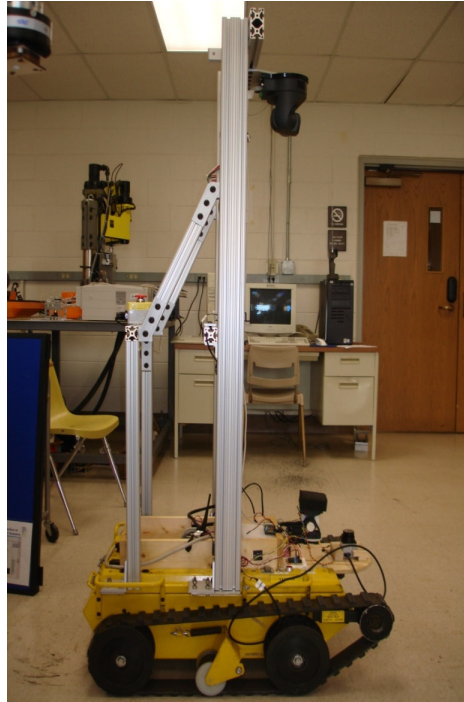


MAV-BOT



Mav-Bot

University of Texas at Arlington

Required Faculty Advisor Statement (*)

I hereby certify that the engineering design and development on Mav-Bot has been significant and equivalent to what is required to award credit in a senior design course.

(*) Co-advisors: Dr. Arthur Reyes, Dr. Kamesh Subbarao and Dr. Atilla Dogan and Mr. Tom Rethard

Professor Dr. Brian Huff

Industrial and Manufacturing Systems Engineering Department

1.0 Introduction

The University of Texas at Arlington is proud to present “Mav-Bot.” This is the first time in twelve years that UTA has participated in the Intelligent Ground Vehicle Competition (IGVC). Mav-Bot is the result of a shared effort among a multidisciplinary group of UTA engineering students. The desire of this team is to resurrect a platform that was found in the closet of an engineering lab and to rekindle an interest in autonomous ground vehicles. In the same way that we are unaware of how and where this platform came from, we were also unaware of the history of UTA’s participation in this competition. The only record found was from the IGVC competition website where we learned of our participation in 1996. We earned 6 out of 550 points that year. It is our sincere hope that in 2008, we will be able to at least match our previous efforts.



Figure 1 Original Israel Military Industries MK-5 Hornet bomb disposal robot

This paper will explain the Mav-Bot design process, descriptions of the mechanical, electrical and software system designs, and the integration of all these systems.

2.0 Innovation

The goal of innovation is to incur a positive change to make someone or something better. The development of a relatively new industry, such as autonomous vehicles, is driven by these changes. Therefore, as engineers and contributors to this industry, we must consider innovation as a major topic in the architecture and design of an autonomous ground vehicle. During the construction phase of Mav-Bot, the main considerations were safety, reliability and economy. Through research and testing, the team was able to develop and apply technological solutions in order to provide innovation to the system. A variety

of techniques and methods have been implemented in the vehicle controller in order to drive innovation, increase accuracy, and reduce variability when performing the diverse challenges:

- Compact, durable, robust and safe platform
- Hardware logical distribution
- Sensor fusion
- Application of dead-reckoning algorithms
- Independent parallel GPS receivers
- Incorporation of two laser rangefinders
- Use of potential fields
- Creation of a Motion Control interface

All these innovations are explained in more detail throughout the document.

3.0 Design Process and Team Organization

Our goal is to create and integrate an Intelligent Ground Vehicle that performs according to the guidelines of the competition. To achieve this goal and accomplish tasks efficiently, the team divided into three functional subgroups: mechanical, electrical and software. Functional roles, responsibilities and deadlines were assigned to each of the members. The functional roles were designated to each member to ensure a better coordination and focus on specific sub-systems.

The team followed a three-step process to develop Mav-Bot. First, all the subgroups reviewed the IGVC requirements and researched the subsystems and the components that could be used to achieve the competition goals. Next, the teams designed, fabricated, tested, and evaluated each subsystem in order to ensure its functionality. Finally, all groups contributed to the integration and testing of the final vehicle.

Modern computer-aided analysis tools were used in each phase of our system development process. Matlab and Simulink were used to design and validate the vehicle motion control algorithms and dead reckoning calculations. AutoCad and SolidWorks were used to design various components needed for system integration. These designs, like the CPU enclosure illustrated in figure 2, were then fabricated with rapid prototyping tools like our CO₂ laser cutting system.

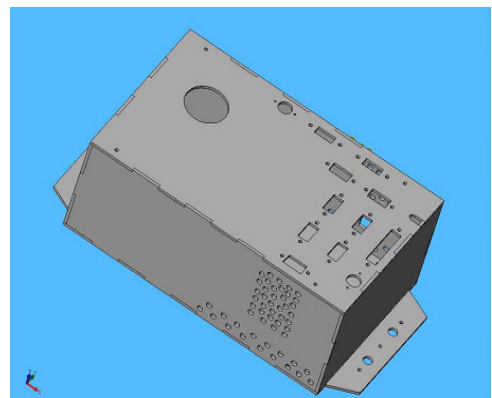


Figure 2 Enclosure for the Embedded CPU

There were three groups of students involved in this vehicle development effort: students enrolled in the Computer Science Senior Design course, students enrolled in the Autonomous Vehicle Design course, and a few students volunteers.

