AMOS III

R·I·T

Team Members:

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Faculty Statement:

I hereby certify that the design and development of the robot discussed in this technical report has involved significant contributions by the aforementioned team members, consistent with the effort required in a senior design course.

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Introduction

The Rochester Institute of Technology (RIT) Multi-Disciplinary Robotics Club (MDRC) is pleased to announce its entry AMOS III into the 2010 Intelligent Ground Vehicle Competition. We have added several new hardware and software innovations including distributed probabilistic mapping, a more robust E-Stop system, and...

Innovations

Distributed, Probabilistic Mapping

A distributed map system was developed to provide 3D map storage for sensor fusion. While navigating the course, the probability of an obstacle occupying an imaginary grid surrounding the robot is is calculated and is accumulated from different sensor models for laser range finder and line detection algorithm.

Robust, Custom E-Stop System

A robust and long-range emergency stop system was implemented in-house. The system is capable of halting locomotion within milliseconds at distances greater than 300 feet using unlicensed 900 MHz Zigbee transceivers.

Subsystem Simplicity

Throughout this report, you will notice how each hardware subsystem strives for maximum simplicity while maintaining robust operation. Previous competitions have shown the that simple hardware subsystems are easier to maintain, debug, and operate while providing solid primary functionality.

Team Organization

MDRC is a small, highly focused team of motivated students. Since our organization is multi-disciplinary, each team member brings his own unique perspectives and talents. Our approach has been to distribute tasks to the team members most passionate about working with or learning about them. Since each member had a vested interest in the robot's success, they remained passionate and productive in their tasks.

To ensure that each team member's work became integrated with the collective effort, work periods were organized in which team members were encouraged to coordinate individual efforts into their larger modules, discuss design decisions, and to generate and receive feedback on new ideas.

Design Process

Initial designs focus on making each system modular to allow changes from troubleshooting to any portion of the robot without requiring additional modifications in related areas. Electronics are also arranged to keep wiring efficient while still having easy access to individual components. Once the individual system has been debugged to confirm its operation separately, it is tested with the rest of the robot during mock runs to test operation with the rest of the robot and check for conflicts.

Training

Our main method for training less experienced members is to encourage them to participate in the collaborative work sessions we hold to design and debug the robot. While we strive to maintain thorough documentation that is accessible to all members which makes a strong starting point, working on current issues helps provide insight on our design and troubleshooting processes; it also gives practical experience on how individual modules operate and interact with one another. From there, they can begin to provide their unique perspective to help overcome obstacles as they become more acquainted with the systems.

Planning

An overall project leader provides guidance throughout the months of development leading to the competition by setting goals and deadlines for various subsystems. A clear goal for each subsystem is stated and consequent deadlines are set based on achieving this goal in time for testing. This year, our goals focused on simplicity in design and robust operation under widely varied conditions.

Implementation

Once tasks are assigned to the individual or group most interested in working on it, a Trac system is used to set milestones and assign due dates for the individual tasks. Trac is an online project management system designed to keep software projects on target. Trac integrates with our subversion code repository and allows code check-ins to reference tickets with progress reports as work is being done. This makes it easy to make sure all tasks are progressing as planned, and to add man power to tasks which are falling behind.

Testing and Integration

The AMOS platform has undergone rigorous testing from individual hardware and software components, up to full navigation system testing. All algorithms were first tested within the Player/Stage robotic simulation environment to assess their reliability.

Testing was performed throughout the building stage. This allowed each new subsystem to be tested when it reached a point of minimal functionality. Once any bugs found were worked out, more features were added and subsequently tested in the same manner. This helps to reduce testing and debugging time by helping bugs to be found early in the development cycle and minimizing the number of changes that could have caused the bug. Once all systems were tested and verified to be functioning correctly, system testing was performed to ensure all the modules function correctly with one another.

Mechanical Design

Modularity

The upper frame was specifically designed with modularity in mind: the upper layers can be easily reconfigured for different purposes. For example, if the payload was to increase in height, we would only have to unscrew 4 bolts and move it up a few inches on the graduated support poles. The lower chassis was designed with a slightly more rigid framework in mind as the components from the motor layer are rarely changed.

The LIDAR mount is also modular in that it can be moved vertically and tilted with simple tools. We have used this ability to tweak the trade-off between range (by adjusting the angle) and angular resolution at small distances (by adjusting height).

