Stony Brook University

P-15

2012 IGVC Competition

Stony Brook University

Stony Brook Robot Design Team

Mika Lai, Phillip Prestia, Sagirah Elson, Asheik Hussein, Frank Pernice, Sebastian Cocioba, Marek Roszko

I hereby declare that the mechanical and software changes implemented in the design and engineering of the vehicle by the current student team has been significant and equivalent to what might be awarded credit in a senior design course.

Professor David Westerfeld
Department of Electrical Engineering
Stony Brook University

Date: 3 MAY 2012

NORTHROP GRUMMAN

Table of Contents

1. Overview

The Stony Brook Robot Design Team is led by an Executive Board consisting of five administrative positions and three engineering team leaders, all undergraduate students. The president, vice president, secretary, treasurer and public relations officer collaborate to take care of the team logistics while the mechanical, electrical and software engineering team leaders oversee the design, fabrication and testing of the competition vehicle. The team leaders report directly to the vice president. The overall hierarchy is shown in Figure 1.

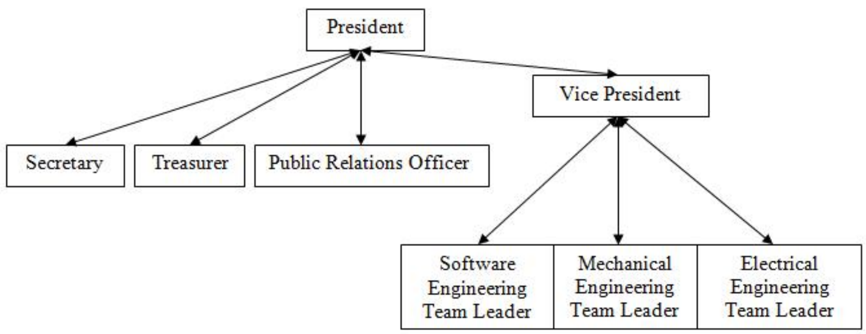

Figure 1: *Team leadership structure*

Each vehicle prepared for competition is a collaborative effort. Although P15 was entered into last year's competition as P14, a senior design project from the Department of Mechanical Engineering at Stony Brook University, we have rebuilt some parts and completely retrofitted its interior.

1.1 Design Process

A five stage design process was used to design, manufacture, and test our robot. The first step in the design process was competition research. Product Design Specifications (PDS) were created to define the key requirements of the robot. Research and parametric analysis was done on prior robots that competed in IGVC to get a better idea of qualities that we would want in our own robot.

The second step was conceptual design. All possible designs were generated and compared by using a set of criteria. An iterative process allowed for the best design to be developed. The third step was detailed design. Sections 2, 3, and 4 will describe the mechanical, electrical and software aspects of the detailed design phase respectively. Each component was justified by a Component Design Specifications (CDS).

The fourth stage is centered on building the robot. Most of the fabrication was done in a four week period. Examples of machinery that were used include a milling machine, lathe, band saw, and rapid prototype machine. The fifth stage was to test and debug the robot in a systematic manner. Sensors were progressively integrated until every sensor had been added and was working properly. Even though each step had specific guidelines and requirements; each task was not done independently. Often, it became necessary to return to previous steps to modify the system. Graphically, this process is shown in Figure 2.

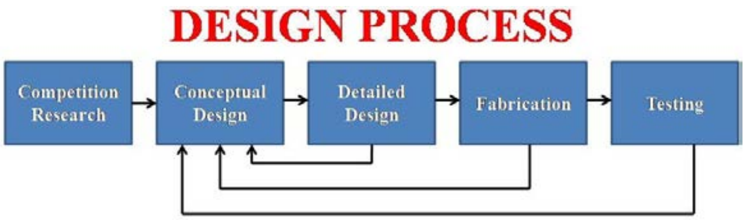

Figure 2: *Design Process Flowchart*

2. Mechanical Design

2.1. Chassis

The chassis of the robot is built from extruded aluminum. The extruded aluminum is easily assembled using right angle brackets, which makes the robot more modular. and easy to change or add parts. In order of to decrease the degrees of freedom as well as increase the strength of the design, the aluminum was milled to have notches, which fit into the channels on other adjacent structural members. Figure 3 shows a CAD drawing of the designed structure.