Team Member	Class / Academic department	Team Member	Class / Academic department
Adam Pham	Senior Design, Computer Science and Engineering	Sion Chaudhuri	Senior Design, Computer Science and Engineering
Carl F Jagers	Senior Design, Computer Science and Engineering	Victor Serrato	Senior Design, Computer Science and Engineering
Crawford Waldrup	Senior Design, Computer Science and Engineering	Diana Martinez	Industrial Engineer, Advanced Studies in Industrial Engineering
JD Evers	Senior Design, Computer Science and Engineering	Mary Campbell	Industrial Engineer, Advanced Studies in Industrial Engineering
Mauricio Aviles	Senior Design, Computer Science and Engineering	Nadia Martinez	Industrial Engineer, Advanced Studies in Industrial Engineering
Nathan Schutz	Senior Design, Computer Science and Engineering	Rodrigo Ramos	Industrial Engineer, Advanced Studies in Industrial Engineering
Rabik Maharjan	Senior Design, Computer Science and Engineering	Patinya Samanuhut	Mecanical Engineer, Advanced Studies in Mechanical Engineering

Table 1 Team Members

The Mav-Bot design team has dedicated approximately 3,500 hours developing the vehicle in order to participate in the 2008 IGVC.

4.0 Mechanical Design

Our twenty-year-old Israeli Military Industries MK-5 Hornet was found in a non-working condition. As a bomb disposal robot, the platform was designed for high torque and low speed applications. These attributes met the IGVC desirable characteristics of a UGV platform. By selecting an existing vehicle the amount of mechanical design required for our reentry in to the IGVC competition was significantly reduced. However, this decision brought about its own unique set of problems: no documentation, no spare parts and obvious wear and tear on the system. That explains why this system sat idle for so many years.

Our mechanical design is advantageous because of its modular, compact, and robust design. All the subsystems that are found in the vehicle can be removed for individual testing, which allows for multiple tests to be performed simultaneously. The platform's measurements meet the minimum size requirements: giving the vehicle the ability to maneuver in confined spaces. The steel chassis, with its low center of gravity, gives the platform its robustness and stability. The vehicle has a compartment inside the frame which provides a safe and secure place for the embedded CPU system and the power source.

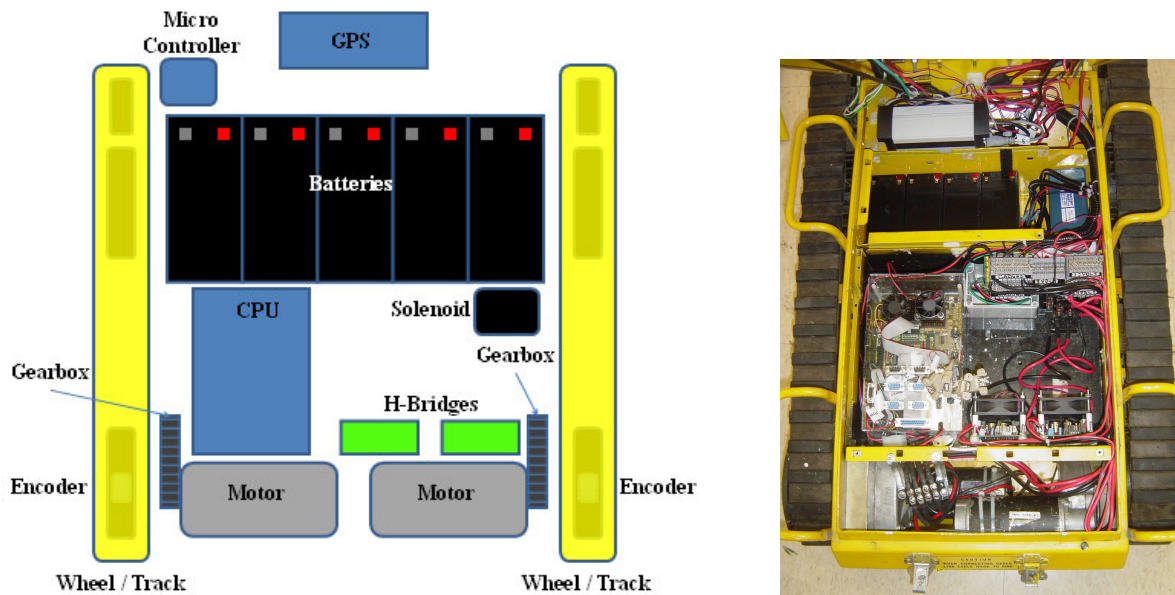


Figure 3 Drive Control System Design

As a tracked vehicle, the tank was designed for all-terrain mobility. The platform is capable of climbing stairs at a 30° incline, which will more than meet the competition requirements. The use of treads provides the vehicle with high maneuverability with a zero turn radius.

The structural modifications made to the vehicle involved the removal of the robotic arm and the installation of a modular extruded aluminum structure in its place. This structure provides a place for the E-stop to be mounted at a distance between 2 and 4 feet above the ground as specified in the competition rules. This also enhances the performance of the navigation and vision systems. The camera and the GPS antenna are located at a distance of 5.4 feet and 5.8 feet from the ground respectively. Having the GPS antenna located in this position provides a clearer view of the satellites. The camera installed at this height will provide a wider range of vision. The digital compass is also mounted on this structure to decrease the amount of magnetic interference caused by the high ferrous metal content of the vehicle chassis and the strong magnetic fields produced by the vehicle motors. Also during testing, this structure provides a place to mount a laptop for vehicle diagnostics.

