thor Pro since its 2009 Introduction. These are listed below and discussed in greater detail later on in various parts of the report. While these discussions are distributed, an effort has been made to explicitly identify innovations introduced this year.

Lithium battery system: This system includes both overvoltage and discharge protection circuitry, includes deep-cycle constant-voltage operation, and doubles the effective vehicle operation time while weighing only one third as much as the prior lead-acid power system.

Smart high-efficiency computer power system: A graceful-shutdown programmable power system for the onboard embedded Linux-based systems is introduced to permit timed, managed, power down for the primary vehicular computers.

Three-computer hybrid computer system: A ROS (Robotic Operating System) and Matlab integrated networked computer system has been developed to provide outstanding real-time performance that enables the use of sophisticated navigation, path planning, and sensor-data analysis algorithms.

Heuristic-Enhanced Vector Polar Histogram (VPH+) Algorithm: A novel navigation algorithm that is superior to the commonly used Vector Field Histogram algorithm and its derivatives (VFH+, VFH*) when navigating in a complex environment has been implemented. The use of multi-modal heuristic-based context switching permits effective operation in the highly cluttered environments specified for the 2015 IGVC Auto-Nav course.

Enhanced image processing techniques: Thor Pro has a new, augmented image processing suite, which employs a series of enhanced region and edged-based techniques. A new hierarchical multi-resolution Hough transform algorithm provides excellent lane-line structure identification in the presence of significant noise. Additionally, a finely-grained adaptive thresholding algorithm combined with a low-distortion calibrated DC-Auto Iris lens system enables stable vision operation even under widely changing ambient illumination.

Vehicle Configuration

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.

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 Lidar), and weighs approximately 300 pounds when fully loaded. The use of right-angle gearboxes in the drivetrain 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 inch wheels using new Zero-Max CD high-load couplings.

Electrical and Electronics Systems

Power Distribution System

Thor Pro derives its power from 4 deep-cycle LiPo batteries configured as two 38Ah and two 20Ah cell packs. This battery system can deliver 100% of rated capacity yielding 1392 watt-hours. Under harshest full-load operating conditions these batteries will allow the vehicle to be operated for approximately 4 hours. A 480W DC battery charger mounted inside the vehicle can be powered from the AC mains to fully recharge the batteries in approximately 3 hours.

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 a power distribution scheme. 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 computer through a USB connection. Thus, if a problem occurs, its source can be located quickly and diagnosed.

Sensor System

Thor Pro incorporates four sensor systems into its compact design: a color camera, two Lidars (one 180 degree and one 270 degree), 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 their easy removal and replacement if it becomes necessary. The following is a brief description of the sensors that are used by Thor Pro (shown in Figure 2).

