RoboJackets 2013 Design Report

20th Intelligent Ground Vehicle Competition

Joseph Hickey, Alex Trimm, Emanuel Jones, William Evans

RoboJackets - www.robojackets.org
Georgia Institute of Technology

Contents

List of Figures

List of Tables

1 Introduction

1.1 RoboJackets

RoboJackets is the competitive robotics organization at the Georgia Institute of Technology. Founded in 1999 as a BattleBots team, the organization has since grown to include RoboCup Small Size League, Intelligent Ground Vehicle Competition, and a large outreach team. While chartered in the school of mechanical engineering, members come from all departments (predominately computer science, mechanical engineering, aerospace engineering, and electrical engineering) to participate in these extracurricular activities. First competing in the IGVC in 2004, the RoboJackets have competed in every IGVC since 2006, finishing in the top 10 on the autonomous course since 2007.

1.2 Team Members

This year's team was unusually young, consisting largely of freshman with some senior and graduate leadership. The members participating on this project are listed in Table 1. As such this year was treated as an opportunity to rejuvenate the team with a completely new design and software architecture.

Table 1: 2012 RoboJackets / IGVC Team

Name	Degree / Class	Role
Matt Barulic	BS Computer Science / Freshman	Software
Kyle Bates	BS Electrical Engineering / Freshman	Software
Al Chaussee	BS Computer Science / Freshman	Software
William Evans	BS Mechanical Engineering / Senior	Mechanical Design and Build
Joseph Hickey	BS Mechanical Engineering / Senior	Project Manager and Mechanical Lead
Emanuel Jones	MS Mechanical Engineering	Mechanical Design and Build
Dea Gyu Kim	BS Mechanical Engineering / Freshman	Mechanical Design and Build
Nikolaus Mitchell	BS Mechanical Engineering / Junior	Mechanical Build
Alex Trimm	BS Computer Science / Senior	Software Lead, Electrical Lead
Jonathan Williams	BS Mechanical Engineering / Freshman	Mechanical Design and Build

The team was organized into mechanical and software subteams, with electrical being a collaborative effort between the subteams. The beginning of fall semester was spent overviewing previous entries into IGVC, forming design requirements, and beginning conceptual design. Fabrication began in the spring semester, completing during the beginning of summer. In total approximately 2500 man hours were spent over the course of the 2012-2013 academic year.

2 Mechanical Design

2.1 Structure & Vehicle Layout Overview

Figure 1: Misti, the 2012-2013 Base

While the team did moderately well in the 2012 competition, certain areas of improvement were noted and emphasized in this year's design. Similar to the previous three years, the design revolved around a four-wheeled drive platform, with focus on reducing build complexity and increasing ease of vehicle maintenance (i.e. accessibility to components, proper wire routing, etc.) The team approached the 2013 design with the following goals:

1. Improve Vehicle Ride Dynamics
2. Increase Ground Clearance
3. Improve Human Interface for Debugging
4. Weatherproofing for Inclement Weather

5. Enhance Night-Time Operability

By following these goals, the team developed the current vehicle which boasts a vastly superior suspension system and drivetrain, as well as much improved component layout and accessibility.

2.2 Vehicle Ride Dynamics

2.2.1 Drive System

The vehicle, dubbed Misti, has a completely customized drivetrain designed to deliver high torque for operating on rough terrain.

The two central gearboxes, custom-made and milled from aluminum, are driven by 4.5 peak horsepower Ampflow A28-400 brushed DC motors. Gear reduction comes from a two-stage gear train inside the gearbox, as seen in Figures 2 and 3, with the output sprocket driving a chain connected to a sprocket affixed to the wheel, producing a total reduction of 30 to 1. The skid-steer approach was maintained from the previous 3 competitions, but the fore and aft wheels are now mechanically linked together to ensure they maintain the same speed. This guarantees that under slippery conditions, the power is always transmitted to the ground through the wheel with the most traction.

