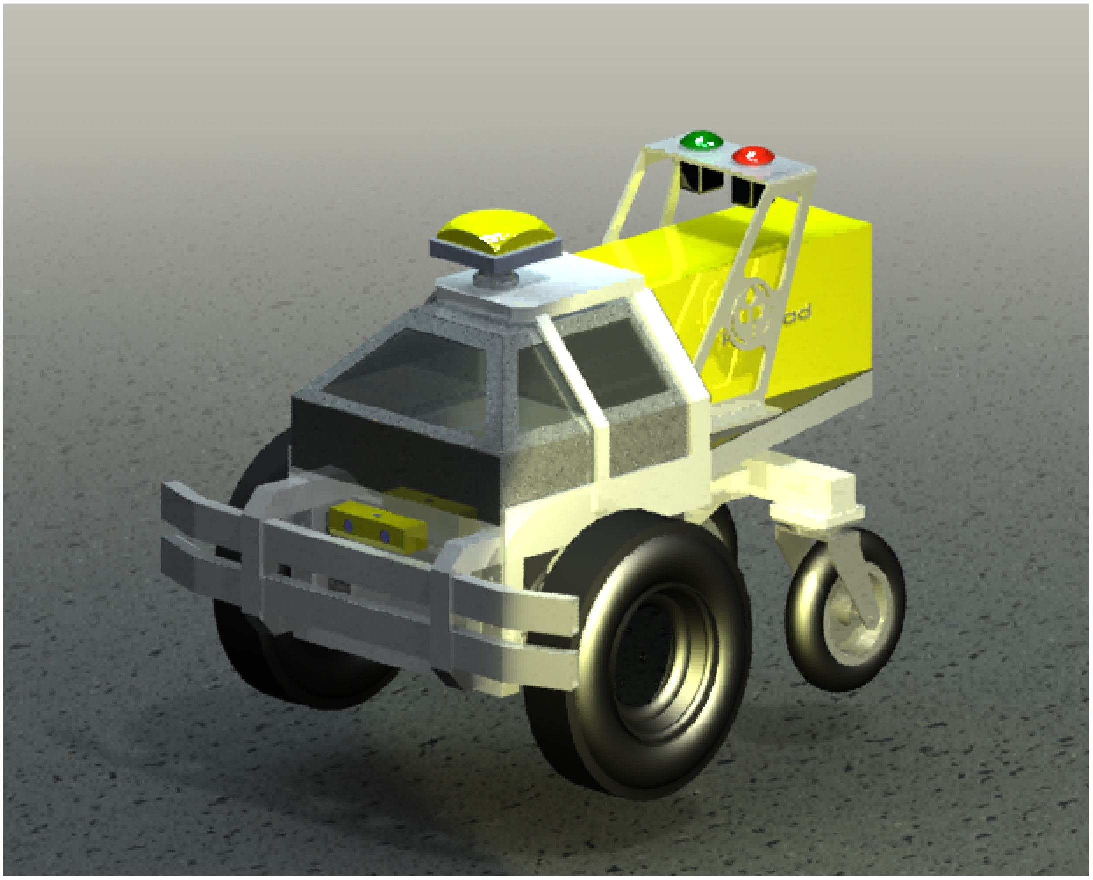
CAT

Chico State's Autonomous Transport



Faculty Advisor Statement:

I, Dr. Ramesh Varahamurti of the Department of Mechanical Engineering, Mechatronic Engineering and Manufacturing Technology at California State University, Chico do certify that the design and implementation of this vehicle has been credited to each team member for their work.

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CALIFORNIA STATE UNIVERSITY, CHICO

CONTENTS

1.0 INTRODUCTION

The California State University, Chico IGVC Team is comprised of different engineering backgrounds including Mechanical, Mechatronic and Electrical. This is the second year for the CSUC team and robot combination to compete, with this project being devoted as an entirely extracurricular educational experience.

The CSUC IGV Team listed below includes leaders and members who meet weekly to set goals, establish tasks and track the progress of the completion for the autonomous vehicle.

- Teresa Muir- President (ME)
- Brian DeWilde- VP (MECA)
- George Wing- Treasurer (MECA)
- Ross Huber- VP of Mechanical Systems (ME)
- Sam Ferguson- VP of Software Systems (MECA)

- Josh Polansky- Computer and Motion (MECA)
- Rich Barry- Motion and GPS (MECA)
- Scott Vanni-Design and Fabrication (MECA)
- Gavin Swanson- Sonar and Compass (MECA)
- Alex Scharf- Design of Cooling System (ME)

2.0 DESIGN PROCESS

The design process began with a compilation of all the rules and requirements to compete in the competition. Designs were then created using a meld of mechanical, electrical and computer theory. An analysis of each consideration taking weight, size and a payload into consideration was used to form a solid outcome.

