UMASS University of Massachusetts Lowell

Stark

2011 Robot Design Report

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Introduction

The University of Massachusetts Lowell (UML) Robotics Team is proud to present "Stark," a robotics platform designed for research as well as competition in the Intelligent Ground Vehicle Competition (IGVC). Stark was designed as a collaborative effort by the Mechanical Engineering, Computer Science, and Electrical Engineering departments at the University of Massachusetts Lowell. UML has been competing in the IGVC for the past 6 years, each year learning from previous mistakes. Those years resulted in three significant mechanical and electrical revisions for the previous robots (named the MCP I through III). Stark is a brand-new platform that incorporates all of this learning and marks the first collaborative effort between departments.

Team Organization

Stark's design team is organized into two groups, focusing on hardware and software. Each has a team leader, senior members, and junior members. Each team leader reports to the Robotics Club president who oversees the entire robotics team.

Organization within the hardware and software teams vary slightly, and adapt to meet the constraints of the current year's problems. This year, the hardware team has one mechanical engineer performing maintenance tasks on the one-year-old vehicle. The hardware team primarily consists of three senior members who focus on electrical engineering challenges of power distribution, emergency stops, and control data paths. One junior team member also joined the hardware team this year to learn.

The software team has three members who work together to solve common problems, such as developing the simulation platform. The three members also have self-determined specializations.

Vehicle Overview

Stark employs a 4-wheel differential drive system for movement. Two motors control the two sides of the robot independently. The outer dimensions of the frame are 28" wide by 37" long. With the mast in the vertical position it stands 57" tall, and only 27" when the mast is collapsed for transport. The estimated weight of the vehicle including payload is approximately 200 lbs.

The electronics are isolated from the rest of the robot in a removable case that sits atop the chassis. Power is provided by two 12 volt, 50 amp-hour batteries, run in series to give 24v. The motors run on 24 volts, and a 24-to-12v DC-DC converter is used to power the computer system and sensors. Under ideal conditions the power system will last approximately 3 hours. The vehicle also has fail-safe and emergency stop systems integrated to keep it safe for operators and spectators. The electrical and mechanical systems will be discussed in detail in the following sections.

Stark will also include a comprehensive diagnostic sensor package along with logging software. Possible sensors include temperature, voltage, ammeters, and accelerometers. These sensors, along with the logging software will allow the team to track the health of the robot as well as the control programs running on-board. This system will be described later.

Mechanical Design

This robot, including sensors and computer was modeled in SolidWorks. This allowed the design of the robot to be tested before the design was finalized. The following sections describe a few of the main parts of the robot and their design.

Motors

Motor selection is critical in designing a robot capable of performing on different surfaces. A careful balance must be reached between efficiency, torque, and speed to optimize battery life while maintaining performance.

Initial assessment began with an energy balance between the mechanical power demands and the power supplied by the batteries. Torque requirements in the various scenarios which the robot will encounter were initially assessed. The scenarios tested were as follows:

- The robot is traveling in straight line motion: During straight line motion, the robot will have minimum torque requirements, only needing enough torque to keep the robot moving along the terrain. The robot is traveling at maximum speed (5mph), and should have minimum power draw.
- The robot is turning: As the robot corrects for direction, each wheel 'skids' while traveling in a circular path about the center of mass. This motion was considered to have the highest torque demand and therefore the highest power demand. Skid steer kinematics were researched to confirm intuitive assumptions about the resistance each tire would encounter to predict load requirements on the motors.