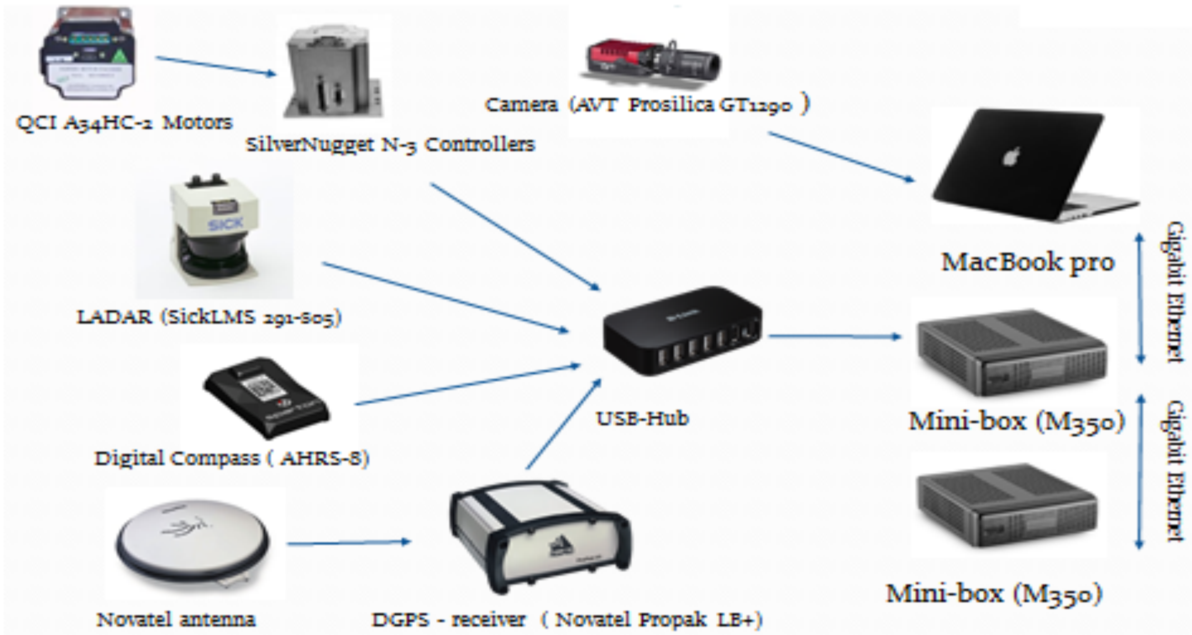

Figure 2. Sensors.

Camera. The AVT Prosilica GT1290C camera was selected as the vision sensor for this vehicle. This camera uses the Gigabit Ethernet (GigE) protocol to relay images. With this camera, 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 C-Mount design is compatible with the Theia SL183A DC Auto Iris lens. The Auto Iris capability of this lens, combined with the camera's hardware options, allows the vision system to adapt easily to situations with varying lighting.

Lidar. A 270° SICK LMS111 LIDAR unit was employed for the purposes of primary obstacle detection. The unit is configured to collect data over a 270° field-of-view with 0.5° resolution, a maximum range of 20 m, and a 50 Hz scanning rate. A secondary LMS-200 180° Lidar is also mounted on the vehicle. This unit can be used to improve terrain classification when driving over ramps or hills.

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. The Sparton AHRS-8 Altitude Heading Reference System was integrated into the vehicle to help determine heading. The AHRS-8 provides accurate heading readings by eliminating external magnetic disturbances that affect heading accuracy, it also provides 3D absolute magnetic field measurement and full 360° tilt-compensated heading, pitch, and roll data. This enables the compass to provide a heading accuracy of 0.2° and updates at 75 Hz, which is sufficient for the vehicle's speed and desired performance.

Remote Control & E-Stop Systems

Although Thor Pro must be capable of autonomous navigation in the 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.

Electrical and Electronics Communication System

The Prosilica GT is connected via a CAT-6 gigabit ethernet cable and a Thunderbolt adaptor 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 LMS111 Lidar is connected to the computer via Ethernet and the LMS-200 uses a custom inline RS-422-to-USB converter. The Sparton AHRS-8 digital compass uses USB from which it obtains its 5V supply for operation. Finally, all the computers are networked via gigabit Ethernet.

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.

Software Development Environment

This year, ROS (Robotic Operating System) is used as the primary development environment. Using a Java-based interface package, MATLAB is set up to communicate with the ROS master. Matlab is used for execution of image processing algorithms for the associated ease of development and availability of sophisticated and efficient core image processing code blocks. ROS is an open source robotics platform that operates on a peer-to-peer model. In ROS all nodes can communicate directly with each other with minimal invocation of a centralized server. As the scale of the system increases to support more nodes, the load on the server remains manageable.

ROS has three layers of functionality. At the lowest (graph) level ROS operates on the basis of a network of nodes. These are modular processes that execute a specific task (such as read in and convert GPS data, transform coordinate frames, send velocity commands, etc.). Nodes communicate with each other by sending messages, using topics with specific names. Nodes can either publish messages to a specific topic or subscribe to one or more topics. The processing of these messages is used to direct the algorithmic flow, as needed.

The ROS environment is effective not only for final implementation but also for simulation as it allows for the use of the Stage and Gazebo simulators. Throughout the progression of algorithm development, Stage and Gazebo accommodate testing via simulation. The ROS/Stage/Gazebo simulators provide a representative and comprehensive simulation environment, complete with models for the robot, obstacles, GPS, camera, LIDAR, etc. Stage and Gazebo also provide graphical depiction of robot motion within their environments which offers a powerful tool to gauge the effectiveness of algorithms.