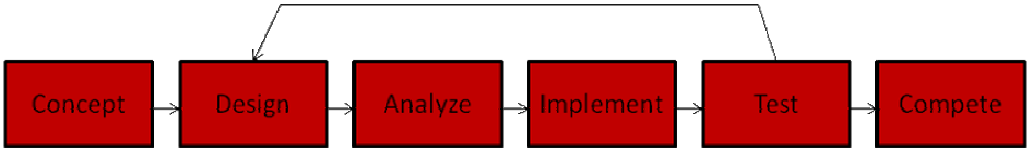


Figure 1: Design Process Flowchart

2.1 Goals

- Autonomously traverse obstacle course
- Waypoint Navigation
- Lane following
- Successfully Navigate:
  Potholes, Ramps, Objects in Path, Switchbacks
- Compact Design:
  Lightweight, Carry Payload, Small Turning Radius
- Stay on Budget

2.2 Our Design Requirements

- Max speed 5 mph

- Height: 7ft max
- Width: 5ft max
- Length: 6ft max
- E- Stop

2.3 Features

- GPS
- Sonar
- Stereo Vision
- Digital Compass

3.0 MECHANICAL

In effort to maintain California State University Chico's sustainability goals, many materials were acquired through scrap recycling and donations. The mechanical design is divided into three parts: Chassis, Drive System and E-Stop.

3.1 Chassis

The chassis was built from 6061 aluminum scrap from a local house boat builder. The chassis was intended to have zero turn radius capability in order to avoid back up situations, and to allow for center pivot of the vision system. This was accomplished by utilizing two drive wheels and two rear pivoting castors, Figure 1.

Figure 1: Chassis Design

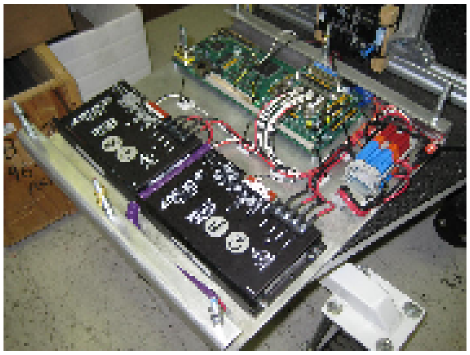


Figure 2: "Brain"

The vehicle is estimated to weigh 260 lb after completion. Wheelchair motors were used due to built-in gearing, high starting torque, low power consumption, and ease of maintenance. The motor mounts were reversed in order to facilitate greater travel in the suspension system. The suspension was custom fabricated from off the shelf springs which were "tool dipped" in rubber for aesthetic reasons.

One innovation of the chassis system is the modular attribute of the “brain”, and its ability to be removed and placed into any other chassis. The “brain” is a rack system containing all sensor hardware, motion control systems, and our operating system, as seen in Figure 3. The “brain” is easily removed by unplugging three quick disconnect sockets, one for the power system, and one for each of the two motors.

The entire chassis was modeled in Solid Works design software before fabrication which allowed for placement of the center of gravity, as well as interference detection.

The final chassis was powder coated because this process has less environmental impact and air pollution when compared to traditional spray painting. The bottom of the chassis as well as the cargo bed were both coated with Rhino Liner bed lining to provide impact and abrasion resistance.

This year the design improvements included: new hub mounts for the new all-terrain-tires, a subsequent redesign of the bumper to include a bigger clearance for the tires, new mounts for the stereo vision camera and sonar sensors as well as a new cooling system inside the electrical component cab. The latter was accomplished by inserting fans at specific points to allow for better flow of cool air, and the transfer of heat away from the electronics.

3.2 Drive System

The vehicle is driven by two brushed servo motors with worm gear right angle gear reductions. The motors are each powered by separate Advanced Motion Controls 50A8 PWM servo motor amplifier, which can supply 25A continuous and 50A peak current. The amplifiers are operated in a closed loop system controlled by a Galil Motion Control DMC-2183 8-axis motion controller. The motion controller receives incremental encoder feedback from the motor and uses it to command a ±10V signal to the amplifiers. It receives commands through a RS-232 serial port. The motion controller was donated by Galil Motion Control, the amplifiers were donated by Advanced Motion Controls and the motors and gear heads were salvaged from a wheelchair which was donated by a private party.

3.3 E-Stop

CAT is equipped with both manual and wireless E-stops. When either E-stop is engaged an abort signal stops the execution of the controller program and turns off the ±10V control signal to the amplifiers. Additionally, if the E-stop is applied at full speed, mechanical relays disconnect the motor power wiring from the amplifiers and apply a regenerative power dissipation resistor across the motor leads, which help slow the vehicle to a quick safe stop.

