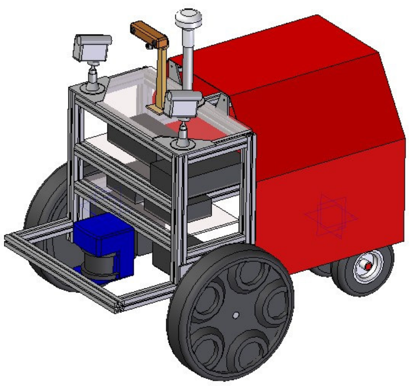
BEARCAT CUB

Design Report

The 14th Annual Intelligent Ground Vehicle Competition
Selfridge Air National Guard Base, Harrison Township, Michigan
June 10-12, 2006



Submitted by:

UC Robot Team
Center for Robotics Research
University of Cincinnati
Cincinnati, OH 45221-0072
www.robotics.uc.edu

UNIVERSITY OF Cincinnati
CENTER FOR ROBOTICS RESEARCH

1. Introduction

The University of Cincinnati Robot Team has continued design and improvement of the Bearcat Cub, our robot, specifically for the Intelligent Ground Vehicle Competition (IGVC) with the possibility of competing elsewhere. The Bearcat Cub is an intelligent, autonomous ground vehicle that provides a test-bed system for conducting research on mobile vehicles, sensor systems and intelligent control. The purpose of this report is to describe the conceptual design of the vehicle, its components and highlight the unique innovative aspects of our design process.

This report is organized as follows: Section 2 describes the design process and team organization; Section 3 describes aspects of the various electrical systems of the robot including the emergency stop, digital compass, motion control electronics, servo motors, the sensor systems, the laser measurement system, vision systems and global positioning system; Section 4 describes design of the mechanical system including the frame to give a lower center of gravity, adding an additional rear wheel to increase roll stability, and a mechanical brake system; Section 5 describes the software that controls the functions of the robot as well as discussing the obstacle detection and avoidance, the line following, and way point navigation algorithms. Section 6 describes system integration; Section 7 describes the safety and reliability issues. A bill of materials is given in the appendix.

2. Design Process and Team Organization

The Bearcat Cub has involved senior design teams since 2002. It has evolved through the past few years following the Kaizen philosophy. This year we continued in the continuous improvement way, we: redesigned the E-stop, added mechanical brakes and a digital compass, added functionality to the stereo vision system, manual control and GPS systems. Project management fundamentals were used to ensure our success in the endeavor.

The process began by defining the project. What requirements were we to meet? How would we define success? How do we balance cost, schedule, and quality? How will the team be organized? Who will hold what responsibilities? How will communication be conducted? How will progress be measured?

Next, we began the planning process. Here we identified risks, developed response strategies, and designed a project control structure. Gantt charts were used to define the work breakdown structure and track progress. This also provided visualization for scheduling so we could plan for realistic time requirements to accomplish tasks.

Tasks	Start Date	End Date
Mechanical		
Added additional rear wheel for stability	10/15/05	10/16/05
Lowered center of gravity	10/16/05	10/20/05
Created laptop mounting system	3/4/06	4/4/06
Reorganized power sources	3/5/06	3/15/06
Created mechanical emergency braking system	12/10/05	06/9/06
Mounted Bumblebee stereo vision system	4/20/06	4/21/06
Electrical		
Rewired e-stop box for redundancy	5/1/06	5/21/06
Rerouted electrical wiring	5/2/06	06/9/06
Implementation of digital compass hardware	5/19/06	06/9/06
Software		
Remote desktop experimentation for JAUS	4/23/06	06/9/06
Modified GPS system input	5/23/06	5/30/06
Improved vision system algorithms	10/5/05	06/9/06
Developed autonomous challenge solution using stereo vision	10/06/05	06/9/06

Table 1. Achievement chart used during development this year

To aide in controlling the project, special focus was given towards communication. The team used resources such as frequent emails and weekly team meetings. This year, extensive use of online groupware kept digital documents organized along with experimentation of remote desktop, for development of long distance control of the Cub. Webcams set up throughout the lab enabled viewing of lab progress and robot motion.