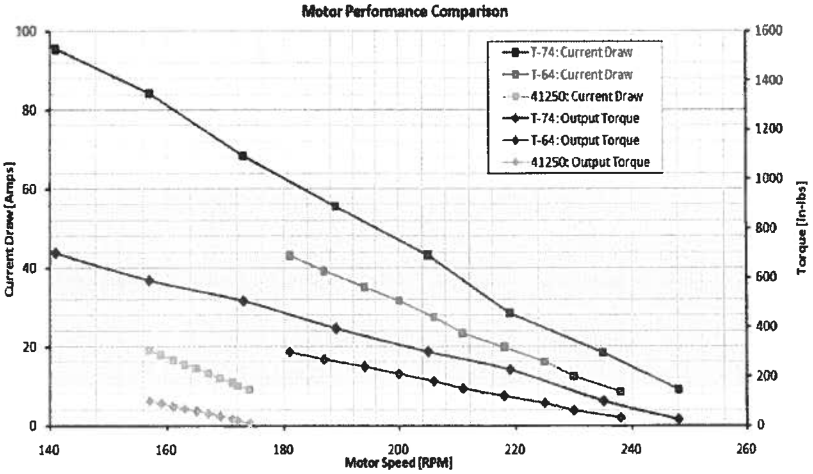

Figure 1: Comparison of motor performance.

To generate a reasonable approximation on the required torque, focus was shifted to empirical testing of the 2009 MCP III.5 platform. After thorough analysis and considering amp draw, motor speed, and torque, NPC T74 motors were selected from a field of likely candidates because of their light weight, high torque output and low current draw. Figure 1 shows some of the motor choices considered.

Chassis / Drive train

To cope with the extra forces caused by the skid steer design, a rigid frame was necessary. Extruded aluminum was used for all structural components due to its strength and light weight characteristics. The diagonal bars of the main frame rails serve a dual purpose. First, they provide diagonal strength to the frame much like the truss of a bridge, a theme that is carried throughout the design to reduce weight, add rigidity, and keep the robot aesthetically pleasing. Second, the diagonal bars give a convenient location for a tensioning sprocket for the drive train. A sprocket positioned at an optimal location restricts the idler slide to a single translational degree of freedom, effectively serving the function of removing slack in the chain. This also increases the chains contact on the gears, increasing the strength of the drive-train. Figure 2 depicts the frame rails and idler slider.

Skid steer kinematics were researched thoroughly to determine the optimal wheel base to reduce the amount of power needed to break friction and to turn smoothly. The wheelbase of 14"L by 24"W was found to give the smoothest turning. The center of mass was also placed directly in the center of this wheel base to reduce stress on the system. The drive-train shown below in Figure 3 was designed to be used with a chain, but is compatible with a belt drive system that could be added later. Chain was chosen to lower cost.

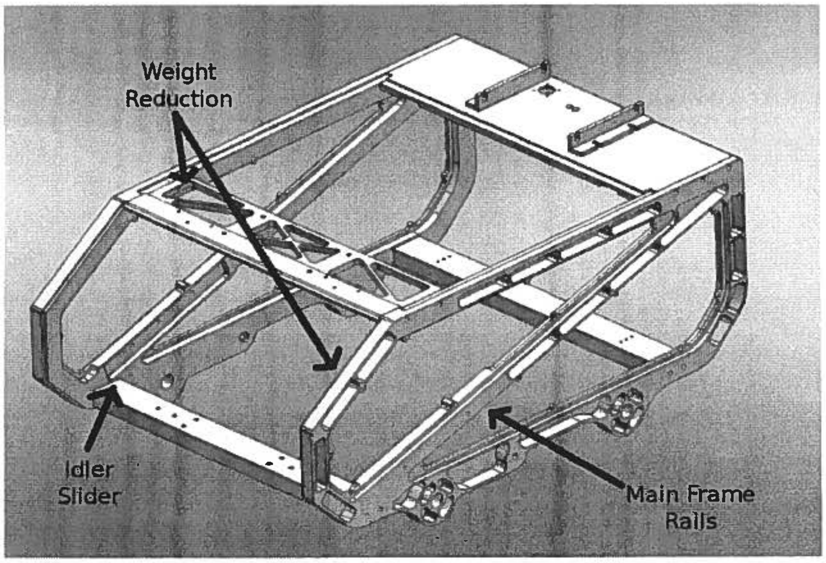

Figure 2: Key points in robot frame.

