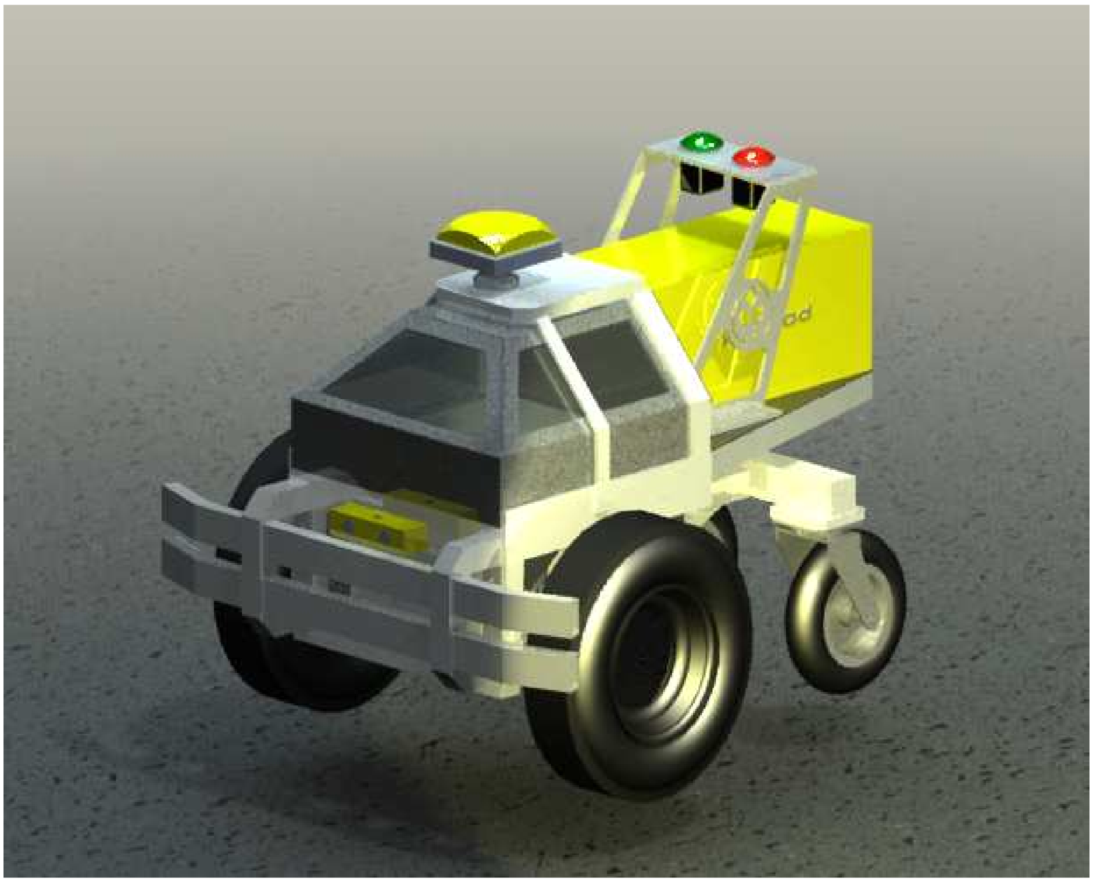
C.A.T

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.

Dr. Ramesh Varahamurti
Dept. MMEM

CONTENTS

1.0 INTRODUCTION

The California State University, Chico IGVC Team is comprised of a multitude of engineering backgrounds including Mechanical (ME), Mechatronic (MECA) and Electrical Engineering (EE) and Computer Science (CSCI). This is the third year the CSU Chico team competed with their extracurricular robot project.

The CSU Chico 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)
- Scott Vanni- VP Mechanical Systems(MECA)

- Rich Barry- Component Systems (MECA)
- Corey Abbot- Programmer (MECA)
- Michael Salmi- Electronics (EE)
- David Stinson- Computer Systems (CSCI)

2.0 DESIGN PROCESS

The design process, as shown in Figure 1, began with a compilation of all the rules and requirements of the competition. Designs were then created using an amalgam of mechanical, electrical and computer theories. Analyses considering the competition objectives, manufacturability, modularity, accessibility of components, and cost were multiplexed into the finished product.