5.0 Electric System Design

Upon acquiring the tank, the only electronic components that remained include a solenoid relay and wheel encoders. As a result, the team had to research, purchase, and integrate all the electrical subsystems needed to turn this original remote control platform into an autonomous vehicle. A major obstacle faced by the team was the lack of Electrical Engineers on the multidisciplinary team. The major components in the electrical system are the sensors, the main CPU, the H-bridges, and the motion controller. These components support the following functions: obstacle avoidance, navigation, motion control, and power.

The electrical components that are used on this platform were chosen based on four parameters: cost, reliability, durability, and safety.

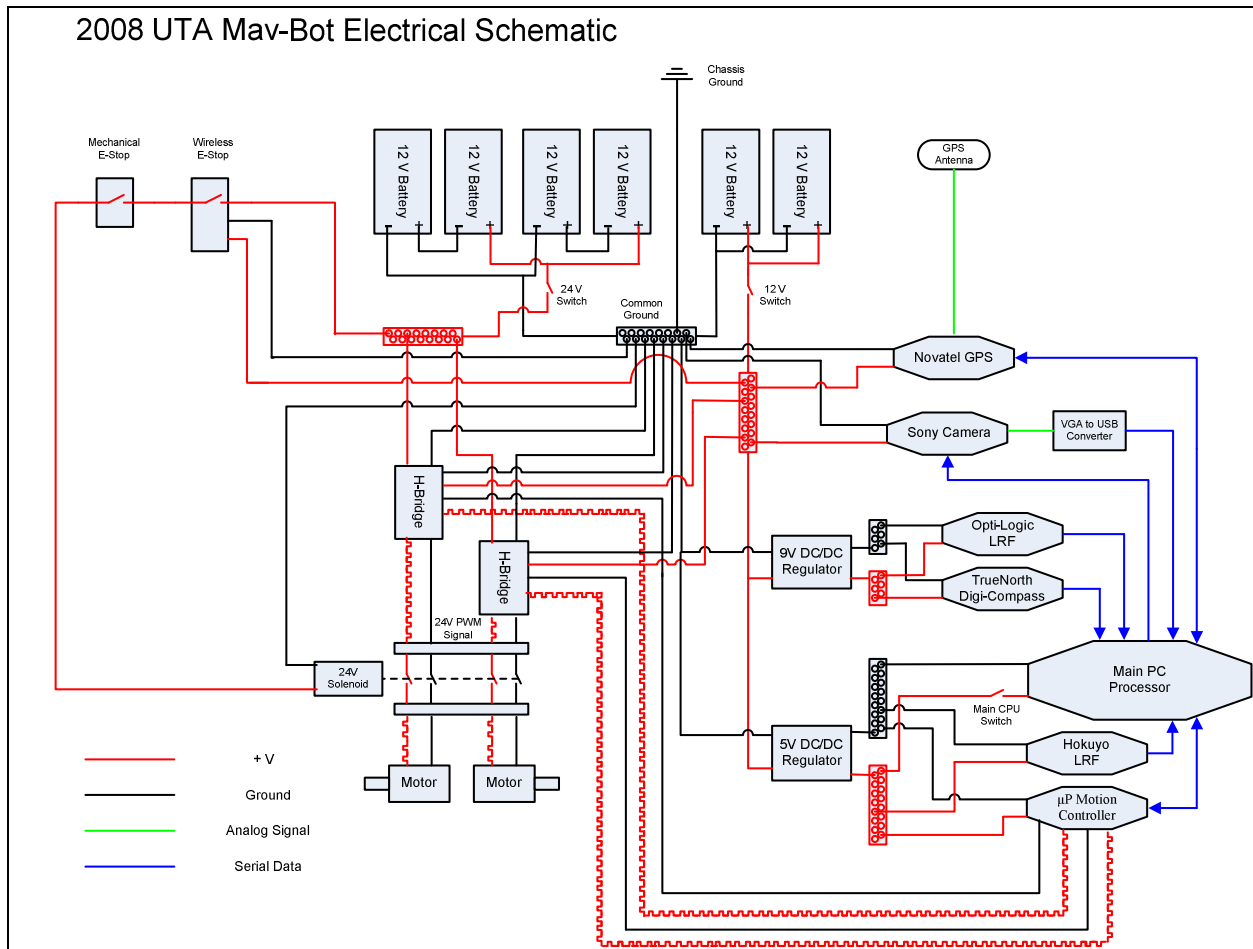


Figure 4. Integration of Electrical Components

5.1 Obstacle Avoidance System

The obstacle avoidance system is powered by a Sony EVI-D70 Color Pan/Tilt/Zoom camera, a short distance scanning laser rangefinder (SLRF), and a long distance laser rangefinder (LLRF). The resolution of the camera is approximately 380,000 effective picture elements. The camera accepts VISCA commands which allows control of the pan, tilt, and zoom functions through an RS-232 connection in order to get a wider range of vision. This gives the vehicle more response time and the ability to detect both boundary lines in the autonomous challenge. The camera is currently being used to detect lines and potholes in the Autonomous Challenge, as well as the entry point from the valley to the mesa in the Navigation Challenge.



The SLRF is a Hokuyo URG-04LX with a 4m range. It has a 240° area scanning range with 0.36° angular resolution. It has USB and Serial (RS-232) interfaces for maximum flexibility. Its accuracy is +10/-10 mm. The scan time is 100 msec. Its high accuracy will enable the tank to detect the exact location of the obstacles with



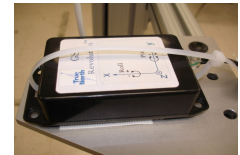
greater precision.

