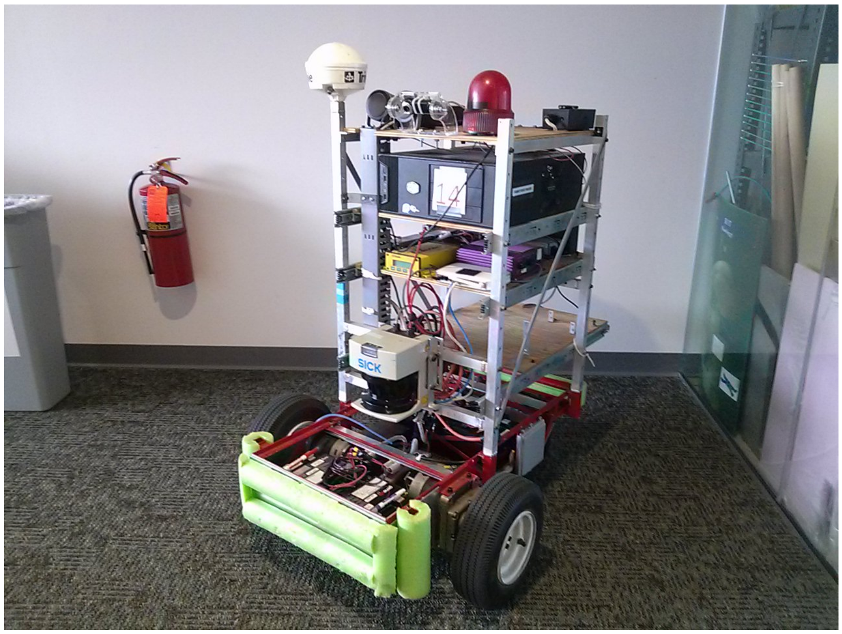
AMOS III Design Report
RIT Multi-Disciplinary Robotics Club



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1 Introduction

The Rochester Institute of Technology (RIT) Multi-Disciplinary Robotics Club (MDRC) is pleased to announce that we will be returning to the 21st annual IGVC competition. As with previous years, we will be using our AMOS III competition platform. We have added several new hardware and software innovations, including a revamped vision algorithm.

2 Innovations

ROS

As a continutation from our entry last year, we have developed and improved upon the ROS control system that was implemented to last year. ROS is a powerful tool which simplifies the integration process of sensors and software. Communication between nodes in ROS is greatly simplified over the interface of systems used in the past. Also, because all ROS nodes run as separate processes, a crash in any one node will not bring the whole system down.

Simpler Vision Algorithm

In previous years, our line detection algorithm has always been the weak spot in our robot's algorithms. Generally, our vision code ended up being quite complex and difficult to manage. This year our vision algorithm is simple, easy to tune for different conditions, and works quite well.

3 Team Organization

MDRC is a small, highly focused team of motivated students. Since the organization is multi-disciplinary, each team member brings their own unique perspectives and talents. Tasks are distributed to the team members most passionate about working with or learning about them so that each member had a vested interest in the robot's success. This way they remain passionate and productive even through the most arduous 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.

3.1 Design Process

Initial designs focused on making each system modular to allow changes to any portion of the robot without requiring additional modifications in related areas. The hardware design was laid out using AutoCAD software to provide intuitive organization by function and to optimize it for space. Electronics are also arranged to keep wiring efficient while still having easy access to individual components. Once the operation of individual systems has been confirmed they are then tested with the rest of the robot in comprehensive field tests.

3.2 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. We strive to maintain thorough documentation that is accessible to all members. This makes a strong starting point, enabling work on current issues and helping to 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.

3.3 Planning

An overall project leader provides guidance throughout the months of development leading up 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.

3.4 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.

3.5 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 in ROS sandboxes 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.

4 Mechanical Design

4.1 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 communications connection between the lower motor layer and the above layers is a USB cable, which uses a highly noise immune differential signal.

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.

4.2 Ruggedness

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

5 Electrical Design

5.1 Power System

The power subsystem is extremely simple and self-contained by design: it consists of four batteries, fuses, 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.

Four batteries are used to power the robot: two are used for driving the motors and two are used for the top computing layers. Each battery is a Genesis 12V 28Ah.

See the Performance Analysis section for battery life estimates.

5.2 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 buying the main computer:

Requirement	Satisfied By	Advantage	Disadvantage

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

5.3 Emergency Stop System

Our E-stop system was custom designed in a previous year, some minor changes to the system were performed this year.

Due to the similarities between the remote and local E-stop modules, a single PCB design is used in both. Both modules also share the same ATMega168 microcontroller and XBee-PRO 900 radio modem. The remote module (handheld unit) is powered by a rechargeable RC battery which will last for approximately 4 hours of continuous use, while the local module is powered by the 12V power-rail from the robot's computer battery. Both units have a pair of LEDs for monitoring current state and observing error conditions.