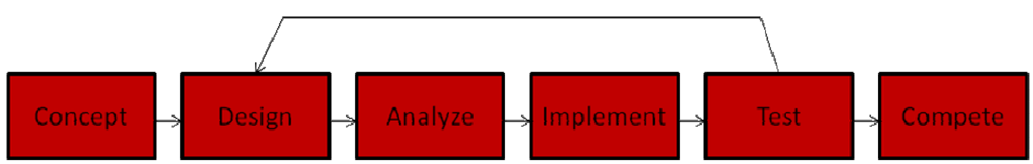


Figure 1: Design Process Flowchart

2.1 Goals

- Recognize lines and obstacles
- Autonomously traverse obstacle course
- Autonomously navigate a set of GPS waypoints
- Maximize use of off-the-shelf components
- Be compact, low weight, portable and have a minimal turning radius
- Stay on budget

2.2 Competition Requirements

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

2.3 Features

- GPS
- Ultrasonic Sensors
- Stereo Vision
- Digital Compass

3.0 MECHANICAL

In an effort to maintain California State University Chico's sustainability goals, many materials were acquired through scrap recycling and donations. The motors were recovered from a recycled electric wheel chair. All of the fabrication was done on-site by CSU Chico students.

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, donated by a local house boat builder. The chassis was designed with a zero turn radius in order to avoid situations where it may inadvertently back up into an obstacle, and to allow for center pivot of the vision system. This was accomplished by using two drive wheels with two rear pivoting castors, Figure 2.

Wheelchair motors were used due to their built-in gearing, high starting torque, accessibility, 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 easily removed and placed in another chassis. The "brain" is a rack system containing all sensor hardware, motion control systems, and the operating system, as seen in Figure 3. The "brain" is removed by unplugging three quick disconnect sockets, one for the power system, and one for each of the two motors.

Figure 2: Chassis Design

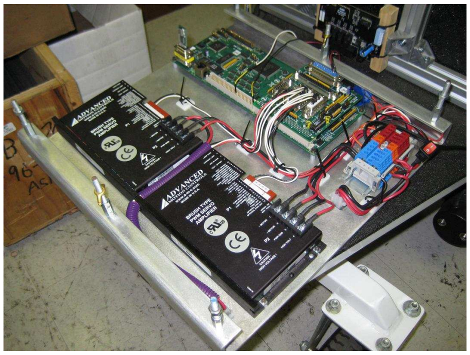


Figure 3: "Brain"

The 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.

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 vehicle weighs approximately 230 pounds.

This year a new cooling system was added to increase run-time and environmental resistance. This was accomplished by inserting fans at specific points to allow for better airflow, to transfer heat away from the electronics. The air is filtered to prevent airborne particles from interfering with the operation of 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 servo motor amplifiers, 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 eight-axis motion controller, using encoder feedback. The six unused axes are provided to facilitate the attachment of actuated modules.

The motion controller receives incremental encoder feedback from the motor and uses it to command a ±10V analog signal to the amplifiers. It receives commands through RS-232. The motion controller was donated by Galil Motion Control, and the amplifiers were donated by Advanced Motion Controls. The motors were salvaged from a recycled wheelchair.

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 mechanical relays disconnect the motor power wiring from the amplifiers and engage a resistor to dissipate the regenerative power present across the motor leads. This brings the vehicle to a quick and safe stop.

4.0 SYSTEM COMPOENTS INTEGRATION

Cost-benefit analyses were used in the electrical resource allocation. A quad-core computer runs all of the high-level systems, including vision, decision making, human-machine interface, and peripheral communication. Certain, specific algorithms, such as the PID loops used to control the motors, are offloaded onto the Galil motion controller. Embedded boards are also used to multiplex data from the ultrasonics and compass to RS232.

A pictorial overview of this can be seen in Figure 4.