The LLRF is an Opti-Logic RS100 unit that outputs readings to an RS-232 compatible port. The RS100 has a range of 100 yards. Its main purpose is to detect the entrance to the Mesa during the Navigation Challenge. The laser range finder will be mounted on a servo motor to provide a scanning capability.



5.2 Navigation System

The navigation system is composed of a digital compass, differential GPS, and two encoders. The Revolution GS digital compass, a critical sensor in our system, consumes low power and renders more than 27 readings per second. The effective dynamic heading accuracy is within three degrees and the pitch and roll accuracy is within one degree. To increase the position accuracy the GPS system includes two independent receivers, a NovAtel Propak-G2plus and a NovAtel OEM4-G2 GPS Card that communicate with the CPU. These units provide the global location of the vehicle. The Omron Encoders, with 100 counts per revolution (CPR), will be used for odometry purposes in order to complement and increase the accuracy level of the information provided by the digital compass and GPS.



5.3 Motion Control System

The motion control system is composed of the embedded Windows XP based computer, a DSP-based microcontroller, and the H-bridges. The embedded computer is a EBC-855 single board computer (SBC) designed by Win Systems for industrial applications. It has an Intel® 1.8 GHz Pentium M processor. It operates over a temperature range of -40 and +70 degrees Celsius. It has 8 serial communication ports, 4 USB ports, and an Intel DA82562ET 10/100 Mbps network interface card. The motion control processor is a New Micros Plug-A-Pod DSP microcontroller. This microcontroller has onboard pulse width modulation and quadrature encoder reading capabilities to control standard brushed DC motors. The H-bridges control the polarity and effective voltage supplied to the motors.

5.4 Power System

During development, all of the components were powered individually. This presented a challenge for the team to integrate the power requirements. There are six 12 Volt batteries that provide the power requirements for tank motion. Table 2 represents the power requirements for the tank. Four of these 12 Volt batteries are used to provide 24 Volt power for the motors. These batteries are configured in two banks of two batteries wired in series, providing the 24 Volt output. These two banks were then wired in parallel.

The two additional batteries were wired in parallel to provide a redundant 12 Volt power supply for all of our processors and sensor equipment. We intentionally separated our drive power source from our computing platforms to avoid voltage fluctuations that might cause the processors to reset. We were also careful to ensure that we have a common ground for all of our electrical devices in the system and that we have not created ground loops within our wiring system. These two battery configurations provide the ability to hot swap each battery bank and also provides a redundant power source for both our motion drive systems and our logic and sensor systems.

Component	Amp	Volt
Camera	1 A	12 V
GPS	1 A	12 V
Short Range LRF	.5 A	5 V
Compass	45 mA	9 V
Long Range LRF	.2 A	9 V
Tank Motors	25 A	24 V
CPU	4.25 mA	5V
Motion Controllers	300 mA	5V
Solenoid	---	24 V
Wireless E-Stop	---	12 V

Table 2 Power Requirements

6.0 Software System Design

The design and implementation of our system software constituted one of the largest efforts within this entire systems development project. Good software must be engineered. The following software design architecture was developed by the team to support our software implementation effort (Figure 6).

6.1 External Systems: The External Systems Layer encompasses all of the possible external methods to interact with the vehicle. These are provided for the purposes of satisfying various competition rules (Emergency E-Stop), allowing participation in the JAUS Challenge through the JAUS input interface and the Navigation Challenge (Coordinate Input entered through the JAUS input interface) and to allow for easier development and testing of the vehicle design (Remote Control Layer and Diagnostic Station).

6.2 Remote Control Receiver Layer: This layer communicates with the Remote Control Subsystem in the External Control Layer and allows the vehicle to be controlled manually. Remote control is used for diagnostic purposes only.

6.3 Wireless E-Stop Receiver: This layer consists of a wireless receiver that is capable of receiving signals from a wireless e-stop transmitter.

6.4 Mechanical E-Stop Layer: This layer consists of all the necessary hardware required for an external emergency stop to be initiated by a vehicle operator.

6.5 Vehicle Diagnostics Layer: This layer provides an on-board log of vehicle activity that can be later retrieved for troubleshooting and performance analysis. This layer also encapsulates

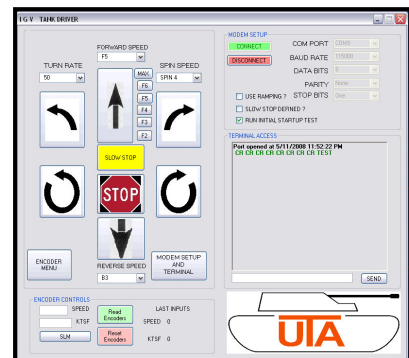


Figure 5 Motion Control Interface

a motion control interface. The Motion Control Interface (Figure 5) is a simple and friendly user interface that reduces the system complexity and improves the testing process. This interface provides a simpler way to control the vehicle movements.