The upper and lower layers have the ability to be separated, which greatly facilitates transportation in vehicles. The only connection between the lower motor layer and the above layers is a USB cable which is electrically isolated to provide noise immunity. The benefit of minimizing interfaces between these layers is that it allows simple physical disconnection as well as an abstracted, reusable motor layer for other projects.

Ruggedness

The AMOS chassis was custom built directly to accommodate our design needs. It is made of a steel rebar with diagonal elements to reduce flexing and it includes slots specifically for our batteries and motors. Despite heavy rain, rough terrain, and extensive test runs, the platform has remained solid and functional for several years.

Electrical Design

Power system

The power subsystem is extremely simple and self-contained by design: it consists only of four batteries, a relay for the E-Stop, and two switches controlling the computer and motor layer power. All battery charging is done off-board; this ensures we can quickly swap out batteries with freshly charged ones. All batteries are enclosed in the motor layer, pushing the center of gravity down towards the ground. Each battery is a Genesis 12V 12Ah.

Computer system

Maximizing computing performance was crucial for a highly responsive system. As our AMOS platform expands and matures, many design requirements need to be fulfilled for the present and future systems. The table below summarizes the design criteria for the main computer:

Requirement	Satisfied By	Advantage	Disadvantage
High performance CPU	Intel Core 2 Quad Q8200	-Excellent performance, multiple cores. -Facilitates multi-threaded nature of Player/Stage	- Comparatively high power consumption
High speed memory access	4 GB of DDR2 SDRAM (in four separate sticks)	- Fills all four motherboard RAM slots, allowing max simultaneous memory access	- None

Requirement	Satisfied By	Advantage	Disadvantage
More than one USB bus	Motherboard with 3 USB buses	-High I/O count motherboard -Meets USB requirements -Form factor is within shelving space	-Comparatively expensive motherboard
Shock and vibration resistance	32 GB Solid state drive	-Unaffected by heavy vibration and shock -Extremely fast read and write speeds compared to conventional hard drive	- Much higher cost per GB than conventional hard drives
High efficiency power conversion	High efficiency 250W DC-to-DC converter	-Small -No need to convert from AC back to DC within the supply	- None

Additionally, a laptop is connected to the top layer of the robot to act as a debug terminal. This debug terminal can be used to see data in real-time to help track down and fix errors as well as initialize initialize the robot through Player/Stage.

Emergency stop system

A completely new and custom emergency stop system was built for AMOS this year; it was designed with reliability and safety in mind.

The complete E-stop system consists of a remote (handheld) unit and a local (robot) unit. Both local and remote modules utilize the ATMega168 microcontroller and a XBee-PRO 900 radio modem. The remote is powered by a rechargeable battery which will last approximately 4 hours with continuous use, while the local module is powered by the 12V power-rail from the robot's power system. Both units have a pair of LEDs for monitoring current state and error conditions.