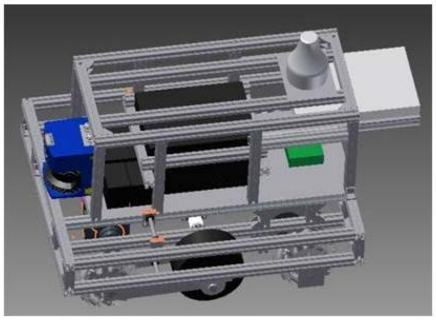

Figure 3: *CAD Drawing*

The second goal was to analyze each component. This was done with Finite Element Analysis (FEA), using Autodesk Inventor. FEA was done on each component designed that would be placed under loading conditions. Special consideration was given to: the locations of stresses, displacement, and factor of safety. An example of this is shown in Figure 4 on the next page. Here, the deflection of the moment arm is considered.

The displacement is zero at the constrained hole and maximizes where it connects to the wheel. The maximum displacement was shown to be 0.0103 inches. The deformations are within tolerances.

The mechanical sub-system is divided into four sections that will be described below.

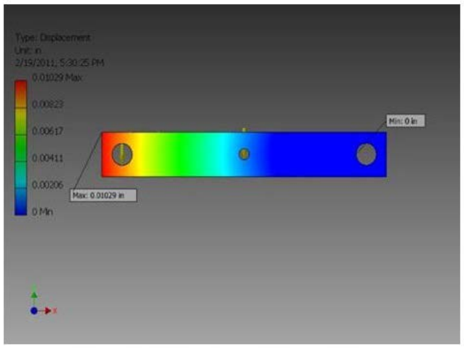

Figure 4: *FEA of swing arm suspension member*

2.2. Drivetrain

This year we decided to modify the sprocket ratio in order to meet the new top speed of 10 mph. Our original ratio was 17:25 which gave us a top speed of around 4 mph, the ratio has been changed to 15:12 which will give us a top speed of around 7 mph. This can be found using the equation:

$$\boldsymbol{\omega_2 = N_1 \cdot \frac{\omega_1}{N_2}} \quad (1)$$

This gives us the angular velocity which was then used to find the speed using:

$$\boldsymbol{V = \omega_2 \cdot \pi \cdot d_w \cdot \frac{60\ min}{1\ hr} \cdot \frac{1\ mile}{63360\ in}} \quad (2)$$

This sprocket system drives the center wheels of the robot. The center drive gives us tighter turns; these turns are made easier with the help of the mecanum wheels (shown in Figure 5 below) which have rollers angled at 45 degrees in order to decrease the shear stress on the wheels when turning.

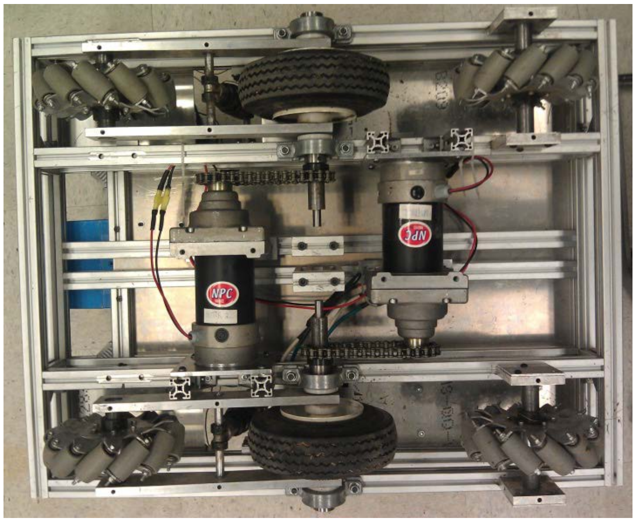

Figure 5: *Powertrain*

The diameter of each shaft that held the wheels had to be determined. 4340 normalized steel was chosen to be the shaft material. The torque was assumed to be 300 lbf*in even though the actual torque is estimated to be 230 lbf*in. The tensile strength, S_{ut}, is 125 kpsi. The distortion energy-Goodman criterion was used to find the shaft diameter which is shown in the following equation:

$$d = (\frac{16n}{\pi}(\frac{(4(K_f M_a)^2 + 3(K_{fs} T_a)^2)^{\frac{1}{2}}}{S_e} + \frac{(4(K_f M_m)^2 + 3(K_{fs} T_m)^2)^{\frac{1}{2}}}{S_{ut}}))^{\frac{1}{3}} \quad (2)$$

The above equation has several unknowns. The factor of safety, n was found to be 3.3. A conservative assumption was made that an end-mill keyset ran through the entire shaft. Because of this distinction: $K_f = 2.14$.Another assumption is made that claims that midrange moments and alternating torques equal 0. In other words: $M_m = T_a = 0$. The shoulder fillet, K_{fs}, was assumed to be equaled to 3. The parameter $S_e = 0.5 k_a k_b k_c k_d k_e k_f S_{ut}$. It was found that $k_a = a(S_{ut}/1000)^b$ where a = 2.7 and b = -0.265, $k_b = 0.879 d^{-0.107}$, and $k_c = k_d = k_e = k_f$ =1.