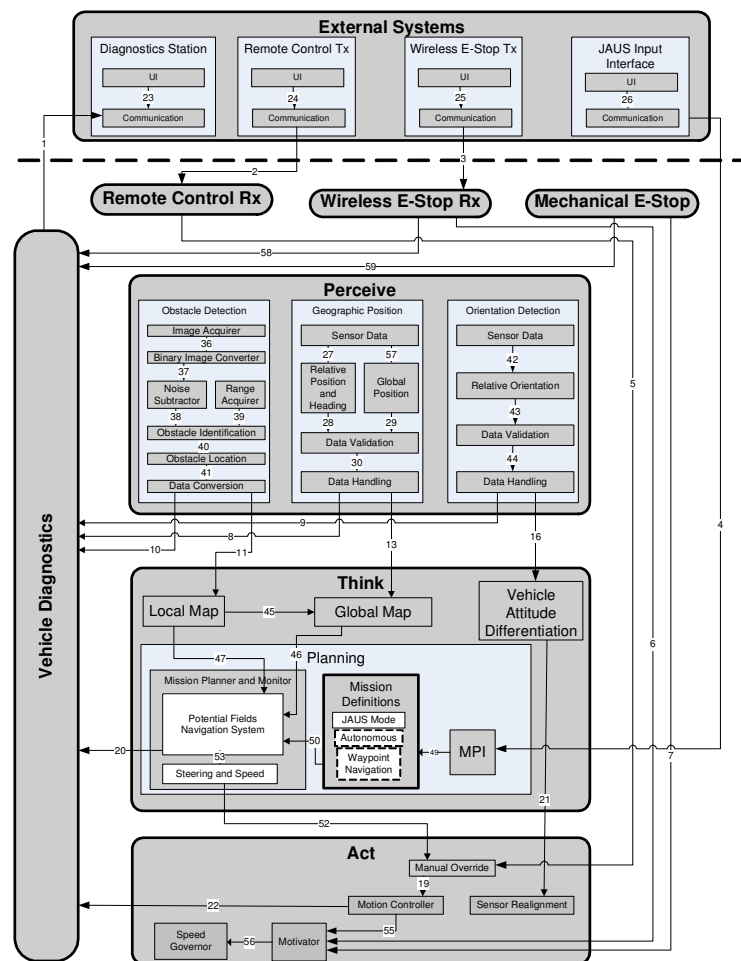


Figure 6 Software Design Architecture

6.6 Perceive Layer: This layer is the “eyes and ears” of the vehicle, all sensor data is acquired in this layer. It also groups all the hardware and software responsible for all sensing equipment on the vehicle. This layer acquires the vehicle’s immediate surrounding and global positioning data, processes it for real-world object recognition, then sends the resulting data to the Think Layer. The Think Layer will in turn group this information together and build a comprehensive knowledge about nearby obstacles, course boundaries, and navigation waypoints.

6.7 Think Layer: Vehicle intelligence resides in this layer. The Think Layer is primarily responsible for

generating vehicle movement commands. These movement commands are generated by an algorithm based on the potential field methodology which is explained in a later section. This layer acquires the required sensor data and creates a local map which is then used by an obstacle avoidance module to reach the desired destination. The global mapping functionality in this layer will be used in the Navigation Challenge to create virtual boundaries for the vehicle and will also be used to store the set of waypoints. The Mission Planning Interface (MPI) gets input from the external systems layer through the JAUS input protocol. The MPI also enables the vehicle to switch between three different modes: Autonomous, JAUS, and Waypoint Navigation. The vehicle attitude differentiation subsystem enables the use of control commands to realign sensors based on orientation data.

6.8 Act Layer: Physical movement of the intelligent ground vehicle occurs at this layer. Movement involves driving on the defined path, climbing up an incline, avoiding obstacles, or going to a specific waypoint. The Act Layer is responsible for the physical movement of the vehicle. It will accept

commands and perform requested actions. This layer is the only means of mobility that the vehicle will have. This layer is also responsible for maintaining the physical orientation of all vehicular sensory equipment.

6.9 Potential Fields Implementation

The motor schema component of a behavior can be expressed with a potential field methodology. A potential field can be a “primitive” or constructed from primitives that are summed together. The primitives being used are uniform, perpendicular, attractive and repulsive fields. The output of behaviors are combined using vector summation. From each behavior, the robot “feels” a vector or force that has direction and magnitude in the form of strength of stimulus or velocity. But we visualize the “force” as a field, where every point in space represents the vector that it would feel if it were at that point.

All objects and obstacles in the vehicle’s immediate surroundings have an associated vector. These vectors can either be attractive or repulsive. The goal emits an attractive field whereas an obstacle emits and repulsive field.

The sum of both vectors, attractive and repulsive, will determine a direction vector thus, the vehicle can decide where to move. As it moves through the world, it makes observations of the environment, identifies new action vectors, and chooses new directions or speeds. The resulting trajectory of the vehicle looks something like the path diagrammed in Figure 7.

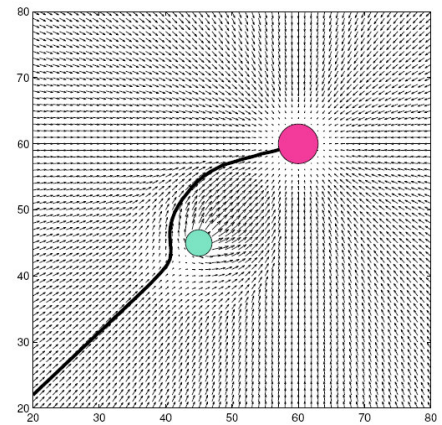


Figure 7 The trajectory experienced by a reactive robot

6.10 Autonomous Challenge

In the autonomous challenge, we’ll be primarily using the Short Range LRF and the Camera for detecting obstacles and lines respectively. The LRF detects physical barriers such as barrels, cones, etc. The camera is used to detect lines and potholes. The sensor data is parsed after being acquired and the distance to obstacles and lines is calculated. The repulsive vectors are calculated based on the distance from the obstacle or the line. The magnitude of the vector which later will be translated to velocity is inversely proportional to the distance from the object.