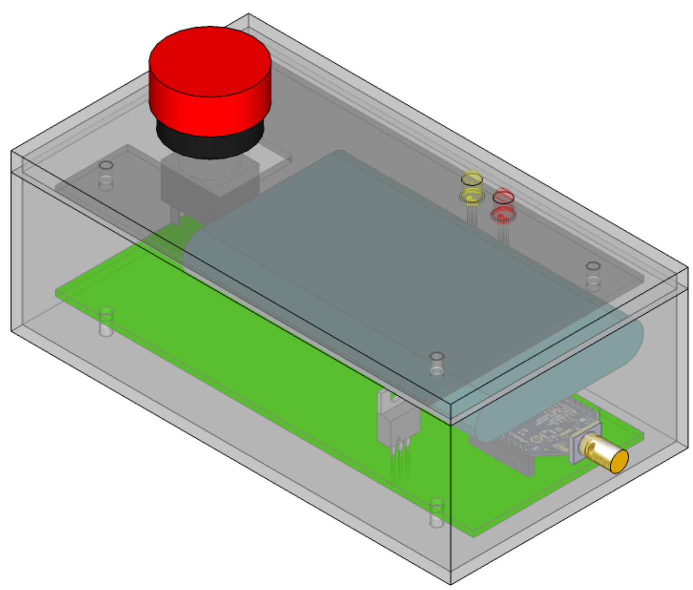


Figure 1: Emergency stop module 3D mockup

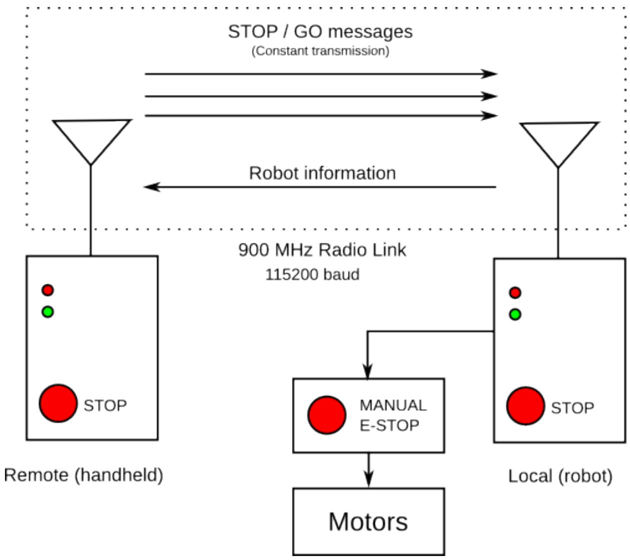


Figure 2: Block diagram of emergency stop system

When turned on, the remote unit immediately begins broadcasting the state of the E-Stop button several times per second at 115200 baud. Upon receiving these broadcasts, the robot checks the CRC provided by the XBee to ensure a complete message. If the message passes the CRC check, it notes the current time and checks the contents of the message. If the message contains the "STOP" command, or no valid message has been received for more than the 2.1 times the inter-broadcast delay, the robot will immediately disable the motors, bringing AMOS to a halt. Once halted, the robot will not re-enable itself until it has received the "GO" signal for more than 5 consecutive seconds without error.

In the previous year's implementation we used standard XBee-PRO modules which worked well around our college campus, but failed on the competition grounds due to high interference from the multitude of 2.4 GHz spectrum devices. After evaluating last year's failure, we identified several key features that must be present in this year's choice of radio-modem. The XBee-PRO 900 meets every one of our design requirements:

Goal	Xbee-PRO 900
Operates in a non 2.4GHz spectrum	- Operates in the 900MHz ISM band, out of the crowded Wi-Fi frequency range
Provides good resistance to nearby signals and EMI	- Frequency-hopping Spread-spectrum (FHSS) algorithm allows a more powerful transmitter due to limited use of individual frequencies - Reasonable level of protection against noise in specific frequencies
Reliable data-transport	- API includes a checksum for all transmitted and received data, allowing the local module to trust every bit in the received message

Motor controller

An in-house motor controller was created to abstract the low-level control of the robot's movement. The controller uses a closed loop, velocity-based PID controller with high resolution optical encoders on both wheels providing feedback.

Experience has shown that high resolution encoders provide much smoother PID control when properly tuned. Low speeds can cause problems with low resolution encoders due to lack of data while the robot is slowly rolling.

Our new encoder selection offers very high precision:

Direct Angular Resolution	180 ticks / revolution
Linear Resolution	~1500 ticks / wheel revolution or 62 micron / tick

Though much of the linear precision is lost due to slippage on the terrain or slack in the motor assembly, the high angular resolution is still directly beneficial for our control system.

The motor controller is based on the Arduino Diecimila (with the ATMega328 microcontroller running at 20 MHz). This controller was chosen due to its widespread commercial availability and open source support. The GCC toolchain - which includes a C compiler and other valuable tools - provided easy setup and integration process.

The motor-controller board has a custom PCB attached to it which provides a point of connection for the PWM signal to the motors, the signals from the encoders, and the measurements from the power monitoring circuit. Instead of using the Arduino's built-in USB to serial UART, the attached PCB includes it's own USB to serial UART which is optically isolated from the rest of the Arduino and motor-layer. Power for the UART and USB side of the optical isolator is derived from the USB port, while the Arduino powers the non-USB side of the isolator. This provides over a kilovolt of protection between the computer and the base layer and blocks any back-EMF noise induced by the motors from reaching the computer.

The motor controller is command by the main computer via serial data stream. Velocity commands are constantly issued by the computer as well as requests for encoder data. If the controller does not receive any velocity commands for greater than 500 milliseconds, it immediately halts locomotion. This is a safety feature designed to keep the robot from losing control if USB cable is somehow disconnected.