4.0 SYSTEM COMPOENTS INTEGRATION

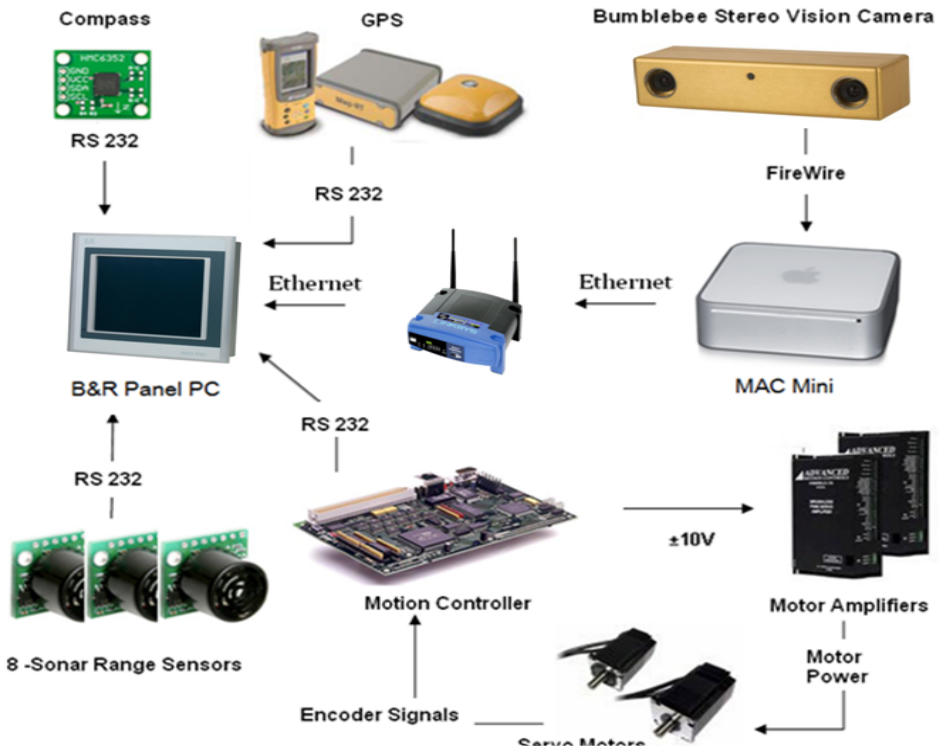


Figure 3: System Diagram

5.0 ELECTRICAL

The electrical ‘brain’ concept was designed to maximize the modularity of CAT's electrical system. Except for sensors and motors, which are located in fixed locations on the vehicle, all of the components are mounted on the ‘brain’ and can be quickly moved between mechanical chassis. The physical wires are run through fused terminal blocks, fastened to the ‘brain’ to better withstand vibration and impact felt by the chassis.

A complete wiring schematic of the motion controller, servo amplifiers and motors is featured in Figure 5. A single RS-232 provides the interface between these components and the main controllers, although another communication line can be added for redundancy.

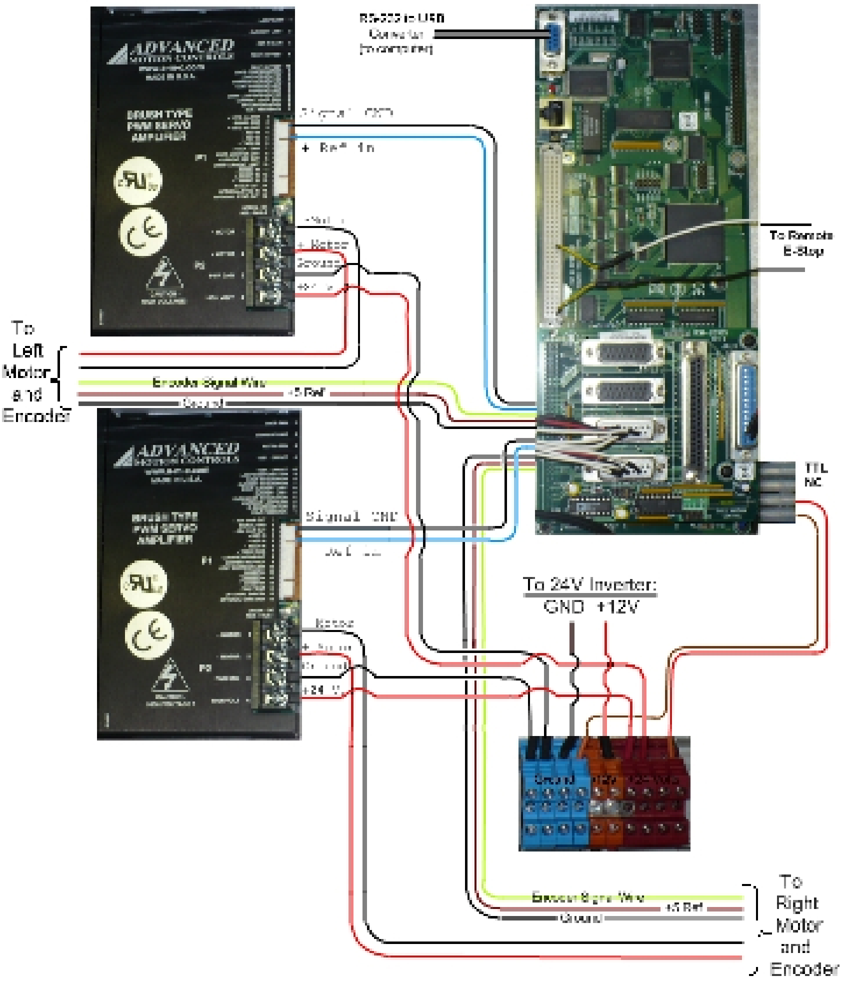


Figure 4: Wiring Diagram for CAT Motion Controls

5.1 Power Supply

Power is supplied by two sealed gel-type deep cycle 12V batteries. The batteries are wired in series to supply the 24V required by the motion controller and motor amplifiers. Additionally a 24V to 12V, 5V and 3.3V converter supplies regulated power to the computer and other electronics.