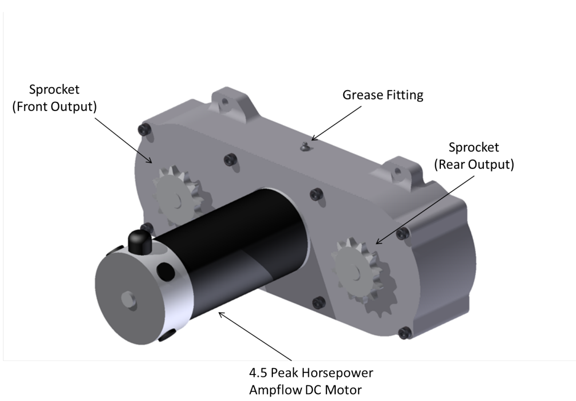

Figure 2: Custom Gearbox

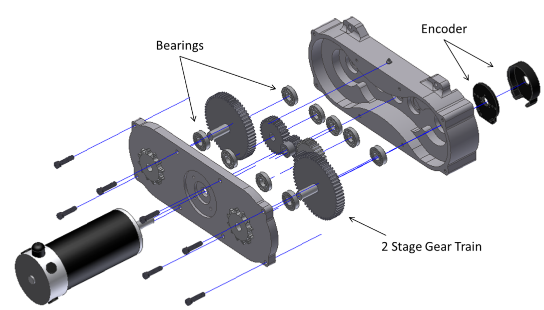

Figure 3: Exploded View of Gearbox

2.2.2 Suspension

The suspension of the robot was greatly improved over the previous years design. Prior designs utilized a trailing/leading arm suspension system, connected away from the main body of the robot. This year, a four bar linkage mounted to the middle section of the robot was developed in order to reduce the cyclic loading on the frame as well as improve the damping characteristics (see Figure 4). Fox DHX RC4 coilover dampers were a much welcomed improvement over previous homemade solutions. The suspension design allows for approximately 5 inches of travel for each wheel, lending the design much superior ride dynamics to ensure stability and dampened impacts while traversing rough terrain. Misti was designed to handle even the roughest of conditions with nearly 8 inches of ground clearance. Using 145/70-6 pneumatic wheels, she can roll over most common obstacles with ease. The larger wheels will improve our ability to traverse small obstacles and climb ramps. While pneumatic tires do offer the potential to go flat, unlike our previous foam core tires, it was determined they would provide a superior ride dynamic and cushion small bumps, particularly at lower speeds.

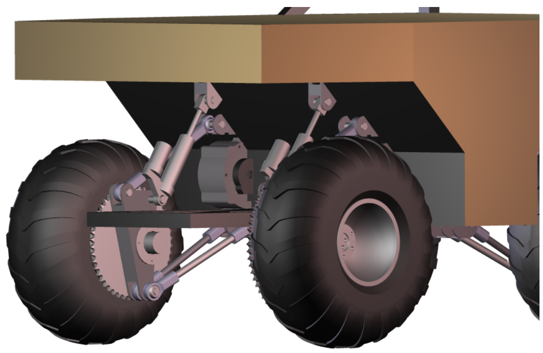

Figure 4: Shock System

2.3 Frame

The frame is constructed out of 1/16" wall 1" sq. steel tube and aluminum panels. Much of the assembly was accomplished with MIG welding and the use of 1/4-20 fasteners. A model of the frame was made in Siemens NX and finite element analysis was conducted using the NASTRAN package. A stress analysis was performed using half inch tetrahedral elements to determine if the robot would be safe to pick up for maintenance and loading for events. The analysis assumed that the final assembly would have a weight of 500 pounds, overestimating the total weight to give a worst case scenario. When the force to lift the robot was applied to each end, the maximum stresses were found to be $2.33x10^4$ psi. This result is shown in Figure 5.