Sensors

LIDAR

For near-field obstacle detection and avoidance we make use a Light Detecting and Ranging module, made by SICK. A spinning mirror inside the device directs the laser over a 360 degree path (180 of which actually visible through the device's shield). At each finite degree, the distance the laser travels is measured and the angle plus distance is returned as part of a sweep. This is done many times per second to produce a horizontal line of points out to a distance of a meter or two.

dGPS

For absolute positioning, AMOS uses a differential GPS made by Trimble. It receives signals from the standard

GPS satellites, as well as differential corrections from ground towers and satellites. Using the differential corrections, the AgGPS132 can achieve sub-meter accuracy anywhere in the continental United States.

Compass

To steer towards specific GPS waypoints, AMOS uses a digital compass from Robotics Connection. The CMPS03 is an I2C peripheral which provides the current heading in tenths of degrees.

Webcams

AMOS is outfitted with three commercial USB webcams. This three camera setup utilizes one high quality webcam, to provide detailed frontal images for use in mapping, and two lower cost cameras to provide peripheral vision. The peripheral cameras can be used to detect dangerous situations that are out side of the field of view of both the LIDAR and the primary imagery.

Current/Voltage

The motor controller uses a combination voltage/current sensor to monitor for exceptional conditions of the motors. Current is software limited per motor to 20 amperes. Voltage sensing also provides a method of testing if the robot's E-stop system is activated.

Encoders

High resolution optical encoders provide quadrature angular velocity measurements of the shaft of each motor. Quadrature capabilities quadruple our resolution as well as give the direction of spinning.

Software Design

Overview

AMOS software uses the open source player robotics framework. Player has a server/client architecture, allowing algorithms and different components of the software to run on different machines and processes. Player robotics also dramatically the reuse ability of software code since a set of standard abstract hardware and software interfaces are defined.

A small number of built-in player drivers are utilized in AMOS software to interface with common hardware, including:

- sicklms200 - communication interface for the SICK LIDAR 2D range finder
- camerauvc - frame grabber from USB video camera
- camerav4l - frame grabber using the video4linux system
- garminnmea - driver for DGPS receiver
- festival - interface for voice synthesis to provide status announcement