When turned on, the remote immediately begins broadcasting the state of the E-Stop button many times per second. The XBee radio modem transmits these messages to the robot using a Frequency Hopping Spread Spectrum algorithm. 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 it to a halt. Once halted, the robot will not re-enable itself until it has received the "GO" signal for more than 5 seconds straight without error.

The communication protocol used in our implementation is unidirectional, and as such the status display on both devices can only show the current "expected" state of the robot, rather than the actual state of the E-Stop relays.

In some of our implementations from previous year's we used standard XBee-PRO modules which worked fine around our college campus, but failed on the competition grounds. After evaluating those failures, we identified several key features that must be present in our choice of radio-modem. The XBee-PRO 900 meets every one of our design requirements:

- Operates in a non 2.4GHz spectrum
- Provides good resistance to nearby signals and EM noise
- Reliable data-transport

The XBee-PRO 900, as the name suggests, operates in the 900MHz ISM band and keeps us out of the Wi-Fi frequency range. Unlike most of the rest of the product line, this model employs a frequency-hopping spread-spectrum algorithm which allows it to use a more powerful transmitter due to limited use of each individual frequency. This also provides a reasonable level of protection against noise in specific frequencies. Finally, the XBee-PRO 900 also provides an API which includes a checksum for all transmitted and received data, which allows the local module to trust every bit in the received message.

Some small improvements were made to this existing E-stop system. Previously, the custom PCB which was designed for the E-stop had a direct connection between the external antenna which provided our extended range capabilities and the Xbee. In our last competition, having the antenna connected to the Xbee resulted in a crack in the Xbee board after a few days of competition use, rendering our E-stop almost ineffective, except for a between runs repair. This year, the hand-held board was modified so that a flex connector could be inserted between the Xbee and the external antenna. This helps to ensure that any torque on the external antenna isnt transferred to directly to the Xbee.

5.4 Motor Controller

An in-house motor controller was created to abstract the low-level control of the robot's movement. Closed loop motor control is accomplished using PID and high resolution optical encoders on both wheels.

This controller, along with motors and control circuitry is located in the lowest section of the robot. In keeping with the hardware layer isolation approach, the only connection between the motor layer and the above layers is a USB cable. The benefit of minimizing interfaces between these layers is that it allows simple physical disconnection as well as an abstracted, reusable motor layer for many projects.

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: 5mm / tick

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

The motor controller is based on the Stellaris Launchpad (with the Arm Cortex M4 microcontroller running at 80 MHz). This controller was chosen as a replacement to the old arduino based controller for the added I/O capabilities, faster clock speed, and cheaper price. ROS also has support for treating the Stellaris as a node in the system, allowing it to be controlled using the same message passing system as the rest of the robot.

5.5 LIDAR

For near-field obstacle detection and avoidance we make use of 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 8 meters.

5.6 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.

5.7 Compass

For steering toward specific headings, AMOS has a small digital compass from Robotics Connection. The CMPS03 is an I2C peripheral which provides the current heading in tenths of degrees.

5.8 IMU

An ArduIMU v2 is used to help correct issues with the lack of tilt compensation with the CMPS03 compass module, as well as report on the orientation of the robot.

5.9 Webcams

AMOS is outfitted with a single commercial USB webcam. This camera setup utilizes a high quality webcam to provide detailed frontal images for use in mapping. The webcam is used to get the images which are processed in order to detect the lines of the course.

6 Software

6.1 Overview: ROS-based System

Our code base uses the open source ROS software. ROS is an arbitrated peer-to-peer architecture, this allows us to run algorithms on separate processes or even separate machines to offload computations as needed. Using already designed and built software allows the software team to focus on the algorithms involved with solving the challenges. Separate ROS programs are organized into packages, collections of related packages are organized into stacks.

6.2 Position

The ROS tf package is used to provide frame transforms for the robot. To allow for SLaM, and both local and global positions, four main frames are used: world, map, odom, and amos. World is a stationary frame placed at the global origin. Map is the origin of the SLaM map and is placed at the starting position of the robot, the local origin. Odom is modified by map to perform localization, it is the origin of the positioning by the encoders. Finally, amos is the position of the robot.

By asking for the transform from world → amos, the global position of the robot can be obtained. Similarly, by asking for the transform from map → amos the local position with localization is obtained. Finally, by asking for the transform from odom → amos the raw encoder orientation is obtained.

6.3 SLaM

A ROS stack called gmapping was used to provide the SLaM capabilities of the system. The slam_gmapping package takes the lidar output along with the robots odom → amos frame transformation to build the map.

Localization is performed by gmapping by finding what the new map $\rightarrow$ amos frame transformation should be, and knowing odom $\rightarrow$ amos, it can find the transform from map $\rightarrow$ odom.