Since the diameter the shaft is a component of one of the parameter for its own calculation, an iterative process had to occur. To speed up this process, a program was written in MATLAB so that, each iteration could be ran quickly. The optimum diameter was found to be:

d = 1 in.

2.3. Weatherproofing

We installed a new weather proofing system, instead of using just plastic to cover the electronics in the chassis, we now use canvas. This canvas is sprayed with a water proofing spray with PTEF, which converts the canvas into a hydrophobic surface. In the event of rain, the droplets will roll off the canvas instead of saturating and permeating it. Using canvas also gave us more room to mount components of the chassis. With our original design components were only mounted in the center of the chassis, with the new weather proofing we are able to mount smaller components on the sides. Along with the canvas covering the top and sides there are plastic plates which cover the front and back. Each of these plates have four holes where fans are mounted on the inside to allow for cooling of the components which tend to overheat, such as the motherboard and motor controller. These fans are oriented so that the flow moves from the front of the robot to the back, the front fans move air in while the back move air out.

2.4. Rear Mount

For components that need to be away from electronic/magnetic interference, such as the compass and GPS, and for the cameras which needed to see the front of the robot a tower was assembled. The tower reaches a height of 5 feet which allows the cameras to see not only what is in front of the robot but also the front of the chassis in order to see its position. In order to minimize the vibrations on the mount, the GPS and compass are mounted lower.

2.5. Suspension

In order to minimize vibrations throughout the robot, air shocks are used as suspension. The air shocks are mounted to the chassis of the robot and an arm which holds the front mecanum wheels of the robot. The air shocks can be calibrated for the amount of play wanted by the knobs on the shocks and also by the amount of air added. This year to give the shocks more play we mounted them high and also angled them off from vertical.

3. Electrical Design

The electrical portion of Project 15 can be summarized by the power source, devices and the design decisions made behind everything.

3.1. Power Source and Distribution

In Figure 6, a basic breakdown of how power is distributed within Project 15 is shown. The robot's main power source is two 12V non-spillable lead acid marine batteries. The marine batteries are capable of providing 300Ah each. Their drawback, however, is their immense 50 lb weight and size. However, the decision was made to use these batteries over lighter and smaller Li-Ion batteries because of their energy storage potential and the convenience of only having to charge two batteries. Additionally, testing has shown the ability of these batteries to maintain a charge between 11 and 13V while running the robot at full load for long period of time.

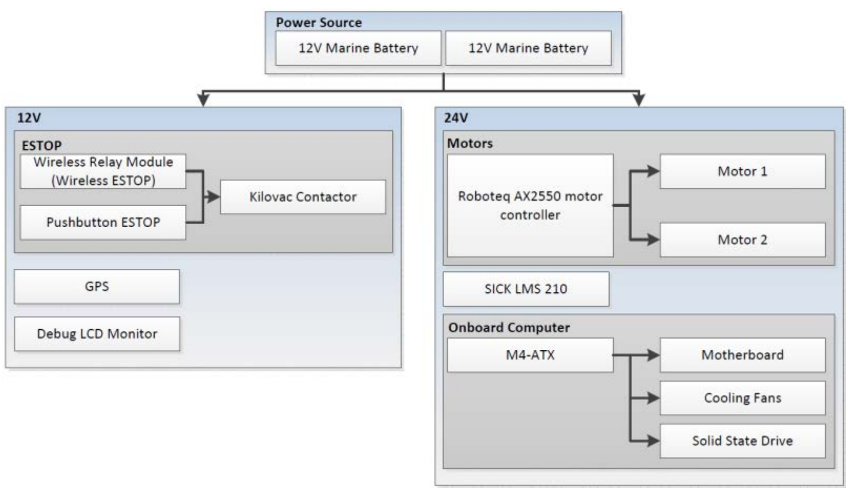

Figure 6: *Diagram showing distribution of power between components*

The two 12V batteries are used to create a roughly 24V source as well as provide a 12V source. Both of these sources are fed directly to most components that require them due to the components having internal power regulation. In situations where a 5V or a regulated 12V source is required, small DC-DC converter packs capable of outputting 5V/12V constantly based on variable input are utilized.