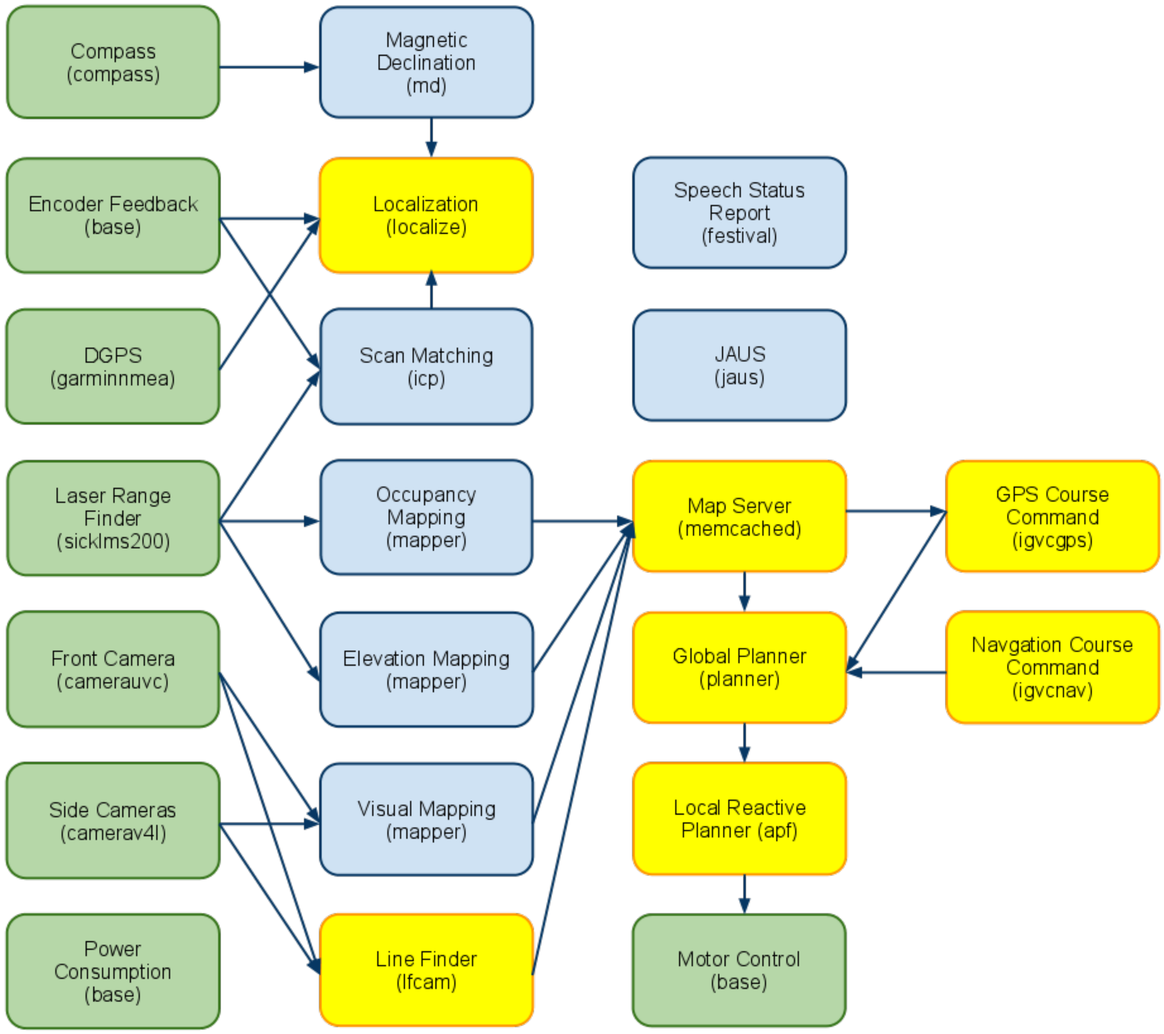


Figure 1: Map of software architecture

Some custom hardware interfacing drivers are also implemented, including:

- base - communication with the base motor layer, providing motor control and feedback as well as system power consumption monitoring
- compass - communication with the compass module mounted on the top of the robot

Intelligent navigation algorithms are built as separate plugins to be executed on the player server. Implementing these subsystems as plugin components allows them to remain small in size and be easily maintained and tested separately. Moreover, plugins utilizes the multi-threaded and distributed nature of player robotics framework enabling efficient use of robot's on-board computing resources. These plugins include:

- md - magnetic declination correction filter to provide true north heading based on information made available by GPS and compass
- icp - laser range finder scan matching by iterative closest point algorithm to assist robot localization
- localize - fusion of location sense data from motor feedback, compass, GPS and laser scan matching

Plugins continued:

- mapper - sensor fusion mapping plugin to map ground elevation, visual data and occupancy probability
- cspace - plugin to automatically create and update configuration space map based on the occupancy probability map
- planner - global planner using A* search algorithm to find optimal path on configuration space map given current location and goal
- igvcgps - command unit for IGVC GPS course challenge, solves traveling salesmen problem continuously to determine the order of visit for waypoints based on the latest information available on the map
- lfcam - line finder vision algorithm to identify lines from camera frame
- igvcnav - command unit for IGVC autonomous navigation challenge

The map server is implemented using the fast and distributed memcached server. It provides simultaneous read and write access to the multi-channel map for all components that utilizes the map. The map itself is formated in tiles and can be stored into and loaded from a sqlite3 database.

Localization

Precise localization is very difficult based on any single source of pose information. To minimize the errors in using encoders for position sensing, compass and GPS data are combined to make a correction. The encoders keep track of an (x, y) offset from the initial position as well as an offset angle. When updates from the compass are received, the error in the angle is calculated, and used for future updates. When a new GPS position is received, the encoder position offset by the error in the angle is calculated, and then the x and y errors are calculated. Between updates from the compass and GPS the encoders are corrected by first rotating by the angle error, and then by translating it by the x and y error. This scheme provides corrections for any wheel slipping.

Mapping

Map Server

A distributed map system is developed to provide 3D map storage for sensor fusion. This new mapping system divides the grid map into small tiles of user defined size. Each tile only gets created and stored when data for such tile is modified. The map can grow without boundary in all directions and remains efficient in using storage space. Each map also has multiple channels allowing probability data, configuration space data, visual data and elevation data to be stored separately for each cell.

The map system uses memcached, a high-performance, distributed memory object caching system, to provide super fast transfer of tile data with low delay. Client library is provided for multiple components of the robot software system to read and write the shared map simultaneously. The client library also takes care of tile loading, locking, and saving, hiding away the internal tile structure from end programmers. And finally, the map that lives on the memcached server during robot operation can be saved onto a harddisk in the sqlite3 database format. These databases can be loaded back into the memcached server if continue exploration of the same area is desired.