The batteries are stored in a compartment beneath the main electronics cab. The 24V supply can be disconnected from the electronics via switch; however there is no switch for turning off the 12V supply to the computer. This is a safety feature that ensures that the computer is not accidentally turned off.

6.0 SENSORS

The main considerations for the sensors on CAT were the benefits of how well each component could perform a desired task with the least amount of cost and power consumption.

6.1 Stereo Vision Camera

CAT uses an off-the-shelf stereo vision camera, the Bumblebee2, sold by Point Grey Research. A stereoscopic vision system was chosen over a laser range finder (LIDAR) product due to the considerations listed in Figure 5. The stereo vision camera itself uses two CCD (Charge-Coupled Device) digital cameras, which are not susceptible to infrared interference, and streams the two images across an IEEE 1394 FireWire connector. The images are received and processed by a Mac Mini running the processing software.

Stereo vision works by using two cameras with parallel lines of sight that are separated by a set distance. The disparity, or distance, between two similar patterns in each image is measured, with greater disparities indicative of closer patterns. These disparity values are converted to an orthogonal distance from the camera, and attached to each pixel.

Consideration	Stereo Vision	LIDAR
Power Consumption	**2.5 W**	180 W
Maximum Frequency	**48 Hz**	10 Hz
Accurate Range	4.5 m	**15 m**
Weight	**0.34 kg**	9 kg
Cost	**$2,000**	$8,000

Figure 5: Stereo Vision vs. LIDAR Comparison

6.2 Digital Compass

The digital compass is used to sense vehicle heading relative to magnetic North. A fully integrated Honeywell HMC6352 compass module is used for this purpose. It has 2-axis magneto-resistive sensors with the required analog and digital support circuits, a microprocessor, and algorithms for heading computation. It works on 3.3VDC and is interfaced with the sensor controller through I^2C bus. The compass plays an important role in the vehicle's operation as it is used to maintain a sense of heading with respect to magnetic north at all times.

6.3 Sonar Range Finder

A low cost ultrasonic range finding solution for obstacle detection is also used. Each sensor has an effective range of 6.45 meters with a 26 degree conical coverage beam. The vehicle utilizes six such sensors to increase the obstacle detection field angle. These sensors are arranged with two facing forward, one facing to each side, and two facing towards the back. They are powered by 5 VDC source through an RS232 interface. The loop begins by bringing the RX pin low for 1 millisecond, this initiates a read cycle in the sonar. The system then waits 50 milliseconds for the analog signal to settle, at which time the reading is appended to a string for later transmission. To help eliminate interference the system then waits an additional 10 milliseconds. Each of the connected sonars are cycled through and the compiled data is sent via serial to the B&R Panel PC. It was determined that a cycle time of 61 milliseconds per sonar was acceptable to wait for the data. The worst case scenario works out to the oldest sonar reading being roughly 488 milliseconds old with the full complement of 8 sonars attached.

6.4 GPS

The Global Positioning System (GPS) is used to determine the position of the vehicle on the field. The vehicle uses Topcon's GMS-110 GPS receiver. The GMS-110 typically detects between 12 and 14 satellites, and is augmented with differential and beacon correction signals to achieve sub-meter, real time accuracy. This device is interfaced with the main system controller via an RS-232 serial interface. Data received through the GPS module plays a critical role as the vehicle position detector for the navigation challenge.

7.0 SIGNAL PROCESSING HARDWARE

This vehicle uses two controllers for data processing. A Mac Mini is used for image processing, while the motion control, sonar, and GPS data is evaluated by a B&R industrial PC. The two computer interfaces communicate through a Linksys router.

The B&R Panel PC has 4 serial communication ports and the capability to add more if necessary. These communication ports are used for communicating to the GPS unit, the sonar module, the compass, and the Galil Motion Controller. It runs a real time operating system to achieve deterministic response times from the sensors, and to prevent a failed sensor from pausing the entire system.

The stereo vision used for line and obstacle detection is processed on a dedicated Mac Mini, running Windows XP. This also serves as the Human Machine Interface (HMI) for the vehicle. The B&R Panel PC communicates to the Mac Mini via TCPIP and the aforementioned router. The wireless router also acts as an interface with the B&R and Mac Mini as long as wireless communications are open.

These two interfaces were used due to their expandability. The B&R Panel PC has the ability to expand I/O using I/O blocks. This makes RS-232 ideal because of the ease and the ability for the B&R Panel PC to expand. TCPIP was chosen due to expandability, but also for speed. This same interface can be used for HMI, programming, as well as allowing data to be universally shared between devices.

8.0 SOFTWARE STRATEGY

The software underlying CAT was designed with reusability and portability as chief considerations. Since the ‘brain’ can be easily moved from one chassis to another, the code was developed to match the same level of portability. The software on the Mac Mini was written in ANSI C, utilizing standard functions and libraries.