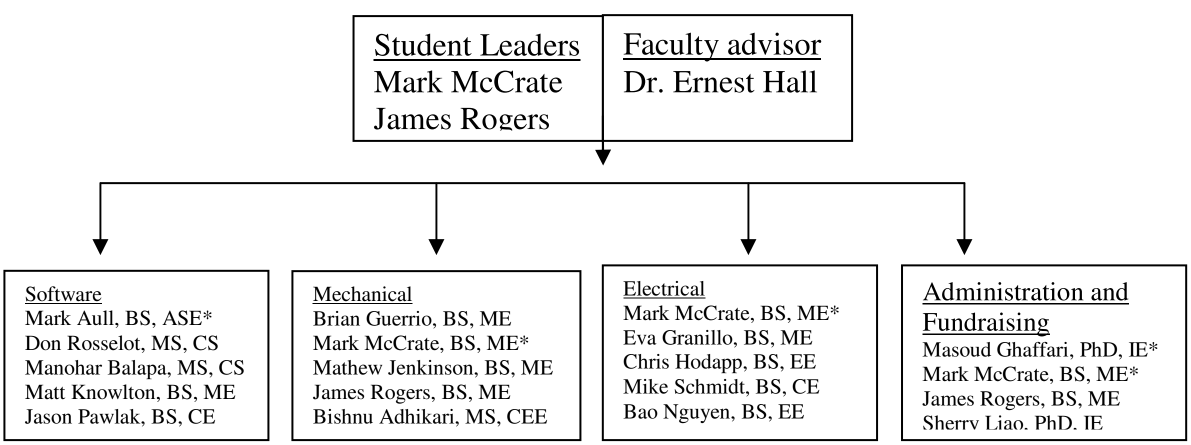


Figure 1. Function-driven team organization (* indicates group leader).

Finally, the team organization was chosen to be function-driven (Figure 1). The team is organized around primary functions such as software or mechanical design. This structure was effective since group members were assigned to work within their own background.

2.1. Innovations in the Design

Several innovations have been made in the Bearcat Cub design since last year.

- Dead Reckoning system established
- Mechanical Breaking System
- Laptop Bay

3. The Mechanical System

The mechanical system of the robot includes its external frame, wheels, brakes, and motor system. It has been designed and constructed in order to be strong and fast yet light-weight and durable.

3.1. Robot frame

The frame is made of 80/20 aluminum extrusions in order to have a light weight structure without compromising strength. The junctions are made using small joining strips at the ends or by utilizing corner brackets which sit inside the joints. The advantage of using this frame concept is that it can be easily reshaped if new components are to be added. Stress and weight calculations for the joints were carried out using a safety factor of 125%. A drawing of the basic structure is shown in Figure 4.

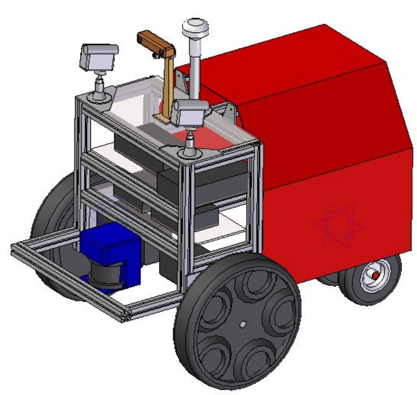


Figure 4. Basic robot structure

3.2. Wheels, Brakes, Motor and Gears

The Cub's mechanical system utilizes two types of wheels – two main drive wheels and a dual rear castor wheel. The main drive wheels are 19" diameter enhanced traction wheels designed by Michelin for the Segway Human Transporter. The rear castor wheel helps improve the stability of the robot during turns such as those with a zero turning radius. This 8", 90 series, dual castor wheel, is from Borne & Co. Since the drive wheel size is 19" and the maximum speed of the robot is 5 miles/hour, a frictional coefficient of 0.125 and a gearbox efficiency of 70% have been used to calculate the required gear ratio. A gearbox with a gear ratio of 25:1 was selected and obtained from Segway. The required motor power has been found to be 1.355 hp per motor. Two Pacific Scientific PMA43R-00112-00 2 hp brushless servo motors have been selected for providing power. The gearbox and motors have been selected based on the calculated values. The robot's power system can utilize a maximum of 2 Honda EU-2000i, super quiet generator sets, however a single generator set has proven to provide 4 ½ hours of continuous power. The advantage of having a generator set in place of batteries is that there is less down-time after losing power, since refueling the generator set is much quicker than recharging a battery.