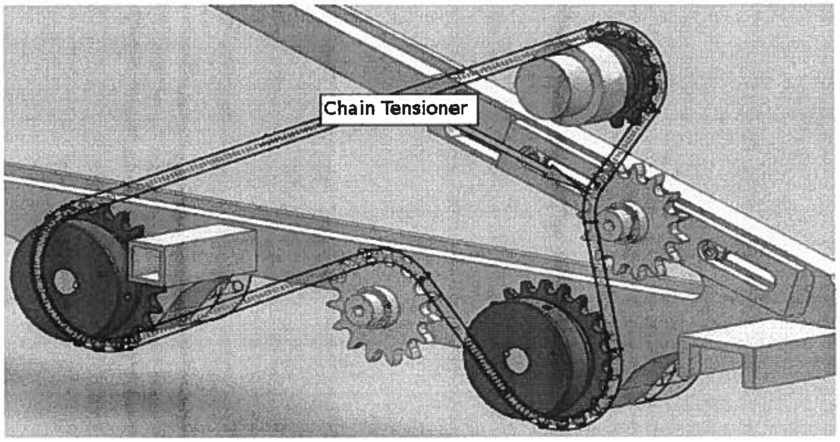

Figure 3: Robot drivetrain.

All components were placed to keep the robot perfectly balanced around its center of mass and low to the ground. The MCP is not well balanced. When traveling up a hill the weight at the back of the robot will cause it to flip onto its backside. The new chassis has been tested and will remain safe up to a 37 degree incline.

After the design was finalized, all heavy parts of the robot were analyzed to determine if weight reduction was possible. Heavy components were lightened by removing material in the form of pockets shown above. The integrity of the lightened components was maintained by staying away from areas of stress concentrations (i.e. holes, abrupt geometric changes, and sharp corners). Also, the remaining geometry did not have a significantly reduced section modulus, again, maintaining its structural integrity.

Sensor Mast

The function of the sensor mast is to position one or more cameras at a high vantage point to maximize the robot's field of view. Minimum functional requirements incorporated into the tower's design included the need to accommodate one Apple iSight camera being at a minimum height of five feet. On the MCP III platform only a single camera can be mounted. Since Stark was designed to be expandable several mounting points were made for the camera. Two cameras may now be mounted with focal points at known distances allowing for stereo vision capabilities or a single camera to be mounted in the center. The mounting positions are shown in Figure 4.

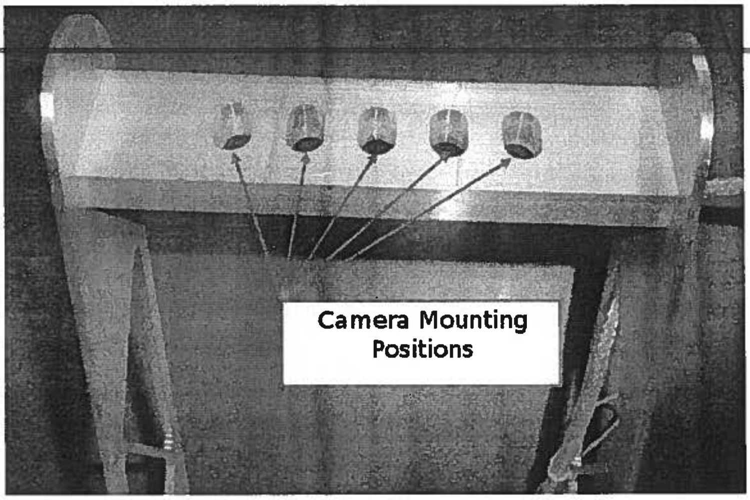

Figure 4: Camera Mounts on Sensor Mast

In addition to housing the cameras, the mast is a convenient place to mount additional sensors such as the two GPS devices and a single compass. Two lightweight mounts were placed on the outside of the mast keeping the two GPS devices at a known distance apart. The reason for two GPS units will be explained later. The compass mount in the center of the mast in addition to the camera mounts provides increased structural integrity keeping it rigid even during vibration induced by uneven terrain.