The Mac Mini, which features an Intel Core 2 Duo processor, produces the depth map on one core, then passes the rectified color images and the depth map to custom code designed to navigate CAT. Since the frame rate is directly determined by the available processing power of the system, the different segments of code were separated into different processes and multithreaded to optimize performance. When the image capture thread receives a new image, that data is then posted to a global semaphore. These semaphores are processed to detect lines and obstacles, as discussed in the Signal Processing section. The multithreaded code is POSIX compliant can therefore be ported over to Linux, Mac OSX, or any number of other operating systems.

The B&R Panel PC takes the recommendation from the Mac Mini, based on the stereo vision, and checks the recommendation against the current sonar, compass and GPS values, before issuing a command to the motion controller.

9.0 SIGNAL PROCESSING

Images from the Bumblebee Stereo Vision camera are received by the Mac Mini through an image processing algorithm The code to compare the two images taken by the cameras to produce a depth map was included in the Bumblebee 2 package from Point Grey Research. This code is written and called in ANSI C.

9.1 Image Processing

The images taken by the stereo vision camera are transformed to remove distortion due to the camera lenses and produce a true, undistorted image that is ready for the pattern matching algorithm used to generate the depth map. The image produced plots the drivable regions and the obstacles on a map which is used for path planning.

9.2 Obstacle Detection

After the depth map has been produced, the custom image processing code processes the data to find obstacles. This is done by checking for gradients that fall within a tolerance of a specified slope, in this case 15 degrees, and based on the height of the mounted camera. If a region falls within the gradient tolerance and the approximate height of the camera, the region is considered drivable. If not, then it is considered an obstacle.

The image plots the drivable regions and the obstacles on a map that is used for path planning, described in the Plan for Path and Control Decisions section. Additionally, a failsafe algorithm, which can override the path planning algorithm, prevents CAT from running into obstacles.

9.3 Line Detection

To detect lines, the drivable region within the image is reduced to the eight primary and secondary colors, including black and white, as seen in Figures 6 and 7. The percentage each pixel is of its respective primary color is used for further processing.

The image is then processed into smaller segments. Within each segment of the image, a fuzzy algorithm rates the percentage white or yellow a group of pixels, known as a cell, is and sorts it for each column of an array within the segment.

Within each segment, the cells with the greatest percentage white or yellow, and their relative proximity to the center of the image, are considered first. The inverse slope between the distances from the camera and the distances to each side from the center of the camera are then plotted. This means that semi vertical lines have slopes near zero, and semi horizontal lines have slopes near infinity.

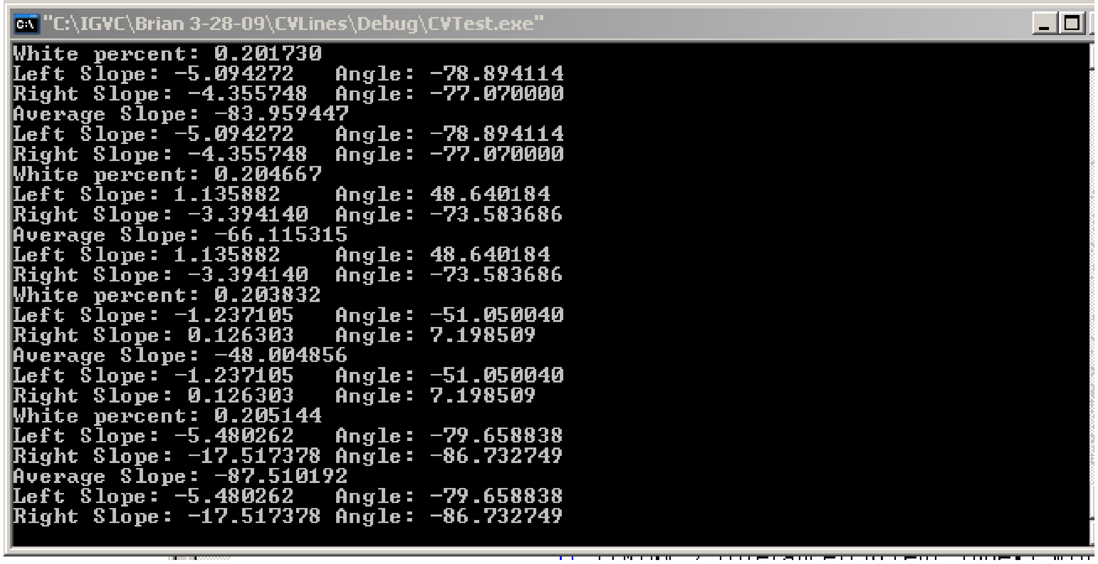
The average slope and the standard deviation of the lines are used to determine whether the average slope is a good linear fit for the region. If not, cells attached to slopes which were beyond tolerance are replaced by the next most white, or yellow, cell in that column. The process is then repeated until either a valid linear correlation is met, or until a maximum number of iterations have been exceeded.

The average slope of each segment, or no slope if there was not a valid linear correlation within that segment, produces a mathematical model of the lines based on range from the current location of CAT. Either or both lines, depending on the validity of their linear correlations, determine an average slope. The inverse tangent of this average slope is the difference between the heading of CAT and the direction of the lines, as seen in Figure 8.