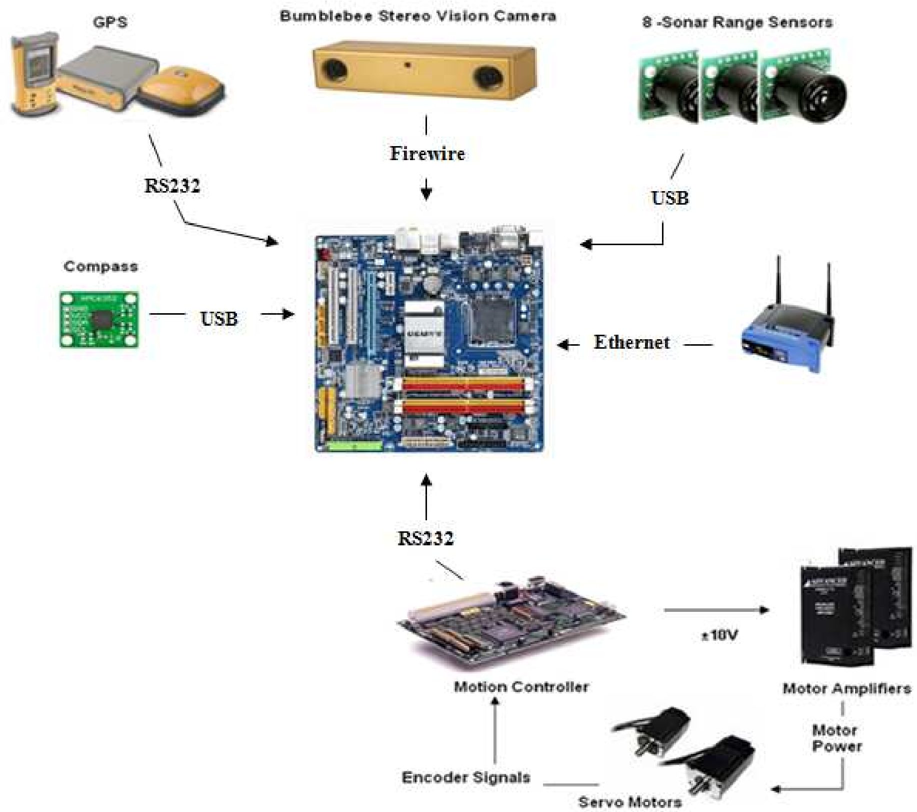


Figure 4: Component System Diagram

5.0 ELECTRICAL

The electrical "brain" concept was designed to maximize the portability and 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 chasses. 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 additional communication lines can be added for redundancy.