Enhancing the Frame Rate

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 computers. Using ROS as a server facilitates setting up this distributed computing architecture and provides a wealth of existing open-source code to draw from. A MacBook Pro is devoted to running components of the overall vision algorithm and utilizes the MATLAB® image processing toolbox to calibrate images and take advantage of available algorithms for image processing. The first of two embedded Linux mini-box computers is responsible for accepting data from the vehicle's sensors, generating a map, and navigating the vehicle. The second Linux system is tasked with goal selection and path planning.

Mapping, Path Planning and Navigation

Mapping: Mapping is an important capability for autonomous robots that facilitates good decision making. It is particularly beneficial when navigating between given GPS waypoints in an unknown environment. It enables the use of path planning algorithms to determine the optimal route between those waypoints and avoid traps.

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. The Sequential Update Extended Kalman Filter (SUEKF) algorithm was used to do this. The SUEKF consists of two parts, the Extended Kalman filter and the Sequential Update Kalman filter. The Extended Kalman filter helps when the system is nonlinear, and the Sequential Update Kalman filter helps to meld sensors that do not update at the same frequency. A high-frame rate SLAM-based Hector Mapping algorithm is used to estimate the global map. DGPS and Hector mapping location results are combined via the SUEKF to provide highly stable location estimation.

Path Planning: Navigating though waypoints is 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 parts of the Auto-Nav course, robot navigation is carried out using a heuristic-based modified version of 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. A context-aware multi-mode switching algorithms is integrated with the core VPH+ code to provide behavior which adapts to obstacle density.

Software

The software for the Autonomous Lane Navigation 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 multicomputer/ multi-core system architecture.

The image processing algorithm begins by utilizing the color characteristics of the various scene elements to simultaneously enhance lane contrast and produce an optimal 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 derivative filtering to eliminate noise, extract lane structure, and highlight edges. The image is transformed to a birds-eye view to give accurate distances. A hierarchical Hough transform algorithm is applied at three different image resolutions the results of which are combined via a voting algorithm in order to find lane edges and produce consistent linked linear segments. In each step of this process, special attention has been paid to computational complexity and possible parallelism. The result 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.

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 single 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). 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.

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 the multi-resolution Hough transform operation that serves to extract line segments. The lines are converted to mimic a Lidar reading which the navigation algorithm can then identify as obstacles. This is shown in Figure 3.

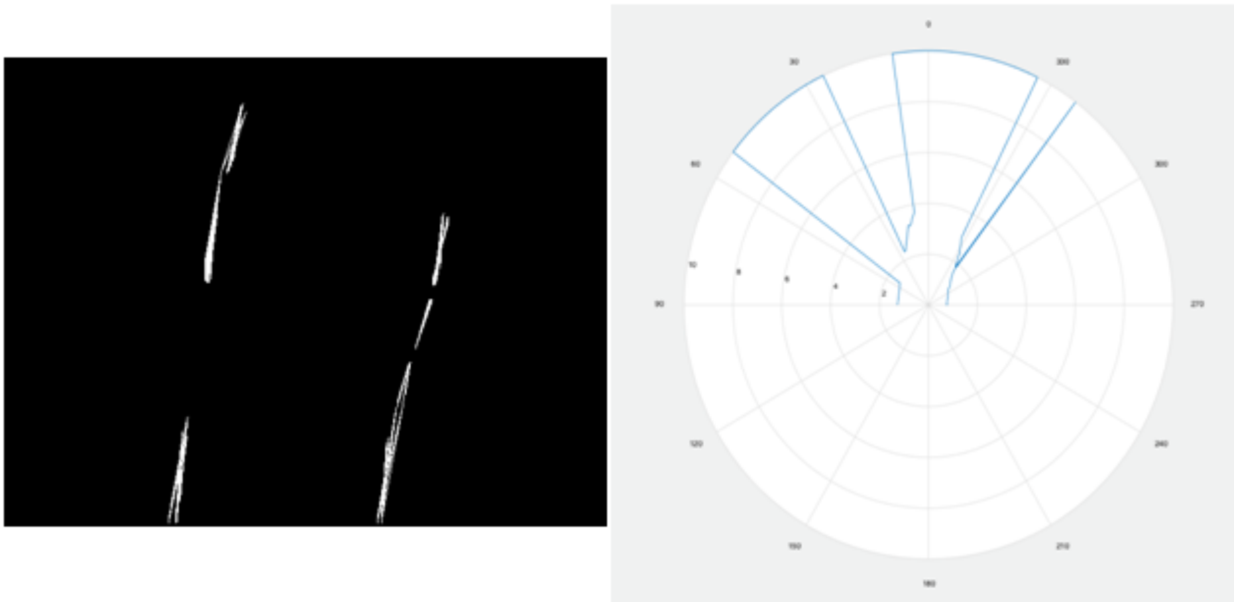

Figure 3. Hough Transform and Corresponding Lidar.