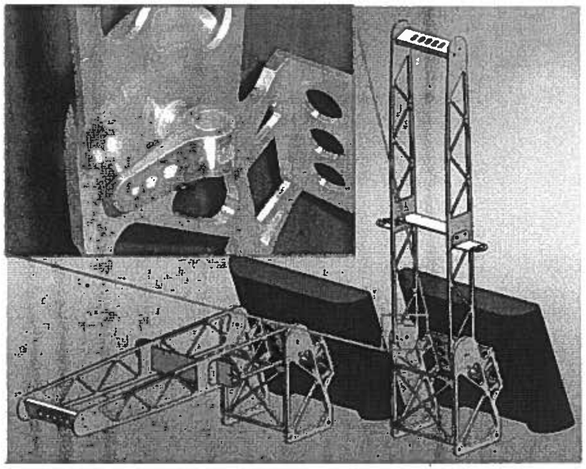

Figure 5: Cam locks in use on the folding mast.

One of the design goals of this robot was to be easily transportable. The first solution was to make the mast fold down. Cam locks were used to allow quick folding of the mast while pins were placed to only let it fold so far in either direction. The cam lock passes through a toggle when it is moved to the locked position; therefore, it will remain secure through intense vibration. Cam locks were also used at the base for quick removal of the tower. The image below shows the sensor mast in both the upright and folded position.

As shown in Figure 5, the sensor mast was designed to be light weight. Truss style bridges were the inspiration for the design. The triangulated geometry throughout the peripheral tower effectively distributes induced stresses to the thin connecting members.

To allow for the quick removal of the mast all wires from sensors, emergency stops, and the monitor needed to be able to disconnect quickly as well. To allow this to happen all wires pass through water tight quick disconnect plugs.

Electronics Case

There were two primary design considerations for the electronics housing:

- The components must be protected from the elements.
- The electronics must be independent from the chassis so that they can be worked on separately.

The robot must be able to withstand light precipitation both while moving and standing still. The immediate solution is to encase all of the components in a box, but this creates concerns with components that generate and are sensitive to heat. To address this problem, vents were placed facing downward in the front of the electronics case. To create air flow across the components, downward facing fans were placed at the back of the control case. All of these openings are protected by the shape of the control case allowing it to stay water resistant during light or moderate rain. Thermistors placed in key points within the robot allow us to run the fans only when needed to keep temperatures down, thus conserving battery life.

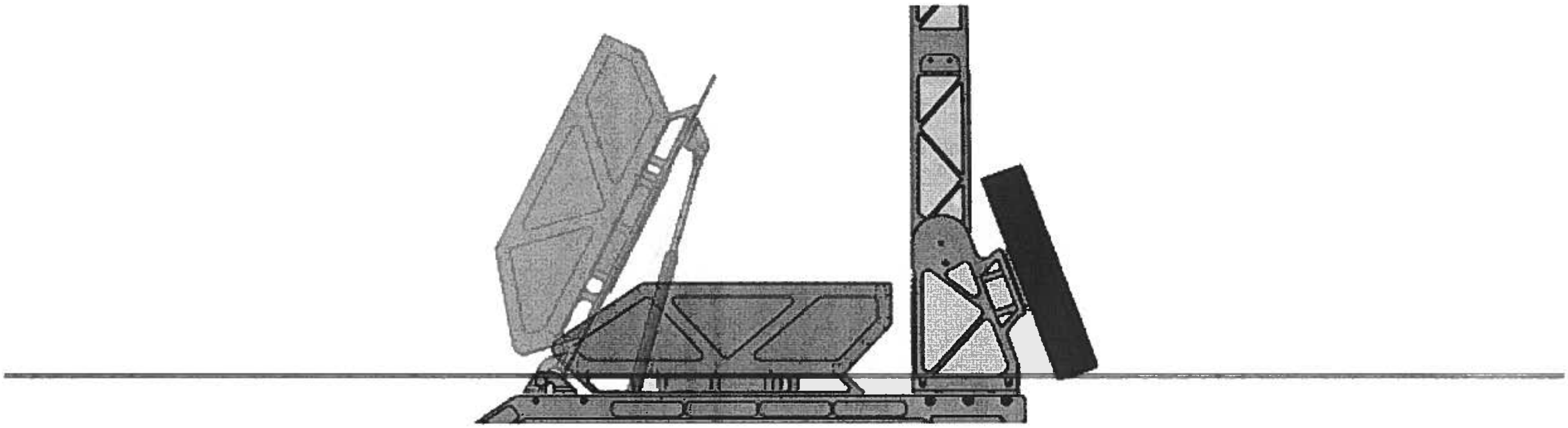

Figure 6: Electronics enclosure positions.