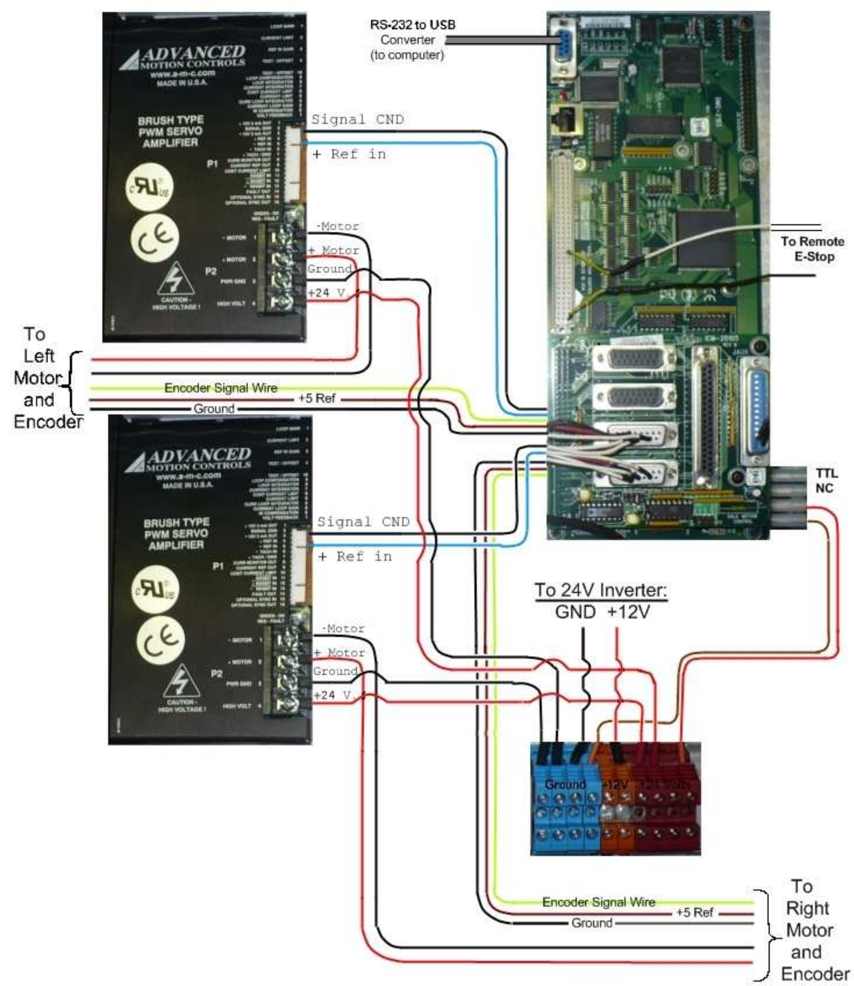


Figure 5: Wiring Diagram for CAT Motion Controls

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 a switch. A port on the side of the vehicle further allows for the batteries to be charged without opening the cab.

6.0 SENSORS

The primary considerations for sensor selection were cost, power consumption, and reliability. At least two of these criteria were met with each sensor that was selected.

6.1 Stereo Vision Camera

CAT uses an off-the-shelf stereo vision camera, the Bumblebee 2, 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 6. 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 an Intel Core 2 Quad, running OpenCV on Windows XP.

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 indicating closer patterns. These disparity values are converted to an orthogonal distance from the camera, and attached to each pixel.

Consequently, however, objects which are closer take a longer time to process, since more of the image must be searched. The processing time increase, with respect to the proximity of the object, is exponential. Thus, in order to process approximately ten frames per second, objects closer than two feet are ignored. This reduces the search space of the disparity measuring algorithm, which significantly increases performance. This increased data throughput means that obstacles can be detected and mapped more reliably, which compensates for the lack of proximity. Ultrasonic sensors are used to detect obstacles within two feet.

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 6: 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. Unlike the heading provided by the GPS unit, which only works when travelling at appreciable speeds, the compass works best at low speeds. Thus, a combination of the two provides a more accurate heading.

6.3 Ultrasonic Range Finder

A low cost ultrasonic range finding solution for obstacle detection is also used. This expands the field-of-view of the vehicle and can sense objects closer than the stereo vision system.

Each sensor has an effective range of 0.15 to 6.45 meters with a 26 degree conical coverage beam. The vehicle utilizes six of these 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. However, they are also less reliable. Thus, for the most part, they provide redundancy, and act as a failsafe should the stereo vision miss an object.

The ultrasonics are multiplexed through an embedded board, and sent via RS232 to the main computer. The ultrasonics are much more susceptible to interference, especially from each other. Thus, the embedded board cycles through each of the ultrasonics systematically, to ensure that no two ultrasonics ping at the same time.

Previously, the ultrasonics were interfaced via an analog voltage signal. However, in further testing, it has been determined that the motors and amplifiers on the vehicle were inducing an electromotive force that added noise to these signal lines. This year, the signals were modified to be sent digitally, to avoid this problem.

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

The main computer is responsible for the stereo vision correspondence, analysis, and decision making and interfacing functions. It runs Windows XP on an Intel Core 2 Quad processor.

Peripheral devices, such as the GPS, ultrasonics, compass and motion controller interface the computer via RS232 to USB converters. This allows virtually any computer to be substituted for the one chosen, if so desired for future design iterations or project derivatives.

Since the computer also acts as a human-machine interface, a Windows-based platform seemed a natural fit. Furthermore, the Point Grey libraries used in the stereo vision processing are readily supported on Windows platforms, whereas support for Linux platforms is much less available.