To comply with the new rules for this year's competition mechanical brakes have been added. Designed statically and kinematically in NX 3.0 the brakes are fail-safe in nature, that is when power is cut from electromagnetic magnets multiple springs provide nearly 80 pounds of force to the drive wheels. Dynamics calculations indicate, and tests have verified, this ensures a top speed to full stop in 3 feet on a level ground in a dry environment.

4. Electrical and Electronic Systems

The electrical systems of the Bearcat Cub consists of a motion controller, 2 amplifiers, 2 DC brushless motors, 2 digital cameras, ISCAN vision processing hardware, bumblebee stereo vision camera, a laser scanner, GPS unit, digital compass and an emergency stop. All power is provided by a Honda GenSet and/or marine battery. This allows the Bearcat Cub to be outfitted with any set of sensors very easily since there is no need for the end user to customize any electronics. The system acts like a hardware equivalent of software plug and play. Figure 5 below shows the general electronics layout.

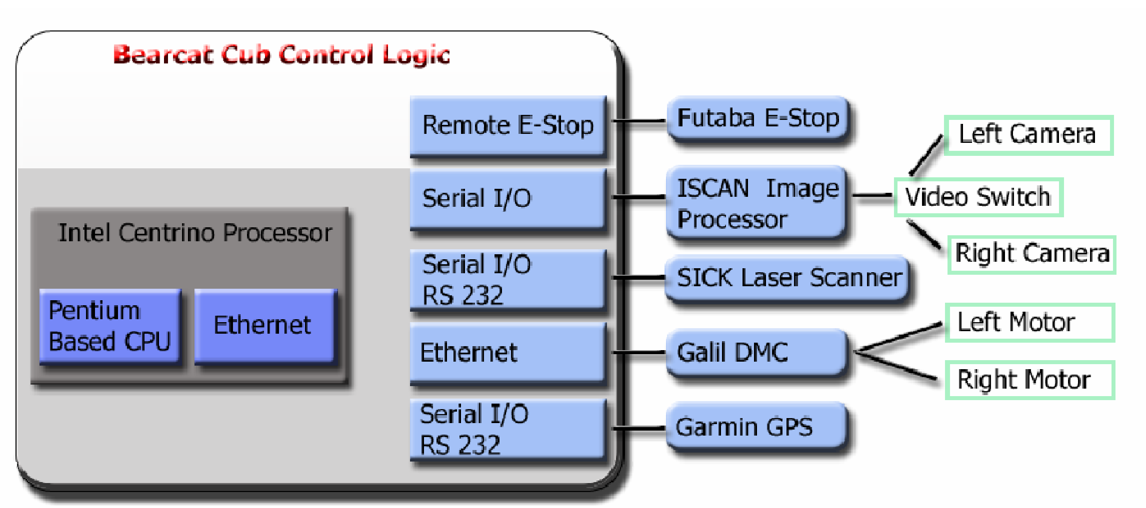


Figure 5. Bearcat Cub block diagram

4.1. Emergency E-stop

Safety is of primary importance on the Bearcat Cub. System operation can be halted in 3 separate ways. A Futaba remote control can be used to cut power from all systems via an FM signal capable of transmitting from 65 feet away. Second a manual, large red laboratory standard, emergency power kill switch is located on the back of the Bearcat Cub in case the remote should fail. Also of note the emergency stop is kept from tripping via an active high signal which ensures that, if ever a case arose when power was not delivered to the emergency stop, the system would automatically stop. Finally an abort command can be sent via the 'A' key on our wireless joystick controller. This kills the current process in software allowing a user to check all systems and determine what may have caused a problem without losing system data. Also, the E-Stop is designed with redundant systems incase vibration etc compromises electrical connections.

4.2. DMC Motion Controller

The Galil DMC 2130 motion control board is the motion controller used for the Bearcat Cub and it is controlled through commands sent via an Ethernet connection from a laptop. Copley amplifiers deliver power to the motors after amplifying the signals they receive from the motion controller. Steering is achieved by applying differential speeds at the right and left wheels. The vision system used for obstacle avoidance sends data to the computer which is processed by the software and then used to generate commands to the motion controller to change the differential speeds of the two motors. The Galil motion controller was chosen because it is web based, has PID and Bode plot tuning software, and is compact and enclosed in a durable package. The controller can accommodate up to 4 axis formats and can control stepper or servo motors on any combination of axes. The Bearcat Cub has the ability to turn about its drive axis effectively performing a Zero Turning Radius (ZTR) pirouette. The block diagram of the system is shown in Figure 6.