The electronics box is mounted sturdily on an access panel on the robot giving a rigid base. The access panel is attached to the frame using quick release hinges. The hinges allow the panel to be removed yet give a pivot point for the access panel to open. To hold the access panel open, gas shocks were placed within the chassis. Amphenol and Anderson Power Pole connectors are used underneath the panel for quick disconnect of electronics. These connectors are water proof, giving added protection within the chassis. Together, the pneumatic shocks, hinges, and connectors allow the control panel to be completely removed from the robot in under a minute. The rendering in Figure 6 shows the electronics case in its upright and normal positions.

Laser Rangefinder Mount

One of the design requirements of this robot was to have a laser mount that was easily adjustable in the field. Using the SICK laser's side mounting holes, a pivotal mount was made allowing 30 degrees of adjustment. The pivot point of the laser is centered at about the focal point of the internal lens. In the future, a four-bar linkage could be implemented with a servo to automate movement, which will allow us to research three-dimensional mapping for future competitions. Figure 7 depicts the movement of the device.

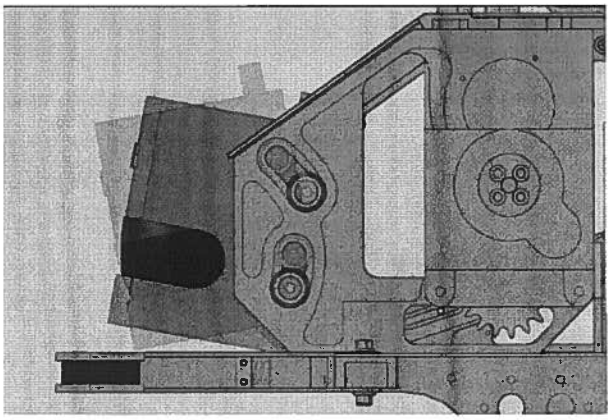

Figure 7: Angular adjustment of the laser rangefinder.

Electrical Design

In the following sections the electronics system of Stark is explained in detail. There are several electronic systems working together to make the robot functional. These include power, computer, sensors, safety, and motor control systems. Below is a simplified block diagram of how the system is set up.

As shown in Figure 8, the safety system gets power directly from the power system as well as from the motor controller. This may seem redundant, however, if a wire were to come loose from the direct power, the safety system would stay operational and the robot would remain in control. If power to the motor controller is interrupted due to a loose wire, the safety system would remain powered. If the whole system loses power, the motors will not be able to run and the system fails safely.

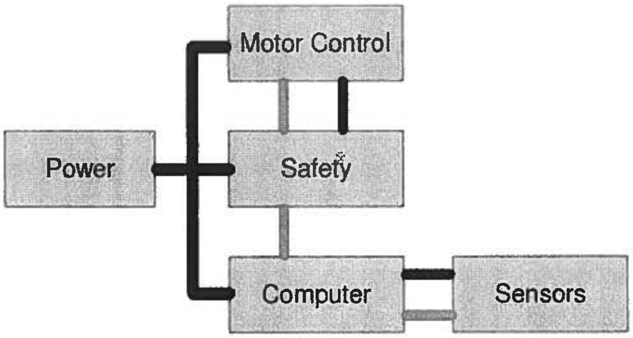

Figure 8: Block diagram of robot electronics systems.

Power System

A significant effort was put into the design of the power system for the new platform. This robot uses a single 24v battery set, but requires two different operating voltages. The 12v logic power supplies are generated by high efficiency Vicor Power DC-DC converters. Rated at 93-95% efficiency, the DC converters provide smooth power for both systems. The motors run on 24v directly from the battery, while the SICK laser runs on a 24v-to-24v converter. Field tests have shown that this robot's effective runtime is between three and four hours.