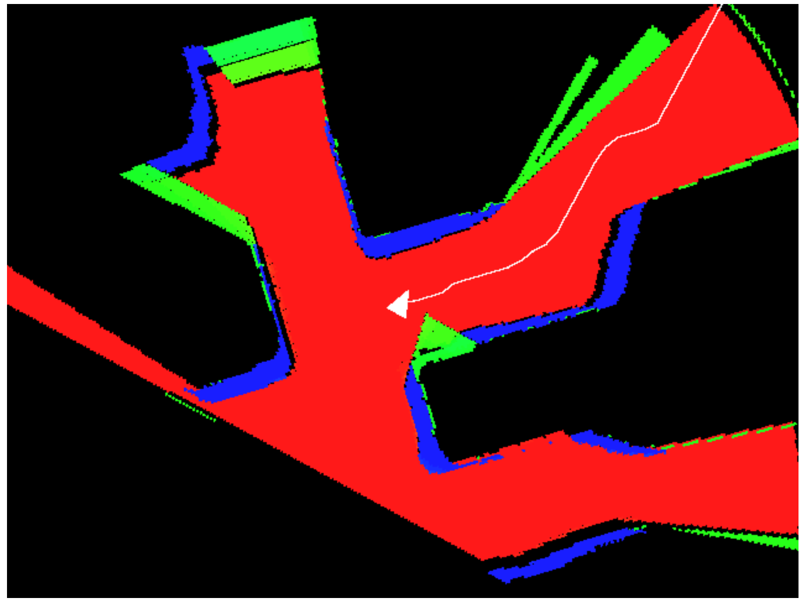


Figure 2: 2D Visualization of map data. Red areas indicate no obstacles, blue and green indicate increasing probability of obstacles

Occupancy Probability

The probability of occupancy for each cell is calculated and accumulated from different sensor models for laser range finder and line detection algorithm. A probability of 0.5 representing unknown spaced is assumed for new map cells. When this probability will gradually grow to near 1.0 as the evidence of obstacles within the cell accumulates. On the other hand, free space accumulates towards a probability of 0.0.

Configuration Space

Configuration space map is generated and continuously updated by a process that monitors the probability map for changes. Obstacles are grown in size by the maximum radius of the robot, such that robot is represented as a single point of mass in the configuration space. This dimensionless representation of the robot simplifies path planning by eliminating the need to consider the physical size of the robot when determining whether a path is feasible. Buffer zones are also created near all obstacles. These areas are intentionally marked with higher costs depending on its distance from the closest obstacle. Buffer zones provides a guidance for the path planning

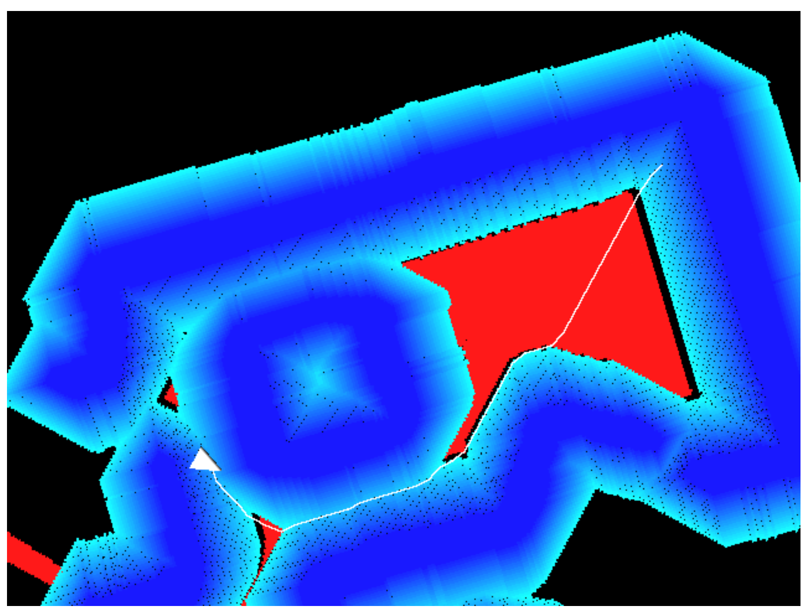


Figure 3: Configuration space map. Red regions are fully traversable, blue shades indicate undesirable traversability scores

algorithm to avoid being too close to any obstacle while not prohibiting such path if it is truly necessary.