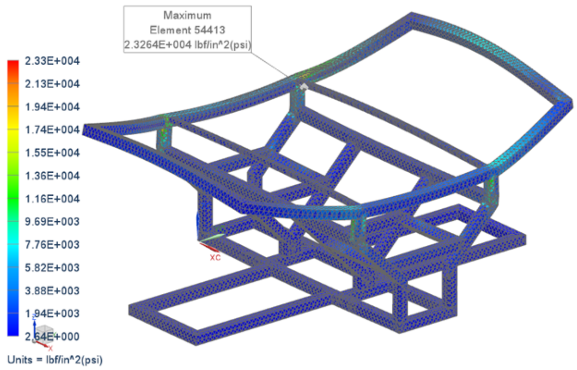

Figure 5: Finite Element Streses

Because this stress is lower than the yield stress of carbon steel of $5x10^5$ psi, a fatigue analysis was conducted to determine how it would behave after one million cycles. Figure 6 shows the number of cycles to failure as predicted by the simulation.

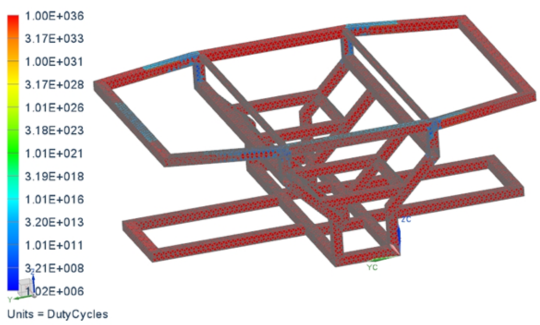

Figure 6: Cycles to Failure

The finite element analysis predicted that the frame would last at least 1 million cycles in the worst case scenarios under this loading condition. Also, it predicted a safety factor of 2.89 at the corner where the stresses were highest. Since the model was assumed to be heavier than the true weight and the joints are also reinforced with steel plates, this safety factor is sufficient.

2.4 Mast

A vertical mast on the aft of the robot supports the GPS, IMU, and stereoscopic camera, as well as a button panel for operating the lights, emergency stop and go buttons (Figure 7).

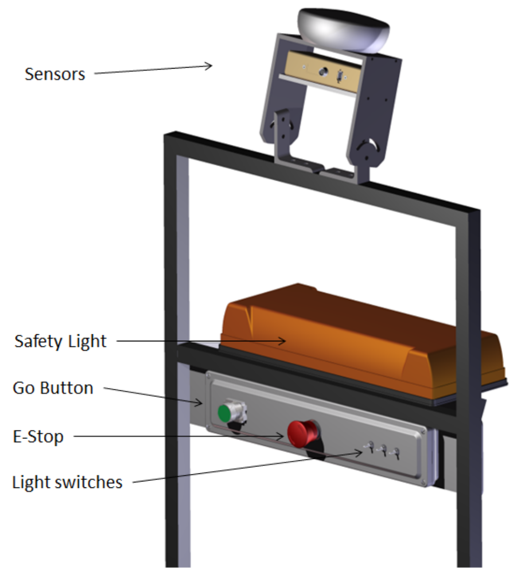

Figure 7: Mast

The mast, which stands 67 inches tall, was designed to give the camera sufficient field of view, while also being just low enough to easily fit inside the RoboJackets transportation trailer for ease of travel. The button panel, and particularly the E-stop, resides at forehead height (Figure 8) with respect to the stance of the user while operating/debugging code onboard computer, a design feature intended to prevent injury in case the robot malfunctions and moves backwards. Components that are exposed to the elements have been weatherproofed by using wash-down enclosures. This provides added robustness, allowing the team to test in inclement weather without worry.