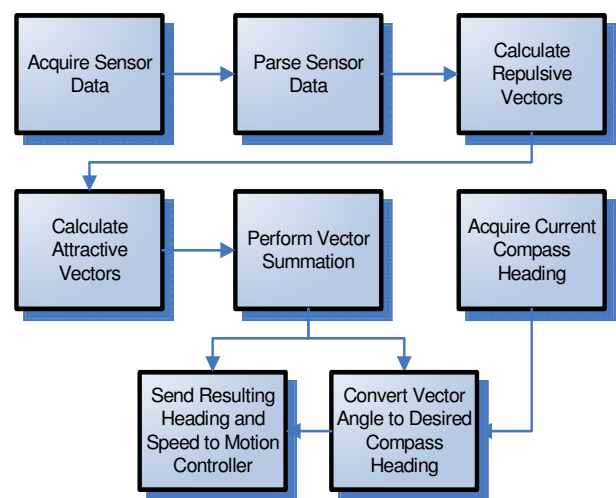


Figure 8: Flowchart for the autonomous challenge (overview)

The attractive vector is calculated based on the direction of the image of the line segment which is generated after the raw image is passed through a series of filters. The magnitude of the attractive vector always remains constant. After the attractive vector and the repulsive vectors have been calculated, the vectors are summed up to get a resultant vector. The latest compass heading is acquired at this point and based on the current compass heading the desired compass heading is calculated by adding the resultant vector angle. This resultant heading and speed is then sent to the motion controller. The image acquisition and obstacle avoidance process is better explained in the next two subsections.

6.11.1 Obstacle detection and avoidance

The Short Range LRF performs a sweep which gives the initial set of raw readings. These raw readings are then acquired and parsed. If an obstacle is detected within the range of 4 meters of the vehicle, the LRF will return a series of Cartesian coordinates indicating the location of the detection points. Then the distance to these points can be calculated using the distance formula and the angle is calculated using the arctan trigonometric function. The magnitude of repulsion increases as we get closer to the vehicle.

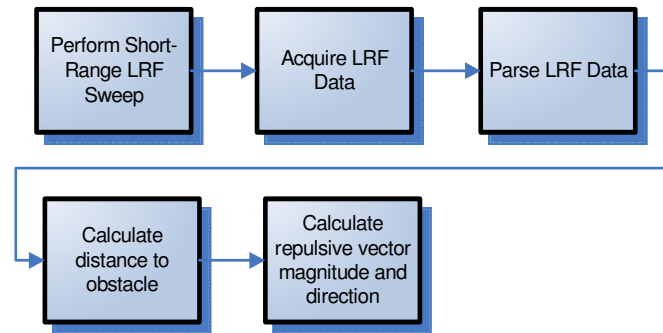


Figure 9: Flowchart for obstacle detection and avoidance

6.11.2 Image Acquisition: Line and Pothole Detection

The Open CV library was used to support the development of image processing algorithms for object detection. Open CV is an Intel-sponsored open source library that provides advanced image processing functions. First, an image is captured from the Sony video camera and scaled down to a smaller size to decrease the amount of time the system needs to spend image processing. The original RGB image is first converted into an HSV color space before it is run through a threshold for certain Colors of Interest, such as white and yellow, to detect boundary lines and potholes. A copy of the original image is also copied and then converted into a grayscale image before a Canny edge detection algorithm is applied. A Dilation filter is applied to the Colors of Interest binary image. It is then combined

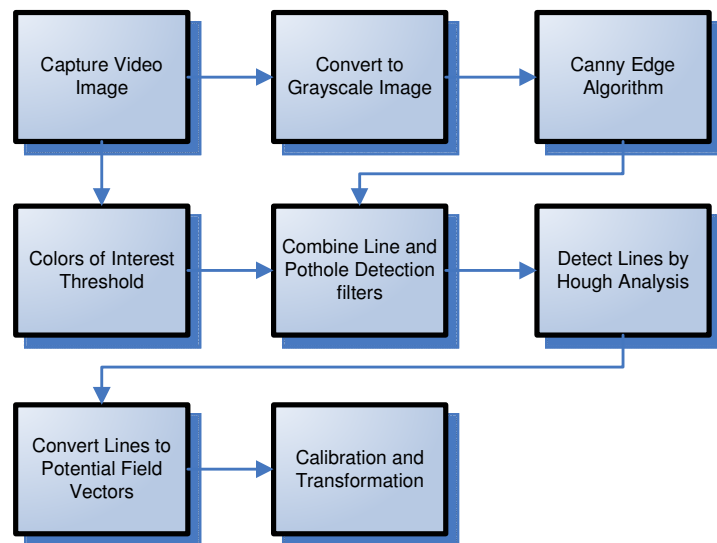


Figure 10. Flowchart for Line and Pothole Detection

with the Canny algorithm images creating a third image. If a pixel is white in both filtered images this pixel will also be white in the resultant third image. The resulting image provides noise-free, potential edges of only the colors that interest us and is ready for a Hough analysis. The purpose of the analysis is to identify potential line segments in the filtered image.

Line segments are stored in a data structure before being processed in a fashion similar to a laser range finder. A virtual sweep across the “image” will be used to convert the line data into potential field vectors, both attractive and repulsive. A short-term history of previous line data will be used to determine whether the vehicle is going forward or has turned around. This data is vital to the direction of attractive forces constantly pushing the vehicle forward. To prevent the vehicle from running into boundary lines and potholes, repulsive vectors are generated, which factor in parameters such as the normal angle of the line segment, the distance from the vehicle’s position (loosely represented by the bottom center of the image), and the relative angle from a point on the line to the vehicle’s position.