Visualizer

Along with the mapping system, a visualizer is developed to render the different channels of a map in 3D. The visualizer uses OpenGL and physical graphic card support to provide fast render of massive amount of sensor data collected in the map. The visualizer is a great tool for analyzing previously recorded map. But it is an even more vital debugging tool for displaying various data in real time. While the robot is in operation, the visualizer shows the location of the robot in the changing environment as well as the path planning decision it is making.

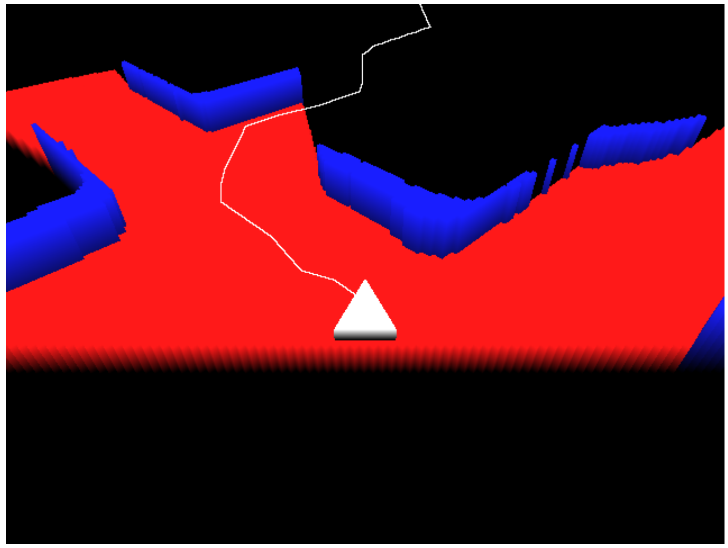


Figure 4: 3D visualization of the probabilistic obstacle map

Global Path Planning

Global path planning is achieved using a combination of A* search algorithm and the concorde traveling salesman problem solver. A* search algorithm provides the optimal path and cost between two given points on our probability map. Concorde TSP solver focus on computing the optimal order of waypoints to be visited. The system re-plans the path based on the latest information available in the map.
The A* algorithm is computed using the probability map to determine to cost of each cell..

$$c = c' + \frac{k}{(1-p)}$$

where c = new cumulative cost and c' = cumulative cost to parent.

$$p = \begin{cases} p = 0.0, & \text{traversable} \\ 0.0 < p < 1.0, & \text{varying confidence of obstacle} \\ p = 1.0, & \text{intraversable} \end{cases}$$

$$k = \begin{cases} 1, & \text{if horizontal or vertical move} \\ \sqrt{2}, & \text{if diagonal move} \end{cases}$$

$$h = \sqrt{(c.x - g.x)^2 + (c.y - g.y)^2}$$

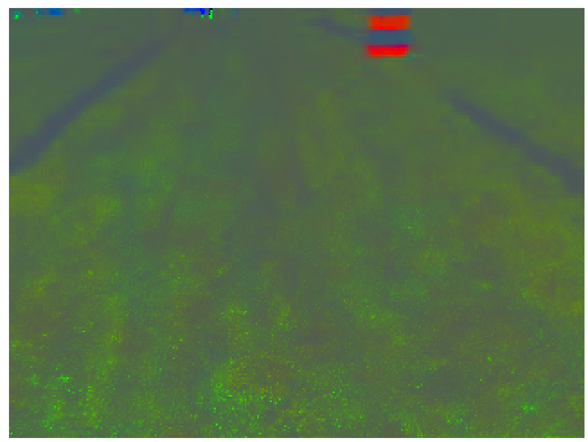
Local Path Planning

For more reactive path planning, a potential field approach is used. This approach allows input from various sensors to be accumulated easily. The algorithm uses obstacles to repel the robot from them, while the robot has a desire to drive forward, or toward a GPS waypoint. The robot will drive close to the mid-point between obstacles because this is the point of equilibrium in the current view. The local path planning allows the robot to react to obstacles not yet present on the map which are missed by the global planner. It also allows the robot to react to a changing environment.