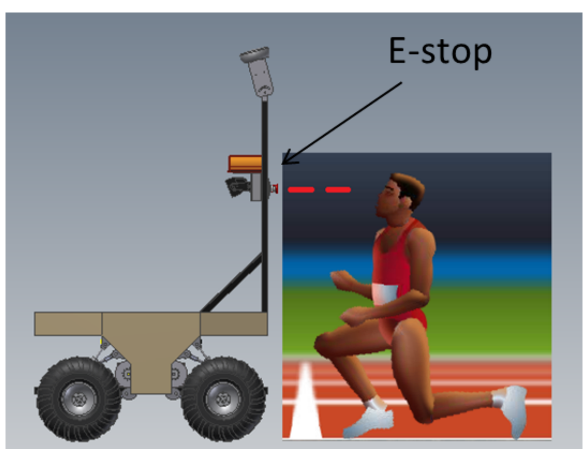

Figure 8: E-Stop at Forehead Height

The sensor loadout (Figure 9) includes a stereoscopic camera, GPS unit, and inertial measurement unit (IMU) on the mast, as well as a LIDAR residing on the bottom of the robot frame and an encoder in each gearbox.

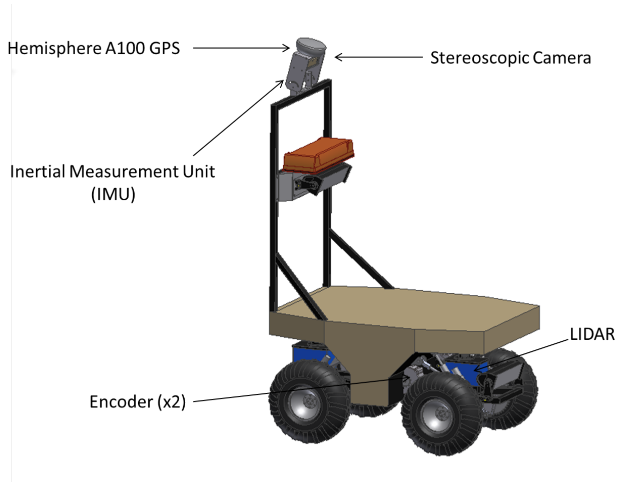

Figure 9: Sensor Loadout

To boost safety and night-time/dusk operability, the team installed a large safety light, as well as two large headlights (Figure 10) to light the field both close and far from the vehicle.

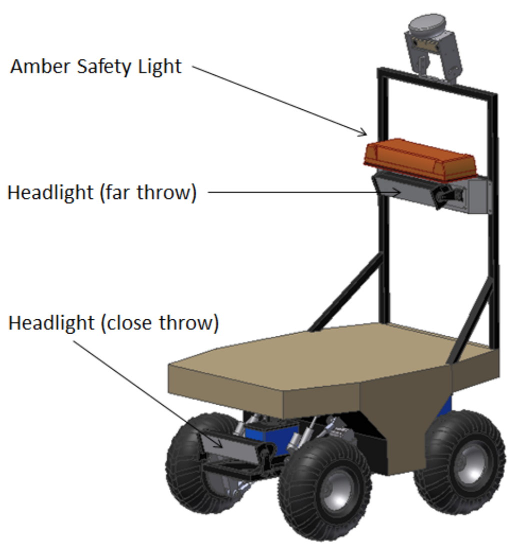

Figure 10: Lights

2.5 LIDAR

The modified SICK NAV 200 LIDAR is mounted in the front of the vehicle and has an unobstructed sweep of roughly 150 degrees. The LIDAR is protected above from rain by an overhang which also serves as a compartment for the electrical power system. The unit is attached to the base through an intermediate aluminum plate. This allows it to be removed from the vehicle with only loosening three 1/4-20 bolts which are the standard fastener for our platform.

3 Electronics Design

3.1 Computers

3.1.1 Main Computer

Nearly all computation is performed on a single laptop containing a quadcore Intel Core i7 CPU, CUDA enabled NVIDIA 285M GPU, and 6 GB of RAM. This computer is responsible for all vision, LIDAR, and GPS data processing and all path planning and control algorithms. It also forms the core of the sensor interconnects, providing the firewire and USB bus which the camera, GPS, and microcontrollers use.

3.1.2 MCU

This year saw a drastic reduction in the number of microcontrollers used. While last year's design utilized 6 Arduino Duemilanove boards to accomplish the task of interfacing with the the motors and encoders, this year's design was able to accomplish the same task while utilizing only a single Arduino Uno board. This was made possible through the design of a custom interfacing daughterboard.