The intercepts of the lines determine how far CAT is from each of the lines. A failsafe algorithm, which can override the path planning algorithm, prevents CAT from driving within half of the vehicle width of the line, which effectively prevents CAT from crossing lines. Another flag is set if it is too far from one of the lines, indicating that it may be crossing over the region of the opposite line.

Figure 6: Drivable Region

Figure 7: Color Reduced Drivable Region



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White percent: 0.201730
Left Slope: -5.094272   Angle: -78.894114
Right Slope: -4.355748  Angle: -77.070000
Average Slope: -83.959447
Left Slope: -5.094272   Angle: -78.894114
Right Slope: -4.355748  Angle: -77.070000
White percent: 0.204667
Left Slope: 1.135882    Angle: 48.640184
Right Slope: -3.394140  Angle: -73.583686
Average Slope: -66.115315
Left Slope: 1.135882    Angle: 48.640184
Right Slope: -3.394140  Angle: -73.583686
White percent: 0.203832
Left Slope: -1.237105   Angle: -51.050040
Right Slope: 0.126303   Angle: 7.198509
Average Slope: -48.004856
Left Slope: -1.237105   Angle: -51.050040
Right Slope: 0.126303   Angle: 7.198509
White percent: 0.205144
Left Slope: -5.480262   Angle: -79.658838
Right Slope: -17.517378 Angle: -86.732749
Average Slope: -87.510192
Left Slope: -5.480262   Angle: -79.658838
Right Slope: -17.517378 Angle: -86.732749
```

Figure 8: Results from Line- Fit Calculation

9.4 Waypoint Navigation

An algorithm stores user input coordinates into an array; a structure that consists of latitude, longitude, distance from current position, and an angle relative to True North. With initial input, the algorithm simply places the individual waypoint coordinates into subsequent cells, then waits either for an entry of another set of coordinates or the pressing of the "Start Test" button. Upon setting of the Start Test variable, the coordinate values in the array are indexed to be used to calculate the distance and direction from the current position to the waypoint, then bubble sorted to achieve nearest to furthest indexing. The first waypoint, which corresponds to the nearest location of CAT, is then treated as the current position. The remaining waypoints' coordinates are then used to calculate distance and direction in preparation for another nearest-to-furthest bubble sort. This calculation/sort process is repeated for n-1 cycles. The effect is to "think ahead" and plan the fastest possible route with regards to current position.

Once the sorting is complete, the array is passed to the motion algorithm at which time the machine begins driving towards the first waypoint.