Goal Selection: The goal selection algorithm is concerned with determining the "forward" direction. For Waypoint Navigation this is relatively easy, as forward is towards the next waypoint. However, when navigating lane lines the forward direction is not as clear, 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.

To deal with this situation, a heuristic layer is created which combines two pieces of information to set the goal direction. The first is a "GPS tail" direction established by GPS coordinates 2-4 meters apart from the immediate travel history of the robot. The second is the result of the Hough part of the Image Processing algorithm with its built-in level of confidence measure (associated with the multi-resolution voting procedure). 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.

Given the set of waypoints, the robot first needs to determine an optimal route, and then plan the best path between pairs of waypoints on the route. What makes the Navigation portion of the Auto-Nav Challenge interesting is the uncertainty in the location of 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. The D*Lite algorithm provides an initial path between waypoints for the robot to follow by laying breadcrumbs. This is shown below in Figure 4. Actual navigation of the path is accomplished using our heuristic-based VPH+ algorithm.

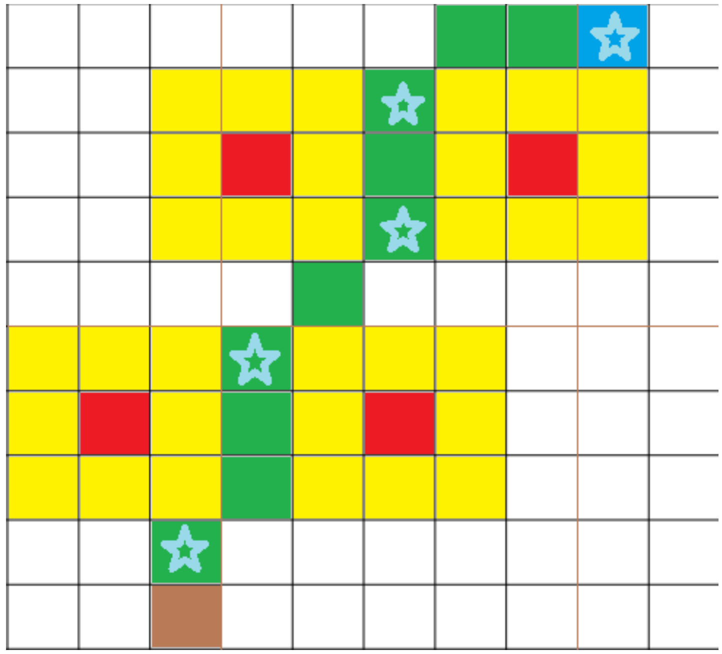

Figure 4. Breadcrumbs.

System Integration

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 the Design Process section. Integration of the low-level mechanical sub-systems has been discussed in detail in the 2009 report. Since Thor Pro is not an entirely new vehicle, that discussion has been omitted from this report.

Predicted Performance

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.

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 Pro 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% (8.50) incline.

Reaction times

For the Autonomous Challenge, it takes a maximum 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 portion of the Auto-Nav 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.

Battery life

It is expected that the vehicle will be able to run for approximately 9 hours under normal operating conditions and slightly less than 4 hours under the worst-case conditions. These estimates have been borne out experimentally.

Distance at which obstacles are detected

The vehicle's Lidar 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 15 feet).

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 +0.1 meters in DGPS mode, and +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 SLAM and sequential extended Kalman filter-based sensor data integration allows excellent positional accuracy to be maintained even with DGPS outages.

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 multiple years. 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 notebook and embedded Linux computer while still providing easy accessibility. 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 Lithium batteries with over and under charge protection circuitry are utilized to eliminate potential safety.

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.

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 participating!

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