Charging Circuit

Charging a sealed lead acid battery involves three steps. The first two steps bring the battery up to nominal current while the third keeps the battery at its nominal charge with floating current. A problem emerges when a computer is running off the battery while it is charging. In this condition, the charger would see an extra five to seven amp load and never leave the second stage of charging, assuming that the battery was still discharged. This condition results in damage to the battery chemistry, noticeably reducing its lifespan.

After a thorough investigation of commercially available off the shelf ICs for power switching applications we came across the Linear Technology 4400 series chips. Initially the design focused on the LTC4411, but it soon became obvious that the power involved would be beyond the IC's operating threshold. Eventually the design settled on the LTC4416 which leverages external P-Channel power FETs to switch connections to the load.

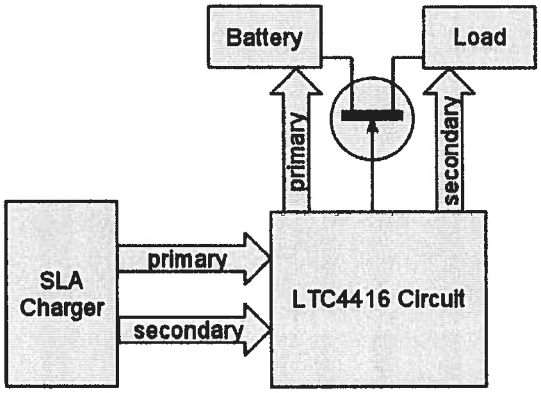

Figure 9: Power and charging system.

By utilizing a charger with two isolated outputs, the LTC4416 affords the ability to hot-swap batteries and automatically switch between battery and AC power during live operation. The LTC4416 has a sense pin that detects when the charger is plugged in. This allows the LTC4416 to switch the power FETs, cutting off the battery from the load—which in turn results in driving the load off of one of the charger's banks. A second bank is used to charge the battery, which is now disconnected from the load by the FETs. Figure 9 depicts the design.

Motor Controller Interface

The Motor Control Interface (MCI) board is a custom control circuit designed specifically to meet the requirements of the UMass Lowell IGVC robots. The MCI was designed to replace three separate existing systems, combining them into a single reproducible unit. The MCI combines the Motor Controller Communications board, the Wireless Emergency Stop System, and the Main Emergency Stop System into a single fail-safe unit. The board is shown in Figure 10.

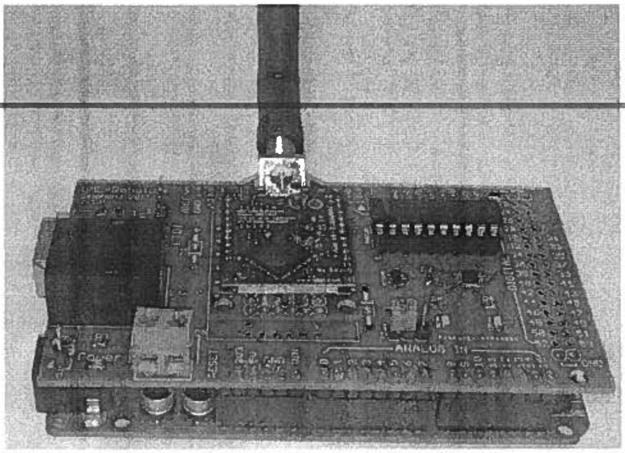

Figure 10: Motor interface and emergency stop board.

Every component of this board fails safely. If power is interrupted, a connection is severed, or the wireless e-stop goes out of operating range, the robot engages emergency stop.

For physical emergency stops, we are using C&K Rafi-x locking emergency stops which are within regulation for the IGVC. A single e-stop is placed at the rear of the robot mounted as part of the monitor. Since the monitor is the part that the operator will most likely be looking at while behind the vehicle, it made sense to put the button within the operator's field of view. A second e-stop is placed atop the electronics case on the front of the robot. This is the optimal position for an e-stop if someone is standing in front of the robot. The two e-stops are wired in series in a normally-closed configuration; pressing either e-stop or a wire coming loose will open the circuit, causing an e-stop condition.