6.4 Global Path Planning

The global path planning system for the GPS portion of the course utilizes A* along with an exploded version of the SLaM map build by gmapping. The exploded map contains probabilities that ramp down from $1 \rightarrow 0$ as you move away from the obstacles. The obstacles are also expanded so that in the new map the robot can be treated as a point to simplify the A* algorithm.

6.5 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 toward a GPS waypoint, or to return to its starting position in the final leg of the course. 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.

6.6 Vision

A new vision algorithm was used this year. It is based of the very simple concept of combining different color channels into one gray-scale image. The gray-scale image is constructed as follows:

$$gray_{ij} = 2 * blue_{ij} - green_{ij} + hue_{ij}$$

The gray-scale image is then normalized to the range [0, 1].

The combination of the blue and green color channels allows for robust detection of the lines in the course. However, it lacked the ability to differentiate between the speed bump and the lines, the addition of the hue channel helps to alleviate this issue, because the hue of the white line and the yellow speed bump are quite different.

Figure 1: Initial image frame

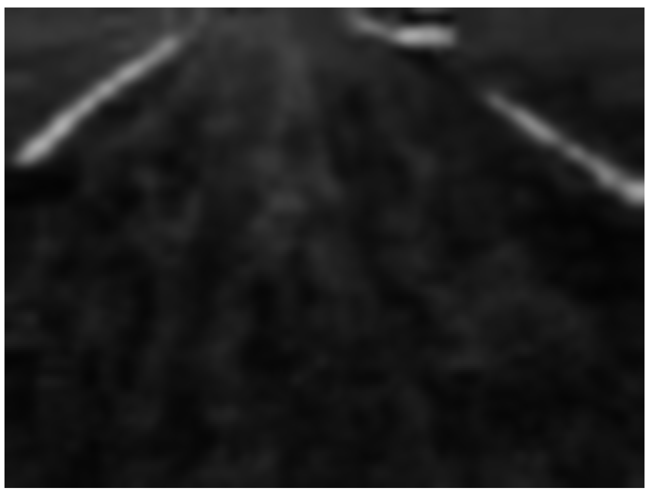

Figure 2: Gray-scale image frame

The gray scale image is then passed through a Gaussian filter to eliminate small areas of noise.

The image is then split into a left and a right half to allow for the detection of lines on both sides of the image, the top part of the image is also cut off to avoid finding and responding to things too far into the distance. Each of these half images are run through an algorithm that marks the brightest pixel in each row, then in each column and builds a new binary image out of the data.

At this stage, the lines in the image are clearly visible and the Hough Lines algorithm can be run on each half to pick out the lines.

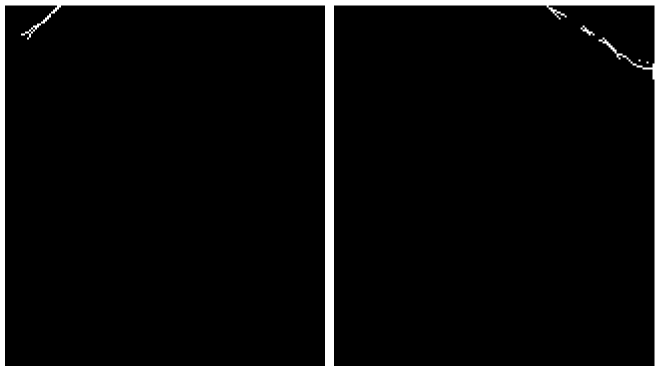

Figure 3: Left and Right halves of the image

Figure 4: Initial frame with lines drawn

Finally, these lines are converted into a format usable by the local navigation system and SLaM and passed out to the rest of the system as a ROS message.

7 Conclusion

7.1 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	Perfect	Near Perfect
Navigation point accuracy	.2 meter	1 meter

7.2 Cost Analysis

Part	Vendor	Part Number	Quantity	Cost(actual)	IGVC Cost
Frame Materials(Steel)	Metal Supermarket	-	30ft	$100	$100
Frame Materials(Aluminum)	Metal Supermarket	-	15ft	$75	$75
Misc. Mechanical	-	-	-	$75	$75
LIDAR	SICK	LMS-291	1	$3000	-
DGPS	AgGPS132	1	1	$500	-
Digital Compass	-	CMPS03	1	$60	$60
Motors	-	-	2	$500	-
Main-board	EPIA	MII	1	$150	-

Part	Vendor	Part Number	Quantity	Cost(actual)	IGVC Cost
Misc. Connectors	-	-	-	$40	$40
Solid state storage	Newegg.com	4 Gb Flash Card	1	$35	-
Webcam	Newegg.com	-	1	$50	$50
Victor Motor Controllers	IFI Robotics	883	2	$149	$149
				$4659	$549