The computer can be interfaced by using a remote connection program, such as a VNC client, or by simply plugging a monitor and keyboard into the computer via standard VGA and USB interfaces.

8.0 SOFTWARE STRATEGY

All of the software on the main computer was written in either ANSI C or C++, using basic Windows functionality available in virtually all modern Windows platforms. Thus, the code can be easily transferred between different Windows devices, or ported to a different operating system by only changing certain function calls.

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. The processes are tied to different cores of the processor using processor affinities, which allows the Windows scheduler to override the core recommendations if deemed necessary.

When the image capture thread receives a new image, a software interrupt is triggered, and the data copied between processes. Inter-process communication is achieved through software interrupt events and critical sections, as they have a significant performance boost of conventional semaphores.

9.0 SIGNAL PROCESSING

Images from the Bumblebee stereo vision camera are received by the main computer 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.

Furthermore, the code used to communicate via RS232 and TCP/IP was custom programmed using C++ for Windows environments. Thus, any embedded Windows environment with the minimal resources available should be able to run this code, without .NET or other runtime libraries.

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 is steeper than 15 degrees, it is considered an obstacle. Otherwise, it is clear.

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 based on ultrasonic input, 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 7, 8 and 9. 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. The quality of this fit is used to weight the current slope of the line.

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, even if it cannot be seen.

Figure 7: Drivable Region

Figure 8: Color Reduced Drivable Region

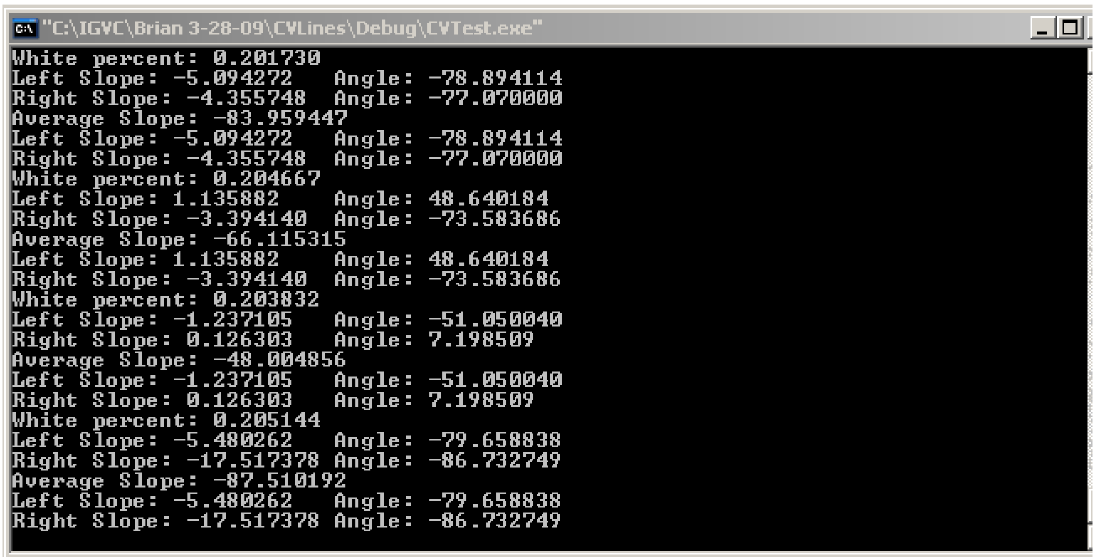


Figure 9: Results from Line- Fit Calculation

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 execution of waypoints is seen in Figure 10.