3.2. Devices

There are various electrical devices utilized in the robot. These devices are mostly commercial off the shelf components. The most important systems formed by the devices are described below.

3.2.1 Roboteq AX2550 Motor Controller

This motor controller directly drives the two brushed DC motors that provide the motion for the robot. The motor controller accepts the raw 24V input for the two motors independently. Additionally, the motor controller is also activated by having 24V applied to a control line. The use of this particular motor controller gives us a variety of features and configurability that also add to the safety to this design.

All power management to the motors is performed directly by the motor controller. The device has the ability to handle currents up to 120A on each motor in the worst case. There are also programmable current limits that can be set to limit the current draw. During testing, the motors were measured to draw approximately 20A each under load and so the current limits were set to 40A for each motor. Another safety feature is the ability to constantly require pinging by the computer to remain in motion, otherwise the controller will shut down.

3.2.2 Emergency Stop

The emergency stop system is implemented as required by IGVC competition rules, and for the general safety of the team and public. It is implemented using a series of 3 relays as shown in Figure 7 below.

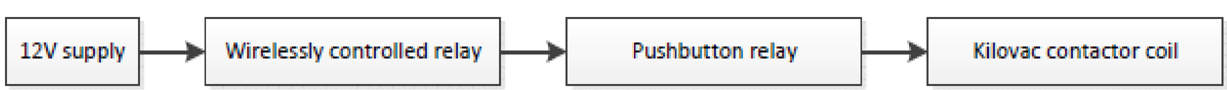

Figure 7: *Emergency stop flow diagram*

The kilovac contactor is a relay in a normally “off” state until energized by a 12V source. The 12V source is controlled by the wirelessly controlled relay and push button relay. The tripping of either of these relays will cutoff power to the kilovac contactor immediately. Once the contactor is turned off, the robot will lose all power to its motors.

3.2.2.1 Wireless Relay Module

The wirelessly controlled relay is part of a device called the “Relay Function Module 2” manufactured by Linux Technologies. It is a box that essentially contains 4 independent relays that can be wirelessly controlled by a remote. One of the available relays is used in the emergency stop module. The relay can be toggled between an “on” and “off” state on demand. Additionally, the relay defaults to the “off” state.

3.2.2.2 Pushbutton Reset Module

In order to have a pushbutton to act as an emergency stop on the robot itself, a PCB was designed and created to act as a triggerable relay circuit. It was made to be compatible with any kind of pushbutton. The module uses no programmable elements as required by the IGVC rules and instead utilizes basic logic ICs. One designed feature of the module is a permanent shut off of the relay until the module has its power switched toggled off and back on. An additional feature is a 5V logical output that indicates when the emergency stop has been tripped. This allows the onboard computer to respond by shutting down the program.

3.2.2.3 Kilovac Contactor

The Kilovac LEV200 series contactor is the biggest relay used in the emergency stop circuit. The motor power travels through the relay before it is fed into the motor controller. It is capable of handling up to 500A and its switched by a 12V source.

3.2.3 On-board Computer

From previous entries in the IGVC, we found that an onboard computer system was potentially more reliable than the previous designs using just a laptop. Two of the major issues that the laptop had were excessive power draw and overheating during the summer. The integration of a standard computer motherboard and components has allowed us to build a more reliable computing system.

3.2.3.1 M4-ATX Power Supply

The most important component besides the motherboard is the computer power supply. This is an off the shelf power supply meant for powering ATX standard motherboards from a DC supply compared to the common AC supplies. It has all the connectors required for the motherboard ATX and CPU connectors, as well as 4-pin MOLEX and SATA power connectors. The power supply is capable of delivering up to 300W at max load and handles all power management of the connected components, making it a perfect component to have been integrated into the design.

3.2.3.2 Motherboard

The motherboard is the most important part of any computer and the one chosen is an ATX standard desktop motherboard. It has 8GB of memory and an Intel i5 processor. The upside in these choices of specifications is a more powerful computing platform. The downside is the increased power consumption by these components. However, after testing we feel the tradeoff in more power for a reliable system is well worth it.