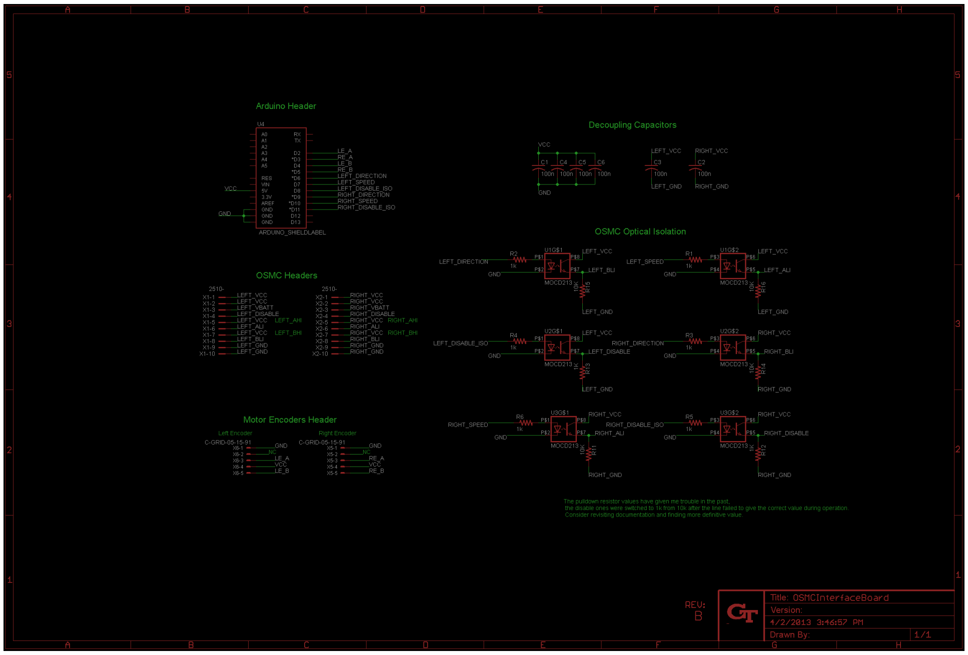

Figure 11: Electrical Board Schematic

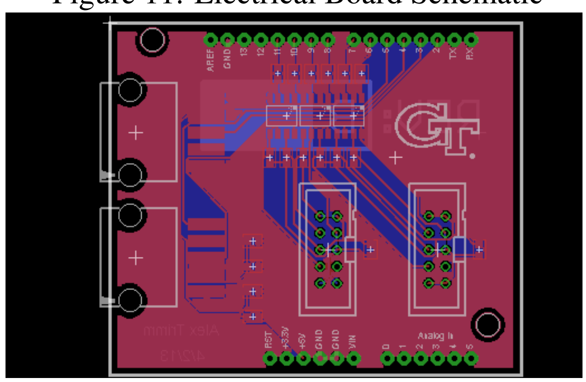

Figure 12: Daughter Board

3.2 Sensors

This year saw a significant additions to the existing sensor system. These included the addition of an ArduPilot IMU and a BumbleBee2 Stereo Camera. Additionally, the new mechanical design led to several changes in the existing sensor system.

3.2.1 LIDAR

Misti employs a Sick NAV200 LIDAR to provide convenient and straightforward obstacle detection. The LIDAR has a 270° FOV and a 10 meter range.

3.2.2 Stereo Camera

Misti will be the first Georgia Tech IGVC robot to utilize a stereo camera. The stereo camera chosen is a Bumblebee 2 made by Point Grey Technologies. This camera delivers two 1024x768 images at 20 fps. The camera uses a Firewire connection to interface with the main laptop.

3.2.3 GPS

A GPS is used to provide world position to the robot, allowing obstacles to be placed in world space and allowing waypoints to be followed. A Hemisphere A100 Smart Antenna GPS is mounted to the mast to allow a clear view of the sky. This GPS is accurate to < 2.5 m / $< .6$ m (GPS / WAAS) and has a "time to first fix" of less than one second. The GPS updates 20 times per second.