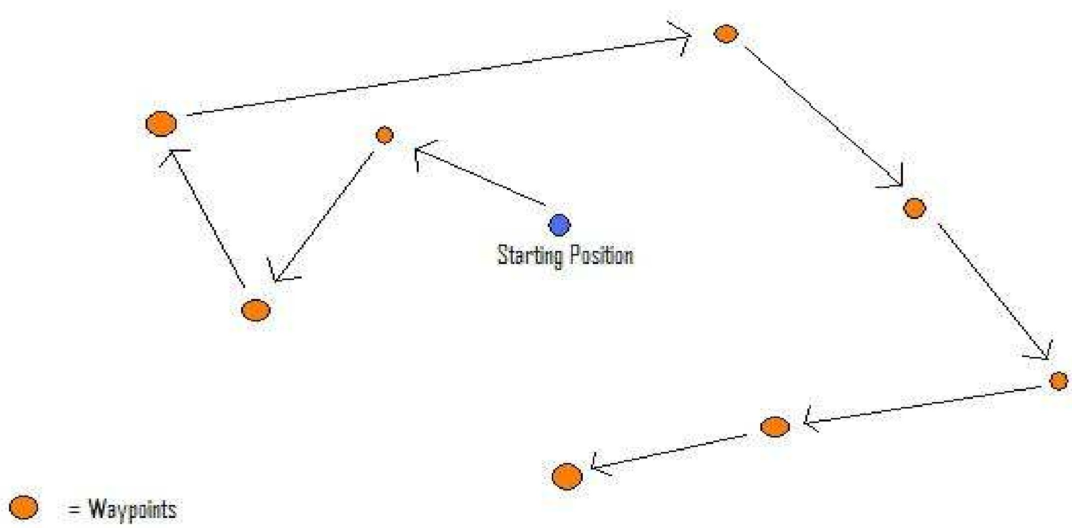


Figure 10: Waypoint Navigation

10.0 PLAN FOR PATH AND CONTROL DECISIONS

Regions seen by the stereo vision camera are classified by obstacle type: known obstacle, probable obstacle, no obstacle, or unknown. These values are then projected onto the two-dimensional plane of the field. The computer processes this information, looking for gaps between known obstacles. Gaps nearer the direction of the lane are more heavily weighted. Once the vehicle determines a gap it should follow, the updated angle is sent to the motion controller.

Ultrasonic rangefinders are further used as soft limit switches, preventing the vehicle from running or turning into an obstacle which may be located outside of the field-of-view of the stereo vision camera.

A new improvement this year includes an active control system to keep the vehicle driving in its desired direction. Previously, the vehicle would stop its forward motion and pivot to face the new direction. This year, a PID loop uses compass feedback to ensure it is driving in the desired direction. However, if obstacles are located in sufficiently close proximity to the vehicle, the zero-turning radius is still used to avoid hitting an obstacle.

11.0 ANALYSIS

Test procedures concerning the ability of CAT to follow lines, reach specified GPS waypoints, and avoid obstacles, in various conditions, are still to be performed. The individual components responsible for the success of these aforementioned operations, including GPS, the digital compass, ultrasonic and stereo vision sensors, and communication with the Galil motion controller, have been individually simulated and tested in a lab environment, and limited tests with these sensors fully integrated on the vehicle have indicated that there are at present no electrical, mechanical or other interference issues. However, CAT has also been designed to meet certain speed and battery life specifications, as explored below.

11.1 Speed

With the compact size of the chassis and the power of the motors, CAT's maximum speed is approximately nine miles-per-hour, but for this competition it will be set and limited to five miles-per-hour. 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 computer.

11.2 Battery Life

When constructed and tested, two Optima batteries were utilized to provide sufficient power to the robot and all its components. Running at constant speed while fully loaded, battery life is estimated at about four hours, and standby time at about ten hours. This exceeds the desired two hour runtime, deemed necessary to perform adequate testing during development.

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	$1,595.00
Expansion board w/ interconnecting module	$0	$195.00
Galil Axis amplifier	$0	$795.00
2 Advanced Motion Controls Servo Amplifiers-	$0	$1,050.00
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	$5,495.00
Bumble Bee Stereo Vision System	$2,000.00	$2,000.00
Rims and Tires	$320.00	$320.00
Linksys Router	$0	$35.00
Gigabyte Motherboard	$985.00	$985.00
Aluminum Material	$700.00	$700.00
USB to serial converter	$0	$20.00
Voltage regulator	$0	$30.00
Total amount paid for components	$5,680.00	$14,145.00
Total hours spent this year	11,460	