6.12 Navigation Challenge

The purpose in this stage is to reach the most waypoints in the allotted six minutes run time. The navigation system will use a DGPS (Differential Global Positioning System) using WAAS (Wide Area Augmentation System) correction service. The system is equipped with two NOVATEL GPS receivers. Using two receivers in parallel will reduce the amount of error and increase the accuracy and reliability.

The use of the NMEA (National Marine Electronics Association) queries for the receiver communication will provide helpful information for conducting and completing the navigation challenge. The Potential Field paradigm is utilized in order to navigate the environment, reach waypoints and avoid obstacles.

The vehicle will first receive the waypoint coordinates set and detect its current location. Based on this information, it will create the field boundaries and local grid. The system will then pop the recorded GPS coordinates of the first waypoint

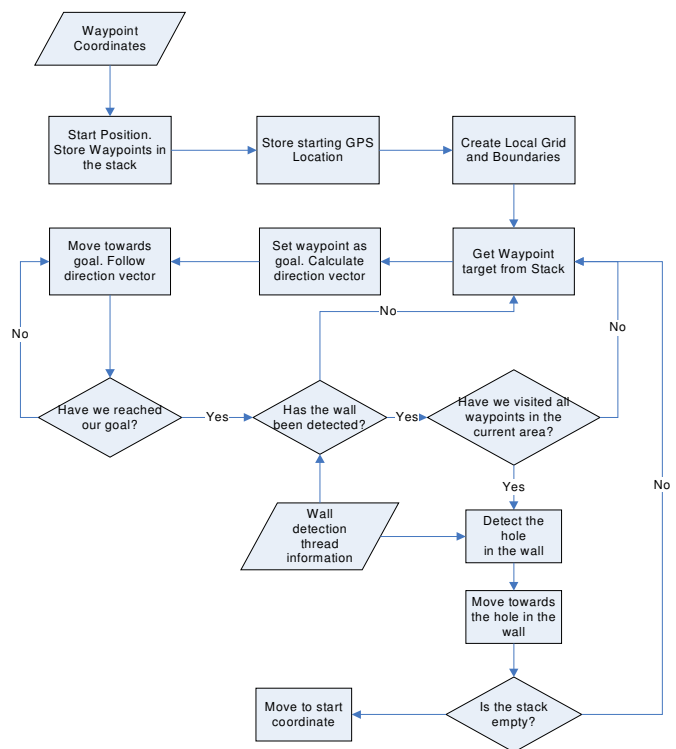


Figure 11 Navigation Challenge Logic

from the stack, and start moving towards it. Throughout these steps there will always be a parallel thread running, whose only job is to filter the sensors information in order to find the wall dividing the Mesa

from the Valley. Once the wall has been detected the vehicle will be able to use this information in order to create two waypoint coordinates subsets, one corresponding to the Valley, and the other corresponding to the Mesa. After visiting all the waypoints in the Valley area, the vehicle will use the information provided by the wall detection thread to identify the hole in the wall, set it as a goal, and move towards it. Once inside the Mesa, the vehicle will follow the same process until all the waypoints have been visited. It will then move back to the hole in the wall and eventually back to its starting position.

6.13 JAUS Challenge

The software architecture was designed keeping JAUS in mind. JAUS-compliance is an important feature of Mav-Bot, because it enables standardization of message-passing and will also facilitate expansion of existing systems with new capabilities.

During the requirements evaluation phase, JAUS was an unknown entity to us. After our faculty advisor provided some basic background information on this autonomous vehicle standard, we assigned the task of amassing information about it to one of our team members. His research was then used as a basis for incorporating JAUS into the software architecture.

Our first goal was to achieve Level 2 compatibility. This was done by creating a server client program in C# which can communicate via an Ethernet cable. The JAUSBox program sends the commands and the JAUSVehicle program receives the commands and sends an acknowledgement if necessary and performs the desired action. Our preliminary testing has confirmed that we can comply with the Level 2 JAUS messaging protocol requirements specified in the competition rules.

Our next goal was to achieve Level 3 compatibility. The JAUS interface is a subsystem of the External Systems layer of our Software architecture. This will enable us to store and retrieve the waypoints in the desired order for the Navigation Challenge.

7.0 Safety, Reliability and Durability

Safety: There are two emergency e-stops integrated into Mav-Bot's systems: a hardwired manual push-button positioned at the center rear of the vehicle and a wireless e-stop. They are both located on the vehicle mast to meet the competition requirements. Both e-stops break the power connection between the motors and the rest of the vehicle's electrical system, causing the robot to come to a quick halt.

Additionally, to comply with the IGVC rules, the maximum speed reached by the vehicle is 3 mph; this guarantees that the vehicle remains under the maximum speed requirement. The electrical wiring is well insulated and labeled to prevent errors in connecting the electrical subsystems and power supplies.

Reliability: The electrical design of the vehicle was implemented to make it reliable. Both 24 Volt motor supply and the 12 Volt processor and sensor power supply are redundant. This design also supports

the hot-swapping of batteries. Extensive testing was performed on the hardware and software components to ensure proper functionality and integration with the rest of the system.

Durability: Mav-Bot uses a rigid and strong steel platform and an aluminum top frame built to sustain an impact. The vehicle also has all its external sensors covered, in order to protect them in case of bad weather conditions.