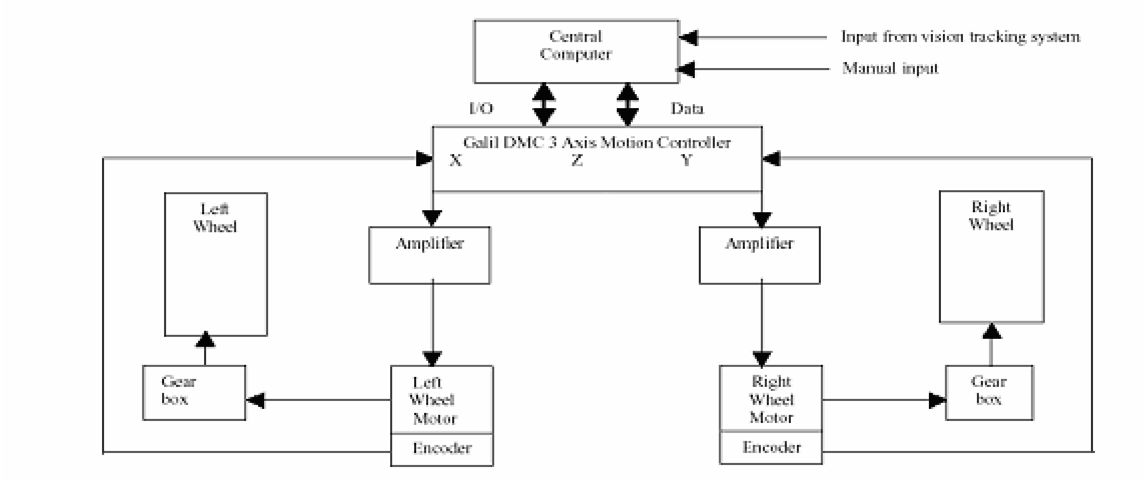


Figure 6. Motion control system

4.3. Sensor Systems

4.3.1. Laser Measurement System

The Sick LMS 200 scans a 2-dimensional plane of 180 degrees at ½ degree increments and returns obstacle distance measurements for up to 8.191 meters based on laser time of flight. The laser scanner has the capability to scan at a variety of angular ranges and resolutions. The range and resolution of the laser scanner can be changed easily since the system is designed to deal with variable sensory data input.

4.3.2. Vision System

Two video cameras, the right and left cameras, provide the images that are used by the line detection system. The cameras used by the Cub are Sony handy cams. Each camera has its own LCD monitor. The images from the two cameras are fed into a digital video switch using standard Audio-Video cables, and the video switch outputs only one of them at a time. The output is toggled between the right and left cameras based on an input bit from the Galil motion controller which is set and cleared via a command from software. The switch allows the ability to use the output from the other camera if the first camera loses sight of the line. An ISCAN RK447-BMP external image tracker is used which computes the center of the brightest area within a region of the image and returns the image coordinate of the center point at a 30 frame per second rate. Two such points in the image are found, and the corresponding real-world points are computed in software via a linear transformation utilizing camera calibration information. The line detection system then receives the real-world points and uses them to follow the line.