3.2.4 IMU

Misti also utilize an ArduPilot IMU. This IMU includes a 3-axis accelerometer, 3-axis gyroscope and a 3-axis magnetometer as well as a barometric pressure sensor. The board contains an ATmega2560 chip and can both be programmed and communicate with the main computer through a USB connection.

3.2.5 Encoders

Each gearbox is connected to a quadrature wheel encoder, allowing wheel rate and absolute distance to be measured. This allows the velocity of the robot to be measured, as well as the distance the robot has travelled. The encoder is a US Digital E3, with 200 counts per revolution and an index channel. This allows for wheel rates to be sensed. One quadrature line from each encoder is connected to an interrupt pin on the microcontroller, which then feeds the state of the lines to a state machine which increments or decrements a wheel counter.

3.3 Power

3.3.1 Sources

Main power for the robot comes from two deep-cycle lead acid gell-cell batteries. These batteries are connected in series to produce a nominal 24 VDC supply. These batteries each provide 48 Amp-Hours of energy, making the robot's total capacity 1052 Watt-Hours. This increased capacity over previous designs counteracts the increased mass of Misti over her predecessor and leaves the total estimated runtime approximately 1 hour of driving.

3.3.2 Distribution

The batteries are connected to a power distribution board, which allows the connection to each motor to be fused with a limit of 40 Amps, allowing power to be cut in the event of a motor stall to prevent damage to the H-bridge and motor. Each motor is connected to two OSMC H-bridges, which allow the motors to be driven from the Arduino microcontroller. Each OSMC is capable of switching up to 50 VDC at 160A cont / 300A peak, allowing significant margin above our standard operating power of around 24 VDC / 20 A.

Power is also provided to several DC-DC buck converters, which output 5 VDC, 12 VDC, and 19.5 VDC for the other electronics on the robot.