When the vehicle is within the minimum required distance from the waypoint, the cells of the array are shifted to delete the current waypoint, and install the next nearest waypoint to be targeted. This process is repeated until there are no elements left in the array, meaning all waypoints have been reached. An example of CAT's exectution of waypoints is seen in Figure 9.

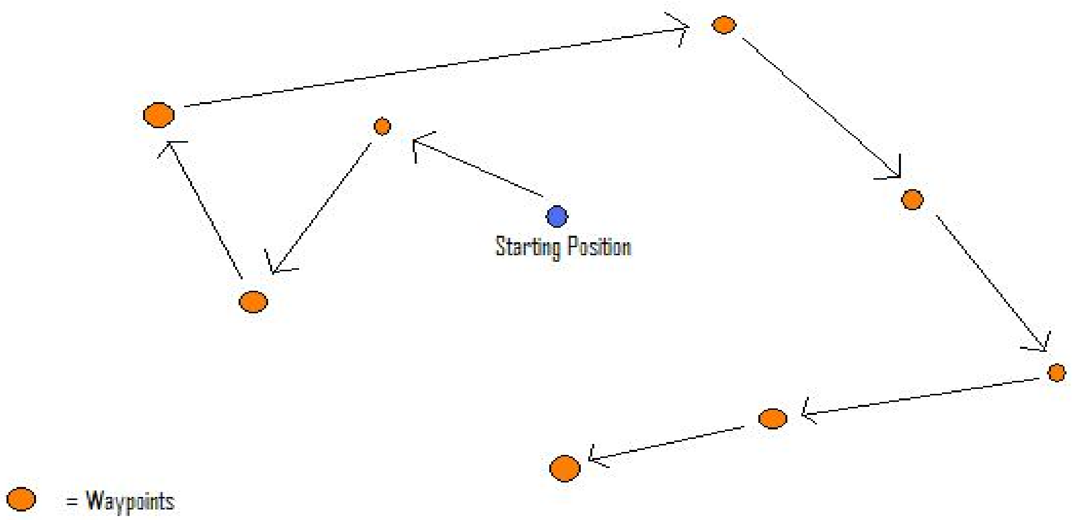

Figure 9: Waypoing Navigation

10.0 PLAN FOR PATH AND CONTROL DECISIONS

The decision algorithm takes information from the Bumblebee camera, each of the six sonar sensors placed on the center and edges of the machine, and data from the solid state compass. Machine vision data holds each pixel's orthogonal coordinate relative to the vehicle's center as well as a flag signifying a white line, an obstacle hit, or an empty space condition. The algorithm interprets the data to create two meshed, overlaying arrays holding hit densities and pertinent flag information, as seen in Figure 10.

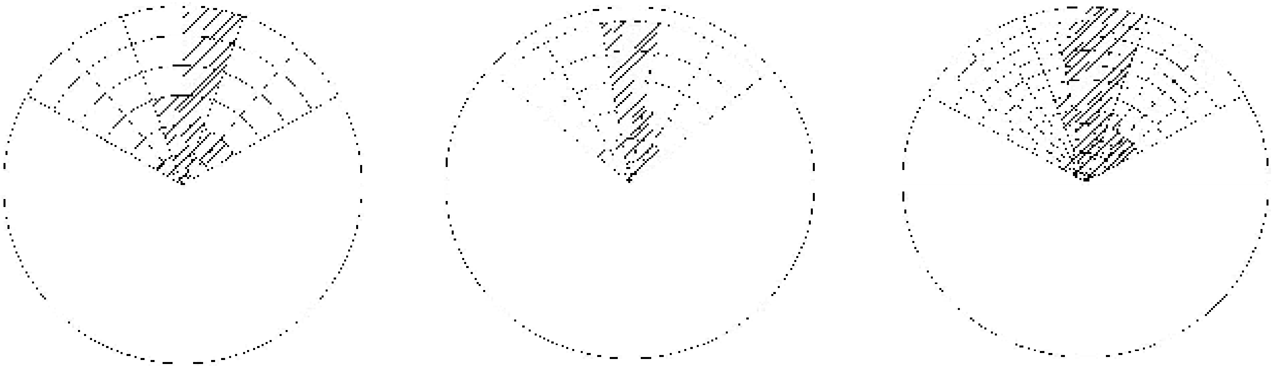

Figure 10: Drivable Region (Shaded): Right, Left, and Total

Each of these maps is in polar coordinates, mapping the region visible by CAT since its last movement. These maps are offset by half of a cell, as seen in Figure 10. This means that each cell in one map overlaps four cells in the other map. This is done to avoid having junctions between cells in memory, which may otherwise show a clear path as blocked, as seen in Figure 11.

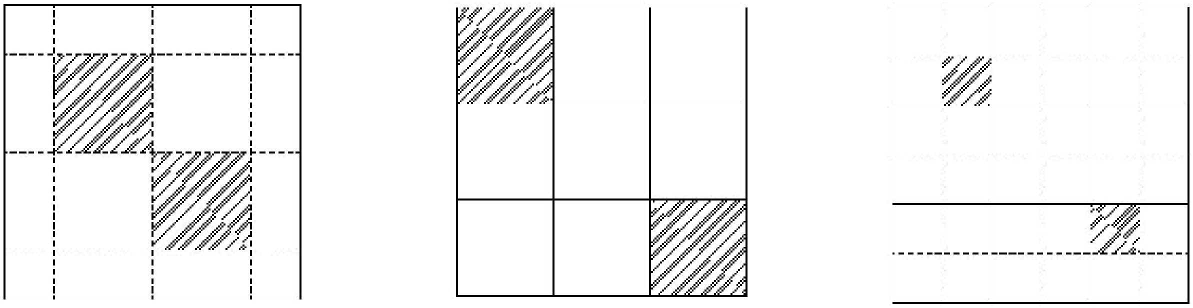

Figure 11: Non Drivable Regions (Shaded)

CAT looks at the two maps and uses a modified "Traveling Salesman" algorithm to approach the desired heading, as determined by the lane following algorithm. It can only travel between cells that overlap in the two maps. This effectively means that it can never cross a junction, thus eliminating the problem presented in the left most image in Figure 11.

If CAT is currently moving, it looks only directly ahead. If it stops moving, it may turn side to side to gather more information. If there is no obstruction in the immediate path of the robot, the turning mechanism will not be enacted and the robot will continue on its forward path. An example of the algorithm for the driving forward state is seen in Figure 12.

Upon encountering an obstacle, the distance between white lines and the edges of the obstacle are calculated and compared to the width of the robot as a clearance check. If passed the machine will target the closest center of an empty region and pass that distance and direction to the motion control algorithm. Sonar readings are used to ensure the robot maintains a buffer while near the obstacles. Changes in heading are marked and maintained by comparing present and past compass data. Upon the loss of a compass signal, a soft emergency stop will be enacted to avoid possible run away conditions.