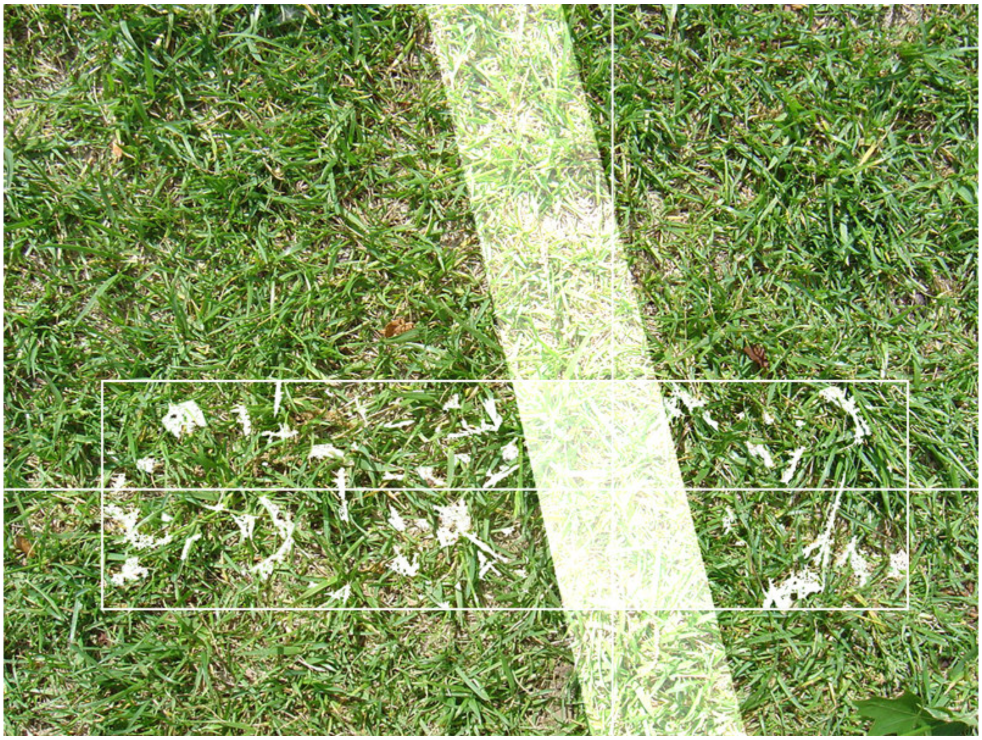


Figure 7. The vision processor locating the centroid of a bright region

4.3.3. Global Positioning System (GPS)

A commercially available GPS system has been used for the Bearcat Cub. The main criteria for selection are Wide Area Augmentation System (WAAS) capability and embedded navigation features. The Garmin 76 has these requirements and has been selected for implementation. The GPS unit tracks the NAVSTAR GPS constellation of satellites. The signals are received by an antenna and are tracked with 12 parallel channels of L1. C/A code is then down converted to an IF frequency and digitally processed to obtain a full navigation solution of position, velocity, time and heading. The solution is then sent over the serial link via the 9-pin RS 232 connector. The unit communicates with the laptop in NMEA format. Garmin's computations are utilized as much as possible to alleviate Pentium computations.

4.4. Servo Motors

The Bearcat Cub uses DC brushless servo motors PMA43R-00112-00 provided by Pacific Scientific. Brushless motors are small and powerful and efficient for servo controls. The servo feedback is provided by encoders mounted on the motor shaft and is used to compute an error signal to the controller. The compensated signal is sent to the motor to turn the robot. The difference between the actual position and position reached is the error signal. This signal is modified by a PID digital filter compensator that is designed for stability and accuracy. Thus, the servo motors are designed to achieving minimal error and maximum accuracy. Having the ability to set PID parameters directly on the controller also allows the

Bearcat Cub the flexibility of different controller responses for different environments. For stepper motors, no encoder is present as it sends signals only in steps.

5. Computer System

A Dell Latitude D800 laptop is the central processing unit of the Bearcat Cub. It processes data from the laser scanner, GPS, motion control system, digital compass and image processing system. The software has been executed on the Dell Laptop running Windows XP. Software has been written in both C++ and C# taking advantage of the .NET Framework where applicable. A user friendly GUI was developed to track the Bearcat Cub's movements and positions. A series of initialization files hold all calibration values and initial values for the system parameters.

5.1. Obstacle Detection and Avoidance

Obstacles are detected by scanning the data returned from the laser scanner and checking for values less than a user defined maximum obstacle distance. Sensor fusion plays a role, laser data can be verified by data gathered using PointGray's Bumblebee hardware and our in-house vision algorithms. The distance at which the user wishes to detect obstacles is defined in a user GUI. Each set of data returned by the laser scanner is scanned for values less than the maximum obstacle distance, if a smaller value is found then the software continues to check values until a value is found that is greater than the maximum obstacle distance or the end of the data is reached. Any section of data that is found to be less than the maximum obstacle distance is used to create a data structure representing an obstacle that is described by a two angle and distance pairs for the left and right edges.