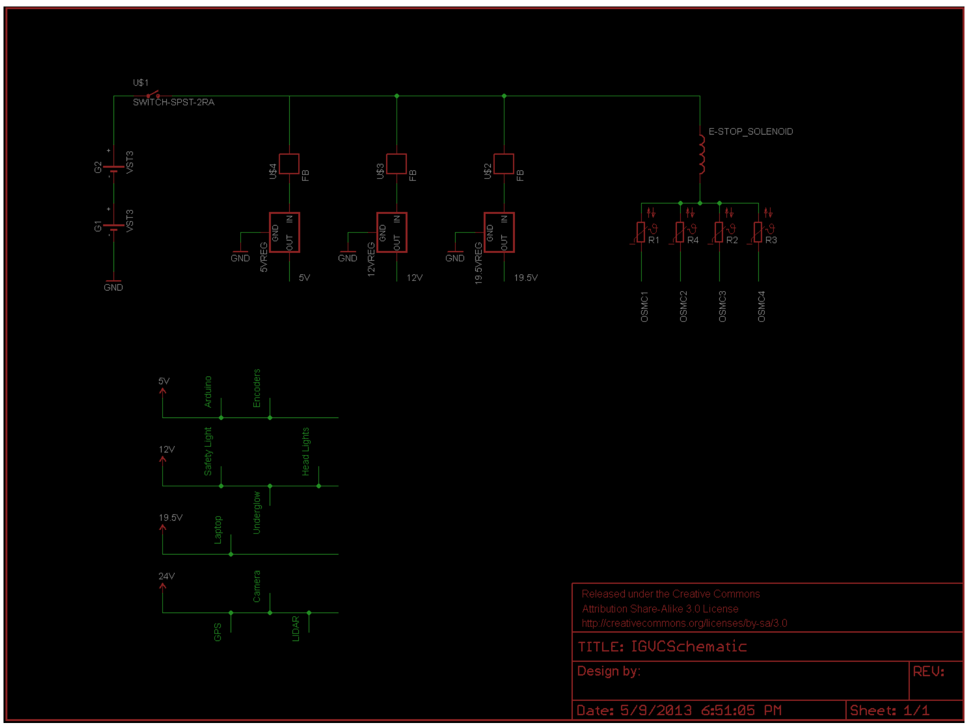

Figure 13: Power Distribution Schematic

4 Software

4.1 Architecture

Along with a new mechanical design, this year saw a complete rebase of existing software. This new software base has had a significant focus on software design principles to ensure the code will be usable both now and in the future. The backbone of the new codebase is a message passing system accomplished through an event/listener design paradigm. Classes are set up to modularize the different stages of data processing, with the creation of each output then activating a callback method within the next step. This pattern provides a greater level of abstration between logical units of the robot. Such a design simplifies the addition and removal of functionality, making it easy to prototype and test new concepts and algorithms. Additionally, because stringent interfaces are a requirement of this framework, simulators can easily be interchanged for functioning components, allowing units to be tested independently.

This redesign also provided an opportunity to reimagine the basic strategy employed for interacting with the world. The new software design has moved away from a purely reactionary system and to a mapping system which includes and synthesizes its current and past knowledge of the world around it to intelligently navigate.

4.2 Algorithms

4.2.1 Vision

Current software makes increasing use of computer vision over previous years. This increase was largely made possible through the addition of our new stereo camera. This addition has give us a means to translate image information from the camera's frame of reference to real world locations. In addition to allowing the robot to more robustly determine the locations of potential obstacles and barriers, this improvement has also provided an opportunity to gain additional information about the robot's position through the use of visual odometry and other techniques. Many of these added technologies are accomplished through use of the OpenCV framework.

Lane Detection

Lane detection is the most fundamental vision task in this competition, While many of the other obstacles may be easily sensed through the use of LIDAR, the nature and position of the white lines make it necessary to use vision to detect them. Our current lane detection algorithm makes use of a number of sequential techniques in order to converge on the location of the lines. The algorithm begins by masking over patterns that match known obstacles with white sections. The image is then segmented and filtered, leaving only pixels that fall within the expected color range of white lines in reasonable lighting conditions. At this point, information about the height above ground and angle of the camera is used to map the remaining points to real-world coordinates for mapping.

Visual Odometry

The visual odometry system employs two separate techniques which complement each other in ability. Visual odometry inherently requires deriving a linkage between the appearance of a point or object in the image and how it relates to its position relative to the robot. The first of the two methods employed accomplishes this through the use of the depth map generated by the stereo camera. By tracking a number of points between frames, using the Harris corners algorithm to identify potential candidates, and seeing how their depth measurements changes, it is possible to determine the change in each of the degrees of freedom between frames. Potential problems caused by inaccuracies in the stereo algorithm or other factors are minimized with multiple random selections of track points for these calculations.

While this process provides a robust solution, the price of the stereo matching algorithm makes this method computationally expensive, limiting the potential real-time ability of such a technique. The second algorithm used circumvents this issue by assuming that the terrain in front of the robot will not impact that the rotational degrees of freedom of the robot. This assumption trivializes finding the physical correspondences necessary for identifying the change in the other degrees of freedom between frames. This is accomplished by creating a filter to differentiate grassy sections of the image from obstacles and other objects. Once everything else is filtered out, potential interest scores are found for the remainder of the map, and those locations found to be accurate enough are used to determine the change in the non-constrained degrees of freedom. Because the same points are monitored in both images, the relative position of the points to each other should remain constant between frames. By using the calculated update function for robot position between frames, a prediction of where points should appear in the second image may be made. Then by comparing this prediction to the actual end locations, the legitimacy of the assumption can be determined.