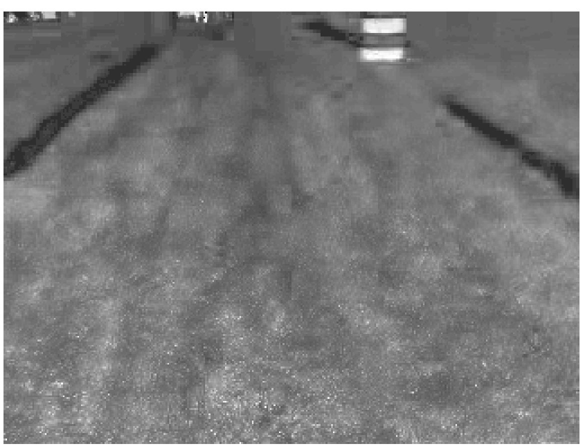
Visual Lane Detection

When a frame is acquired the image is converted to the normalized RGB color space. This transformation helps reduce the effect of changing lighting conditions. Next color segmentation is used to select areas in the image which are closest to the expected color of the white lines. The above color distance image shows the result of measuring the error for all pixels to the expected color value. The dark regions are close to the desired color while lighter areas have colors which are far from the desired value. A threshold is applied to the distance image and tested against the model of white lines. The model will only select masked areas which are narrow enough to possibly be white line segments. The location of the masked areas are projected into the the robot's coordinate frame and are then passed to the local planner as the coordinates of obstacles which must be avoided.

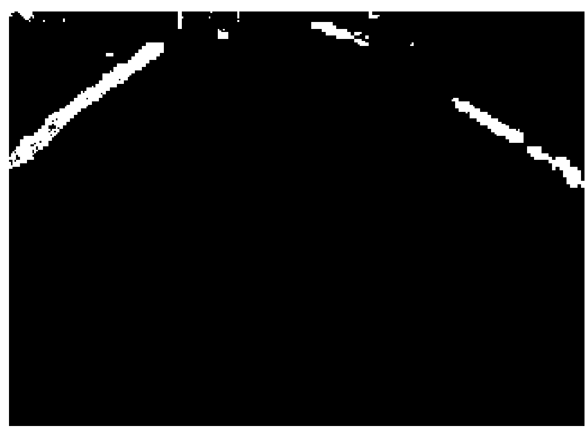
Step 1: Input image



Step 2: Normalized RGB



Step 3: Color “distance”.



Step 4: Thresholded final image of lane lines

JAUS Compliance

We use Jr. Middleware's open source implementation of JAUS SAE-AS4 standards in a custom Player driver and device proxy to realize JAUS compliance. The Player driver and device proxy break down JAUS communication into a simple API and signaling process to minimize the amount of processing code required.

Conclusion

Performance Analysis

Attribute	Design Goal	Final Product
Speed	5 mph	4.5 mph
Reaction Time	Near Instantaneous	100 ms
Battery Life	2 Hours (normal operation)	2 Hours
Obstacle detection distance	8 meters	8 meters
Vehicle performance with obstacles	No collisions	No collisions under normal circumstances
Navigation point accuracy	0.2 meter	1 meter

Bill of Materials

Category	**Part**	**Vendor**	**Part No**	**Qty**	**(Market)**	**(Market)**	**(Actual)**
Chassis	Frame materials (steel)	Metal Supermarket	-	30 Ft	$100	$100	$100
	Frame materials (alum)	Metal Supermarket	-	15 Ft	$75	$75	$75
	Misc. hardware	Various	-	-	-	$75	$75
	Misc. elec. connectors	Various	-	-	-	$40	$40
	Motors	Unknown	-	2	$500	$1,000	$0
Sensors	LIDAR	SICK	LMS-291	1	$5,000	$5,000	$0
	dGPS	Trimble	AgGPS132	1	$500	$500	$0
	Digital compass	Robotics Connection	CMPS03	1	$57	$57	$57
	Optical encoders	US Digital	E8P	2	$38	$76	$76
	Front webcam	Logitech	QuickCam Pro 9000	1	$80	$80	$0
	Side webcams	Lego	Legocam	2	$30	$60	$0
Computer	Motherboard	Newegg	N82E16813128358	1	$135	$135	$135
	CPU	Newegg	N82E16819115055	1	$169	$169	$169
	Memory	Newegg	N82E16820231144	2	$32	$64	$64
	DC-DC power supply	Minibox	M4-ATX	1	$90	$90	$90
E-Stop	XBee-PRO 900	Digi	XBP09-DPSIT-156	2	$45	$90	$90
	ATMega168	Atmel	ATMEGA1284P-PU	2	$8	$16	$16
	Emergency Stop Switch	Omron	A165E-S-01	1	$41	$41	$41
Batteries	Genesis 12V 12Ah	Genesis	G12V26AH10EP	4	$120	$480	$480
					Totals:	**$7627**	**$987**