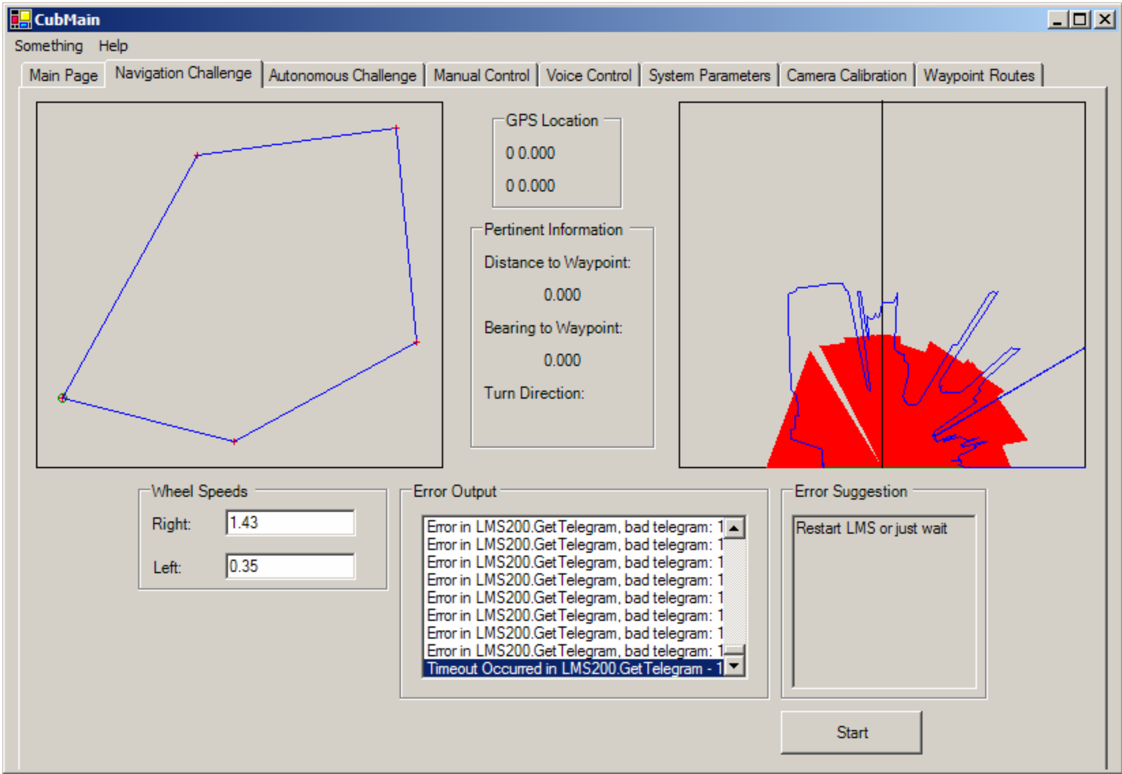


Figure 8. Graphical output for the Navigation Challenge

The obstacle avoidance system then widens the edges for each obstacle by half the robot's width plus a specified safe distance, thereby finding the minimum angle the robot must steer to safely avoid hitting the obstacle. The system then throws out the safe angles that overlap, grouping overlapping obstacle regions together. The safe angles that bound the obstacle regions are then compared, and the angle which causes the robot to deviate the least from the desired bearing (i.e. the bearing to waypoint in the Navigation Challenge) is selected. Figure 9 shows this process in action, with the blue dot representing the next waypoint.

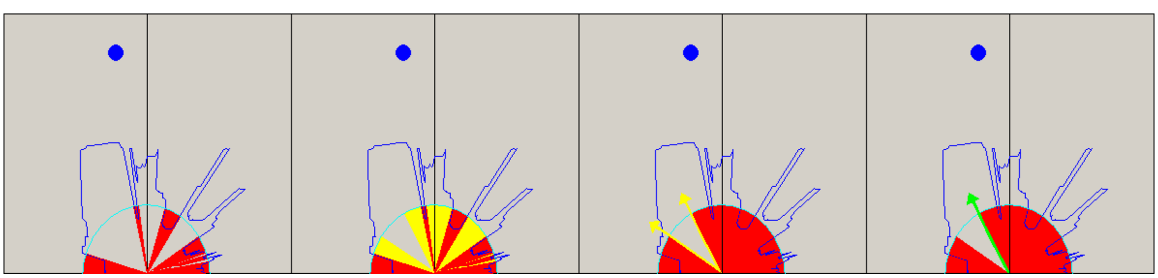


Figure 9. Selecting the proper angle to steer through a cluttered environment

5.2. Line Following

For the line following competition, the Bearcat Cub has been designed to negotiate an outdoor obstacle course in the minimum time while staying within a 5 mph speed limit and avoiding obstacles. The line following system receives as input a line from the line detection system and a series of obstacles detected by the obstacle detections system. The line is first abstracted as a wall obstacle, and then added to the list of other obstacles. The desired angle to steer the robot through the course is then calculated using the algorithm described in Section 5.1. Figure 10 shows the graphical output from the line following system. On the left, the line (in red) with respect to the robot (in blue) is shown as detected by the line detection system. The right graphic depicts the region to avoid for the line obstacle in yellow, with the regions for the rest of the obstacles in red.