Figure 14: Full Track

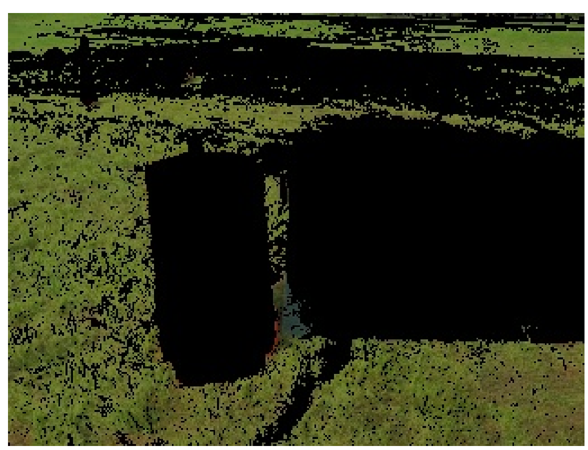

Figure 15: Filtered

4.2.2 Mapping

Mapping is accomplished through the use of the PointCloud library, which allows for efficient creation, storage, and query of 3-D points. This representation integrates information from both the camera and LIDAR into a single representation of the world which can then be used as an input for the path planning algorithm.

4.2.3 Path Planning

This year's robot will employ the A* algorithm to perform path planning. This algorithm will use the PointCloud map as an input and will output an optimal path, which will then be translated into an implementable set of movements for the robot to perform.

4.2.4 Controls

Two levels of controls algorithms will be used to provide a convenient interface for controlling the motion of the robot. The first of these two algorithms is a closed loop PID controller which will be implemented on the arduino. This algorithm uses the encoder readings that it processes to provide a measure of distance travelled. While this loop provides a fast feedback mechanism, it fails to account for real-world conditions such as wheel slippage and rough terrain. Commands for motion will be dictated by the mapping algorithm as commands to move or turn certain amounts, and the errors accumulating from such causes would undermine the usability of the system. To account for this, an additional control system will be running on the main laptop to ensure that these commands are properly processed. This system will use more accurate measure of the robot position to ensure that these commands have been properly processed, issuing corrective commands to account for the deviations from the required condition until the robot arrives at the proper location.

4.2.5 Sensor Integration

The sensors and related algorithms added this year have added an additional level of complexity that did not have to be considered in previous years: how to integrate multiple differing readings of a value. This problem surfaced most noticeably in the area of robot pose tracking, where there are at least four sources of pose information. To accommodate this, a common timing interface was created and integrated throughout the codebase in order to ensure an accurate synchrony among the different pieces of information. All new readings are then passed to a central object responsible for fusing this information into a single estimate of robot pose. This class takes in a number of different data types and converts them all into a common update format. Kalmann filtering is then used to combine all of these readings. The result is a more robust and accurate description of robot pose than could be acquired through the individual use of any of the sensors or techniques.

5 Cost

As an attempt to maintain working condition of older robots, many replacement components were purchased this year. A cost estimate of this robot is included in Table 2, showing the value of each of the components, how much our team paid for them, and how much of that was spent this year. In total, Misti is worth approximately \$19000, with our team spending approximately \$9640 this year.

Table 2: Misti BOM

	Value	Cost to Team	2013 Cost
Steel Tube	200	200	200
4x Dampers	2380	2380	2380
Lidar	5000	50	0
Stereo Camera	2495	1380	1380
2x DC Motor	900	900	900
4x Motor Controller	820	820	820
2x Gearbox	1000	1000	1000
Laptop	1300	1300	0
Firewire Card	40	40	0
2x Battery	460	460	460
IMU	180	180	180
Arduino Uno	30	30	30
2x Headlights	500	500	500
Safety Beacon	350	350	350
E-stop	80	80	80
Wireless E-Stop	50	50	50
USB Hub	5	5	5
Laptop Power Converter	50	50	50
24v-12v converter	30	30	30
GPS	1500	1500	0
2x Optical Encoder	170	170	170
Misc Mechanical	1250	1250	1000
Misc Electrical	200	200	50

This project was made possible through the support of Caterpillar, General Motors, National Instruments, United Technologies Corp., Student Government Association, the George W. Woodruff School of Mechanical Engineering, the College of Computing, and the Robotics and Intelligent Machines research center.