For the wireless e-stop, a 900Mhz Zigbee transceiver was chosen. This radio system is rated to maintain communication within a six miles line-of-sight range. Additionally, the wireless controller periodically sends a heartbeat signal to the robot. If the robot does not receive the heartbeat signal when expected, it assumes the controller is disabled or out of operating range and engages emergency stop.

The controller can also send an explicit emergency stop signal when the button is pressed, which causes immediate e-stop.

Sensors

In the following sections we will discuss each of the sensors in use on the robot and why they were chosen.

SICK laser

The single most expensive part of this robot is the SICK laser. This sensor allows the robot to "see" 180 degrees in front of itself, allowing us to create an accurate map of the world in-front of the robot. With the design of the laser mount, Stark has the option to perform 3 dimensional mapping for future research.

GPS

In previous years, we found that the drift from a single GPS receiver can cause problems when trying to perform robot localization. A solution to this problem is to use a Differential GPS (DGPS) system. However, these are very expensive and require a lot of power to run. Our team is currently researching the use of multiple low-cost GPS sensors to produce higher quality location data. Stark uses two off-the-shelf USB receivers from Garmin and USGlobalSat to more precisely navigate. This solution cost $120 whereas a DGPS system would cost over of $1,000.

Vision

The primary task of the vision system is to identify and locate white lines on the ground. The cameras selected are Sony Playstation Eye peripherals. Vision software techniques are described below.

Software Development Environment: ROS

ROS Overview

ROS can be thought of in similar terms to a meta-operating system, handling inter-process communication and providing an abstraction of hardware (akin to the popular Player/Stage framework.) However, unlike Player's client-server architecture ROS provides a distributed graph-based messaging framework that allows process nodes to operate and communicate between one another anywhere within an accessible TCP or UDP network. This allows for greater flexibility in allowing external systems or even teams of robots to shift work to whatever machines have the cycles necessary to complete the task at hand. Processing nodes publish and subscribe to topics in a many to many publisher-subscriber format. In addition to topics, nodes can also supply services similar to the client/server approach using the familiar request-response model. This can be useful when a node requests a unique item from another node that cannot be provided in the broadcast model.

In addition to the node data passing mechanisms comes the ability to record and playback data for repeatable trials and debugging purposes. Since every segment of data flowing through the ROS graph has a time-stamp, it is easily captured by the system for analysis. For example, entire trials containing camera images, laser scans and odometry information can be played back at user-chosen data-rate gains for repeat analysis and simulation.

Navigation and Coordinate Frames

The ROS platform provides a "stack" of nodes that provides high-level access to localization and navigation routines. With the navigation stack up and running, a software program would only need to issue commands like "go to X, Y, Theta in the world." However, under the hood you'll find a far more complex picture.

ROS has been designed with the idea of coordinate frames and transforms built directly into the system. A laser scan is associated with the laser range finder's coordinate frame, which can be mapped back to the robot's base through a transform tree. Generally, the root of the tree contains the map or world coordinate frame. This allows any piece of data that has an associated transform element to be explicitly related in some way to the world at large. If a laser returns a reading of 0.3 meters, the navigation stack can see that the laser is mounted 0.4 meters from the center of the robot's base and can reason, based on elements in the transform tree, that it is about to hit an obstacle and react to it appropriately.

Since algorithms for localization are implemented within nodes that export common interfaces through topics and services, they can be swapped out to fit the specific needs of the problem at hand. If the robot has a known map it can utilize the Adaptive Monte-Carlo Localization node, or if the robot needs to operate without a known map and perform mapping simultaneously it could instead leverage the GMapping SLAM (simultaneous localization and mapping) node.

Vehicle Cost

Component	Price
Raw Materials (aluminum/acrylic stock/wire)	$1,000.00
2x Sony Eye Cameras	$50.00
2x USGlobalSat USB GPS	$70.00
Phidget IMU/Compass	$150.00
Computer System	$200.00
Motor Controller	$375.00
Emergency-Stop system	$200.00
Power System (batteries, inverters, etc.)	$300.00
Charging System	$250.00
Motors	$700.00
Sick LMS-200 range finder	$5,000.00
Total	$8,295.00