3.2.3.3 Solid State Drive

A Solid State Drive (SSD) is utilized due to the elimination of spinning disks utilized in hard disk drives. An issue that exists with using conventional hard drives is that they need to be relatively stable while writing data or else many mechanical problems may occur internally. Hard disk drives are not ideal in environments subjected to vibrations or shock for this reason. The solid state drive is for the most part unaffected by the movement of the robot and a logical choice.

3.2.4 Other Components of Interest

One of the main sensor systems used is the SICK LMS 210. Beyond wiring it to a power source, very little electrical work had to be performed to get it running. Additionally, a compass system to be decided was integrated to provide feedback on the robot's heading. An array of fuses was implemented for the motherboard, motors and LIDAR for a second set of short circuit and overcurrent draw protection.

3.3. Overall Design Decisions

There were a few electrical design decisions made in Project 15. They consisted of component layout, power distribution, and components used.

3.3.1 Layout

The component layout on the robot is potentially suboptimal but was decided on as shown in Figure 8. The space between related components was minimized for the ESTOP and computer system. Additionally, the electrical junction block and switches/fuses were put as close to the power source as possible to minimize excess wire. The side with the motor controller was left relatively clear for unrestricted air flow to allow for cooling via forced convection because of overheating concerns.

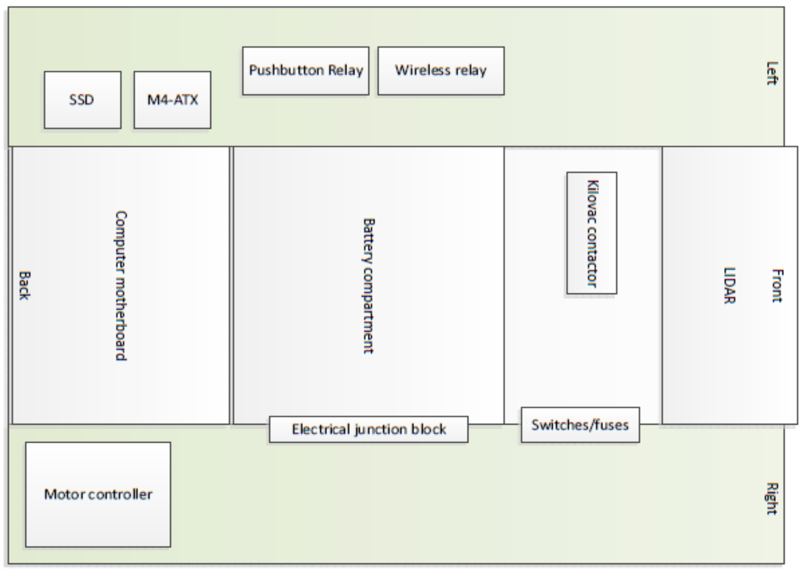

Figure 8: Component Layout

3.3.2 Power Distribution

The power source created by using the two 12V marine batteries was fed directly to most components. No attempt was made to regulate the voltage fed to the motor controller, LIDAR, and computer power supply. These devices all have internal switching based voltage regulation of some form and thus, space is saved by not requiring a large 24V regulator component. In the cases a 5V source was required for the smaller sensor systems (compass), a small DC/DC converter module was wired to 12V to generate the 5V.

3.3.3 Component Usage

The use of off-the-shelf components allowed for an expedited build of the robot. Additionally, the components have more features than would be possible if for example the motor controller was self-built. The AX2550 has a full feature programmable system capable of various operating modes and data. Finally, a cost saving is incurred by using components without having to waste money on prototyping and implementation.

4. Software

4.1 Overview

The layout for this year's robot is focused on the achievement of a fusion of all available sensors as opposed to instinctive and reactionary methods for autonomous navigation. The software structure of the robot is categorized based on a three tier system: Low Mid, and High Functions. This concept was chosen as a fail-safe for ensuring the effectiveness of the robot's navigation system. This was needed due to the fact that as the complexity of the algorithms utilized increased during development. In order to accomplish the concurrent usage of multiple sensors, an onboard computer system was implemented. The embedded system consisted of one high end desktop motherboard with a high performance quad core processor, and ample RAM. The specific system chosen was MIL-SPEC rated for long term use, solid state components (included hard drive) and overall durability in the most demanding of environments.