Sonar is considered only when turning an angular distance greater than the horizontal field of view of the Bumblebee. The digital compass is used to maintain direction and heading relative to true north, especially when turning. All of these large turns are stored in non-volatile memory, to assist in navigation if the vehicle finds itself in dead ends, figure eights, or switch backs.

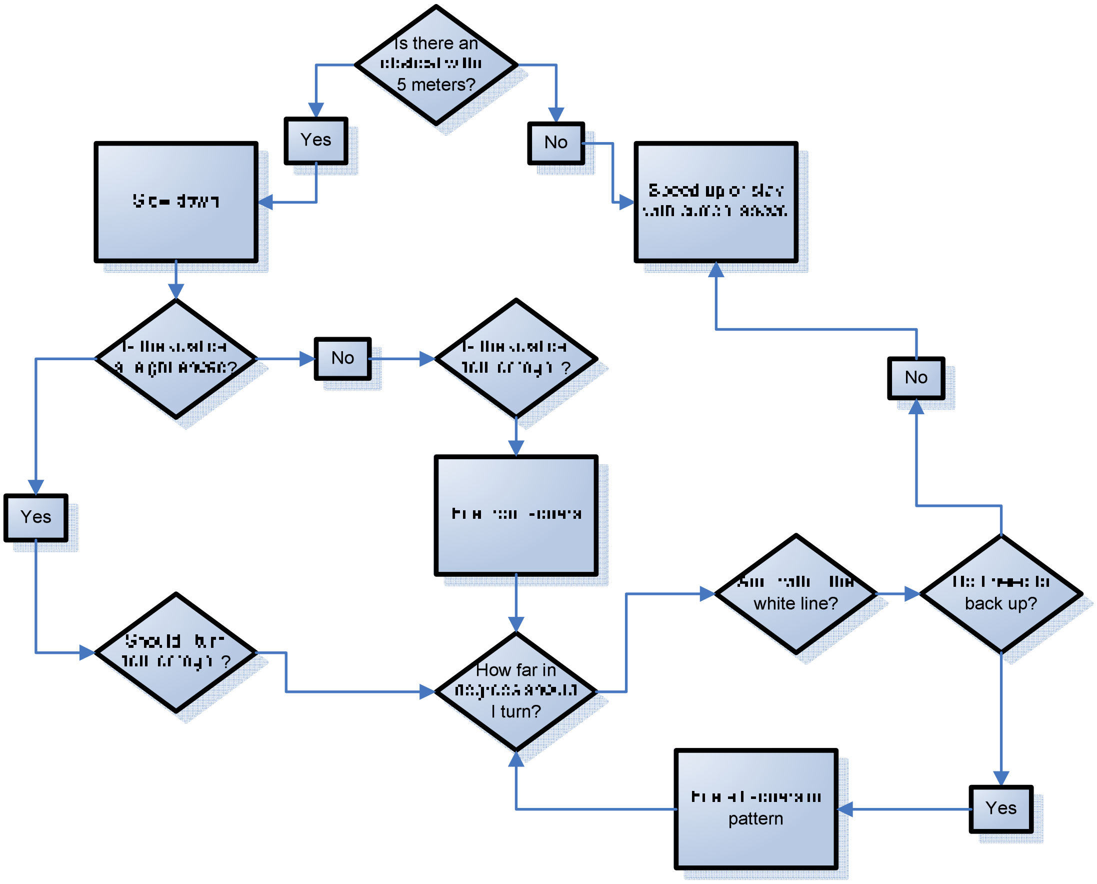

Figure 12: Flowchart for Driving Forward.

11.0 ANALYSIS

CAT was built with certain specifications and performance factors which included speed, obstacle detection and avoidance along with ramp climbing ability and reaction times. With the integration of GPS, Sonar, and Stereo Vision components as well as its physical factors of being compact with a small turning radius, CAT has no problems turning about its axis in an efficient manner in order to avoid obstacles.

11.1 Speed

With the compact ability of the chassis and the power of the motors, CAT's max speed is approximated at 9 mph, but for this competition it will be set and limited to 5 mph. This is accomplished by using a limiter set with the Galil motion controller. During the execution of the path planning algorithm, the velocity of CAT is calculated from the distance of the unobstructed driving space available from the stereo vision data, and sent to the motion controller and motors through the B&R Panel PC.

11.2 Battery Life

When constructed and tested, two optima batteries were utilized to provide the sufficient power to the robot and all its components. Running at constant speed while fully loaded, battery life is estimated at about 4 hours, and standby time at about 10 hours.

12.0 PARTS LIST AND PRICES

Below is a table depicting the money spent to replicate our autonomous vehicle CAT.

Purchased for Robot:	**Cost to Team:**	**Retail Cost:**
2 Optima deep cycle batteries	$300.00	$300.00
2 Pivoting castors	$40.00	$40.00
Integrated compass	$70.00	$70.00
Battery charger	$70.00	$70.00
Motion Controller	$0	$1595.00
Expansion board w/ interconnecting module	$0	$195.00
Galil Axis amplifier	$0	$795.00
2 Advanced Motion Controls Servo Amplifiers-	$0	$1050.00
Emergency stop remote w/ receiver board	$70.00	$70.00
Fans	$20.00	$20.00
Sonar modules	$200.00	$200.00
2 Microcontrollers	$120.00	$120.00
Voltage sensor	$25.00	$25.00
Temperature sensor	$10.00	$10.00
Topcon GPS	$750.00	$5495.00
Bumble Bee Stereo Vision System	$2000.00	$2000.00
Rims and Tires	$320.00	$320.00
Linksys Router	$0	$35.00
B&R Automation Panel PC	$0	$4800.00
Mini Mac	$650.00	$650.00
Aluminum Material	$700.00	$700.00
USB to serial converter	$0	$20.00
Voltage regulator	$0	$30.00
Total amount paid for components	$5345	$18610
Total hours spent this year	11460	