8.0 Performance Analysis

Component Testing

Tests were performed on all sensors to determine what kind of error could be expected from their performance. The tests performed on the GPS, digital compass, the camera, and the SLRF were all validated and are being used without any adjustments. However, the LLRF had significant errors associated with it. The LLRF test was performed by placing obstacles at measured distances in front of the laser in order to determine the distance read. The test range was from 3ft – 108ft at 3ft ascending increments. The recorded distances were then plotted showing a linear trend. Therefore a linear regression was run in order to find a predictive equation for correcting the laser readings. Table 3 is a report of the regression analysis.

SUMMARY OUTPUT								
<i>Regression Statistics</i>								
Multiple R	0.999							
R Square	0.999							
Adjusted R	0.999							
Standard E	1.202							
Observator	37.000							
<i>ANOVA</i>								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>				
Regression	1.000	38962.243	38962.243	26967.376				
Residual	35.000	50.568	1.445					
Total	36.000	39012.811						
	<i>Coefficient</i>	<i>standard Err</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>ower 95.0%</i>	<i>pper 95.0%</i>
Intercept	-2.630	0.415	-6.342	0.000	-3.472	-1.788	-3.472	-1.788
X Variable	1.123	0.007	164.217	0.000	1.109	1.137	1.109	1.137

Table 3 Regression Analysis

Notice that the R-Squared value is .99. This suggests that the regression was valid. The following equation will be used for correcting the readings in this laser.

$$\text{Distance} = 1.122636 * \text{Reading} - 2.63026$$

Performance Testing

Table 4 represents the performance predictions and results. When operating the vehicle, we have observed that there is excessive vibration experienced by the camera system. Between now and the time of the competition, we plan to implement a damping system to reduce the amount of vibration experienced by the camera. If we are unsuccessful in reducing these vibrations, we will be forced to reduce the speed of our vehicle to ensure adequate image quality.

The vehicle can climb an incline of at least 30°. This will be sufficient to climb the 15% grade ramp in the competition. The reaction time, between perception and action, has been estimated to be 0.5 seconds. Testing confirmed that this reaction time was adequate for the vehicle to avoid obstacles. The obstacle avoidance tests were performed on a test course setup to imitate the obstacle challenge. The tank was able to see and avoid obstacles at a distance of 4 meters. These obstacles include center islands, potholes and switchbacks. The vehicle is not yet equipped to deal with traps.

Performance Measure	Performance Predictions	Performance Results
Speed	3 mph	Software Restricted
Ramp Climbing	30° incline	30° incline
Reaction Times	.5 seconds	Approximately .5 seconds
Battery Life	4 hours	< 3 hours
Obstacle Detection	4 meters	4 meters
Center Islands	Can avoid center islands	Avoids center islands
Switchbacks	Can perform switchbacks	Perform a switchback
Traps	Cannot exit a trap	Cannot exit a trap
Potholes	Can see and avoid potholes	Sees and avoids potholes
Waypoint Accuracy	1 meter	< 1 meter

Table 4 Performance Measure

9.0 Vehicle Systems Cost

The following table summarizes the total component cost for Mav-Bot. The cost of the original MK 5 robot is unknown. The robot platform, GPS components, and batteries were donated to this project.

Device/Sensor	Description	Retail Cost	Team Cost
Camera	Sony Color Video Camera EVI-D70	\$620.00	\$620.00
GPS receiver	Novatel Propak-G2-DB9-RT2	\$8,495.00	\$0.00
GPS Antenna	Novatel GPS-702	\$995.00	\$0.00
Digital Compass	Revolution GS True North	\$553.26	\$553.26
Main Board	WinSystems Pentium M EBX SBC 1.8Ghz 1Gig Ram	\$1,379.16	\$1,379.16
Micro Processor	New Micros Plug-A-Pod Embedded Controller	\$89.00	\$89.00
H-bridge	Robot Power OSMC H-bridge (2X)	\$420.00	\$420.00
Laser Range Finder	Hokuyo URG Series C-42-3320-A	\$2,500.00	\$2,500.00
Laser Range Finder	Opti-Logic RS100	\$495.00	\$495.00
LRF Pan/Tilt Unit	Servo-City Pan/Tilt Unit	\$200.00	\$200.00
LRF Pan/Tilt	New Micros IsoPod-SR1 Embedded Controller	\$149.00	\$149.00
LRF H-Bridge	New Micros NMHI-0050	\$29.95	\$29.95
Digital Compass	OceanServer OS5000-US Evaluation Kit	\$299.00	\$299.00
Batteries	12V lead acid batteries (6X)	\$181.08	\$0.00
Electrical	DC/DC power regulators, fuses, connectors, wire	\$90.00	\$90.00
Fabrication Supplies	Fasteners, insulating material, material for enclosures	\$57.00	\$57.00
Vertical Structure	80/20 Aluminum Extrusion	\$235.00	\$235.00
Platform	Israeli Military Industries Hornet MK-5 Robot	N/A*	\$0.00
Total Cost		\$16,787.45	\$7,116.37

Table 5 Vehicle Cost Breakdown

10.0 Conclusion

The Mav-Bot is the first UGV to be entered in the Annual Intelligent Ground Vehicle Competition by the University of Texas at Arlington since 1996. Over the last year many dedicated students and faculty have researched, implemented, integrated and tested the mechanical, electrical, and software subsystems. The end result of this combined effort is a functional autonomous vehicle. Although there has been a great amount of time and effort put into this vehicle, there are many opportunities for improvement in the future.