The interlinking of all onboard sensors required a modular and robust device management system that was custom coded. Each device had event-driven connection and data management processes which allowed for worry-free connectivity and data visibility. These new features also provided safety checkpoints during the robot's initialization and autonomous states. Each component was configured so that in case of a disconnection, the robot stops any dangerous actions and displays the state of every part of the robot platform for debugging.

4.2 Sensors

4.2.1 LIDAR

The on-board LIDAR system is the SICK LMS 221. We utilize the 0.5cm resolution with a scan range of 180 degrees at around 20 feet away from the robot with a refresh rate of 10Hz. The LIDAR driver was built for optimization of data handling, error handling and seamless integration and connection with the LIDAR. A separate Comport manager was created which was designed to ping comports and attempt to establish connections between any drivers that are registered with the manager.

4.2.2 Camera

The computer vision system is comprised of two Microsoft LifeCam Cinema cameras placed at a known distance apart on a five foot boom in the rear of the robot. The cameras faced downward at a specific angle so that the furthermost edge of the robot is the only portion of the chassis visible in the camera systems field of view. This placement allows for the detection of obstacles in and around the robot with a focus on its blind spots.

4.2.3 IMU

The Inertial Measurement Unit utilized is the X-IO ARHS IMU system imported from the UK. This device contains 3 accelerometers, 3 gyroscope and 3 compasses with an advanced Kalman filter for near perfect noise removal. All measurement devices on the unit are at 16 bit resolution which will give more than enough accuracy and precision in terms of measuring the forces on or by the robot as well as the direction and geographic heading.

4.2.4 GPS

The onboard GPS system is the Raven Invicta 115 Marine GPS. It utilizes the WAAS DGPS system with a final accuracy of about 1.4 meters with all satellites in sight. We chose this model due to its powerful antenna, waterproof design, and ability to use the DGPS ground station system with standard NEMA communication protocols.

4.2.5 Ultrasonic Sensor Array

An array of ultrasonic range finders with a terminal range of about 60cm was placed around the perimeter of the robot. The devices utilized were less expensive versions of the Parallax PING))) ultrasonic range finder and were attached to an Arduino Mega 2560 for co-processing.

4.3 Program Hierarchy

4.3.1 Low Level Functions

The LIDAR system is implemented in its simplest state and scans the area around the robot and notes obstacles of interest based on reading size and proximity to robot. The Initial LIDAR scan data manager categorizes obstacles by proximity into three groups, negligible, mid-range, and close range

The Camera system performs its basic function and obtains images of the course in front of the robot. The images are blurred to create a more uniform distribution of color on the floor in front of the robot. The system then performs a Hough Transformation to detect lines on the ground. Initial Camera Data Manager creates an array of points from the images that contain the x and y position of each pixel detected by the Hough Transformation.

The GPS unit obtains positional data and plots a bread crumb trail of where the robot was with the point of origin being when the robot first initiated its autonomous mode. The Initial GPS data manager uses a Kalman filter to remove any “noise” from the GPS data to give a more accurate reading.

The IMU system obtains data of the three-dimensional forces sensed during the motion of the robot in terms of acceleration. The Inertial Data Manager uses the acceleration data to calculate the displacement of the robot using the following equations:

$$x = x_o + V_x \cdot t + \frac{1}{2}a_x t^2 \qquad y = y_o + V_y \cdot t + \frac{1}{2}a_y t^2 \qquad z = z_o + V_z \cdot t + \frac{1}{2}a_z t^2$$

- x,y,z = current displacement
- xo, y_o, z_o = initial position
- V_x, V_y, V_z = the velocity
- a=acceleration
- t = time since start

The ultrasonic array uses sound waves to detect obstacles of close proximity (<60”) for use with navigation at the immediate level. The Ultrasonic Data Manager plots the points around the robot in the form of a “heat map” which visually depicts the range of objects in a quick and comprehensible manner. During the autonomous state, the graphical heat map will be suppressed but the data will still remain virtually as an addition to the LIDAR scans as an overlay.

4.3.2 Medium Level Functions

The stereoscopic nature of the camera system will provide a disparity (depth) map of the images acquired which will give true-to-life distances from every part of the detected white lines to the robots center. Using a specific printed glyph, the cameras are each calibrated for distance detection in a manner similar to the Microsoft XBOX Kinect accessory. The flowchart for this process is shown in Figure 9.

As the robot moves, the LIDAR scans and refreshes the current field of view. Each scan represents the obstacles detected in the environment at that point in time. The scans are then correlated to the displacement of the robot by means of IMU data and a “mosaic” of data points which provide a simple map of the surroundings.

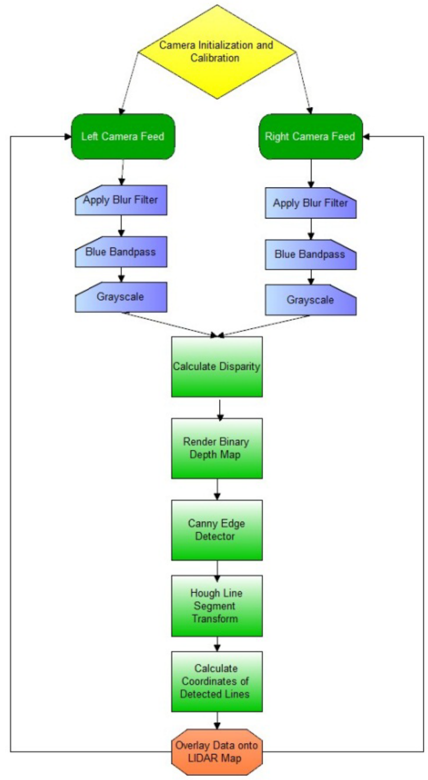

***Figure 9:** Disparity Mapping Flowchart*

4.3.3 High Level Functions

A sensor fusion is performed using SLAM algorithms to produce a detailed map of the surroundings using all of the sensors (LIDAR, GPS, IMU, ULTRASONICS, CAMERAS). The data from the LIDAR, cameras, and ultrasonic are overlaid and aligned to bring further detail about the immediate surroundings and the GPS and IMU give a noise free (by way of Kalman filter) odometry to correlate the relative map with real world coordinates.

The GPS waypoints that are given to the robot will act as the bearing for the robot’s navigation system, to which the robot will continuously attempt to align itself to a straight line towards the waypoint. This works as a simple GPS navigation system. But in order to perform more intelligent navigation we take the data received from the other sensors and utilize all data to navigate more intelligently.

Using the data received from the various sensors, a grid is created and portrays a strict “pathable” or not “pathable” grid to the robot. The map will be constructed using a variety of sensors. For example it will take the LIDAR data which is transforming each coordinate the LIDAR from the local, to the world point of view. We can also examine the camera data and perform obstacle recognition on the feed so as to recognize the difference between ground and other obstacles. By using stereoscopic vision we can easily discover obstacles and the distance between them and the robot. Using that we can place these obstacles on the map and consider them in our obstacle avoidance algorithm. Similarly white lines will also be detected by the camera, so we can use transforms and place white lines on our grid of “pathable” or “unpathable”.

From this grid the robot utilizes the A* pathfinding algorithm to estimate the shortest path between our current location and the target location given by the GPS way point. A* works by constructing two lists of nodes: an open list and a closed list. Nodes that have been examined are added to the closed list while nodes that have not yet been examined are on the open list.

Initially the only node in the open list is the current node. The node with the smallest path length is picked from the open list and then examined. Nearby walkable nodes are then added to the open list and the process repeats. In this way we are able to construct a path which nearly represents the shortest distance to reach the GPS point. The robot will attempt to travel along the path constructed by the algorithm and the given grid.

In order to utilize A* algorithm in an efficient manner there are a couple of speed improvements we can use. Rather than using a grid, we construct a Navigation Mesh which is updated by new obstacles being registered, or obstacles being lost. The navigation mesh speeds up performance by decreasing the number of nodes we traverse via A* as well as accommodate path finding for a robot with some size.

As an emergency stop we will implement a function that determines if an obstacle comes within some threshold distance. If this occurs, the robot will attempt to come to an immediate stop and then fully evaluate the situation and then determine the next course of action. This mode will be known as EMode, which will override most navigation functionality to attempt to remove itself from any obstacles it's tangled up in. After it is free, it will then resume normal navigation.

6. Conclusion

P-15 was designed, built, and tested to compete in the 2012 Intelligent Ground Vehicle Competition. Physically, our robot was designed to be robust, and yet also mobile enough to be able to navigate around tight corners that may be present during the competition. Sensors were implemented to take the environment and turn it into a series of digital signals that the robot could use to find and negotiate a path through obstacles while staying within line boundaries. Through IGVC we have gained knowledge on the challenges and awards that come from working on a problem as complex as navigation of an autonomous vehicle.