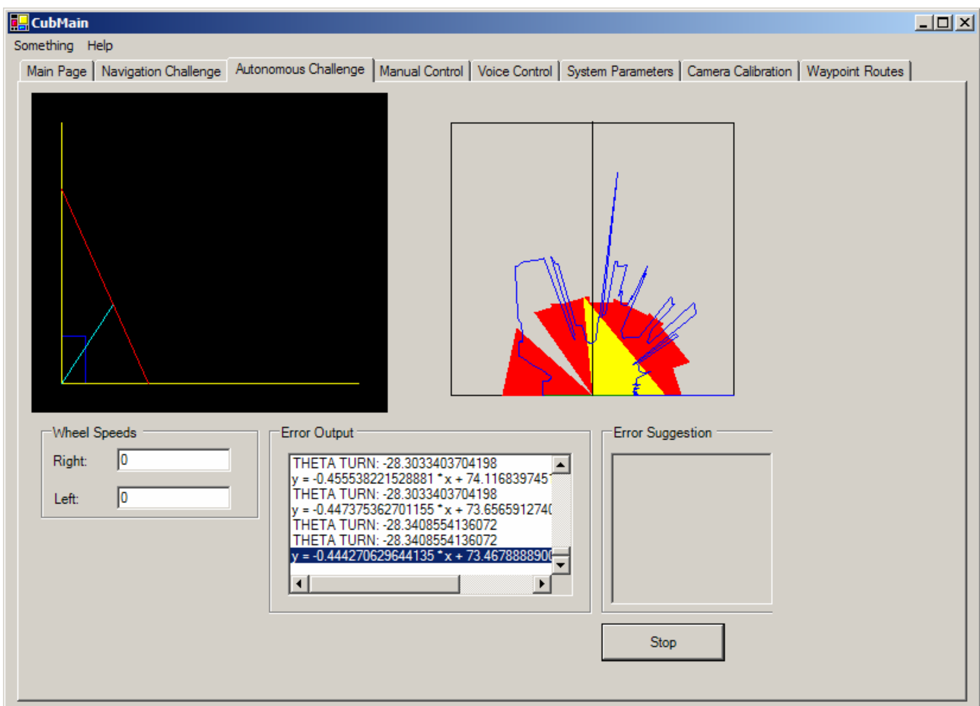


Figure 10. Graphical User Interface for Autonomous Challenge

5.3. Waypoint Navigation

Global Positioning System (GPS) technology provides the basis for waypoint navigation in the Bearcat Cub. The classical closed feedback control loop was utilized in the modeling of the navigational challenge problem with an input command, feedback signal, error signal, and output transfer function characteristics. The target waypoint destinations are specified as the input command and the feedback signal is provided by the GPS unit based on its position with reference to satellite data. Using the current position co-ordinates and velocity the GPS unit provides bearing, tracking, signal validity and range from the target waypoint to determine the error. The bearing to the waypoint is passed to the obstacle avoidance system, which then determines the best path to the target while avoiding any nearby obstacles and returns the safe bearing. The Waypoint Navigation sends the new bearing to the motion control system, which translates the commands into motor control voltages that steer and propel (right, left or stop) the robot on the course. Once the target range has been reduced to the required tolerance, the robot has reached its target destination waypoint. The process continues for all the waypoints in the input file finally returning the robot to the starting point. To comply with the new requirements for the 2006 competition a dead reckoning algorithm has been written to compute range and bearing data between GPS updates. While the robot is navigating its route between waypoints, the system graphical user interface (Figure 8) displays current information regarding the robots current position, the map of waypoints, the field of view from the obstacle detection system overlaid with red for all areas where the robot cannot go, and any appropriate error or feedback information.

6. System Integration

The run-time system sensory input consists of two digital cameras, an image processor, a laser scanner system, a GPS unit, and in certain cases a joystick for manual control. The software allows initialization information that is input before the autonomous system begins operation in order to properly calibrate various parts of the system. The output is commands to the motion controller will set the speeds of the two independent drive wheels. The system will use the input information and apply various algorithms to determine the proper course of action, based on the current competition, and output the motion commands to the motion controller.

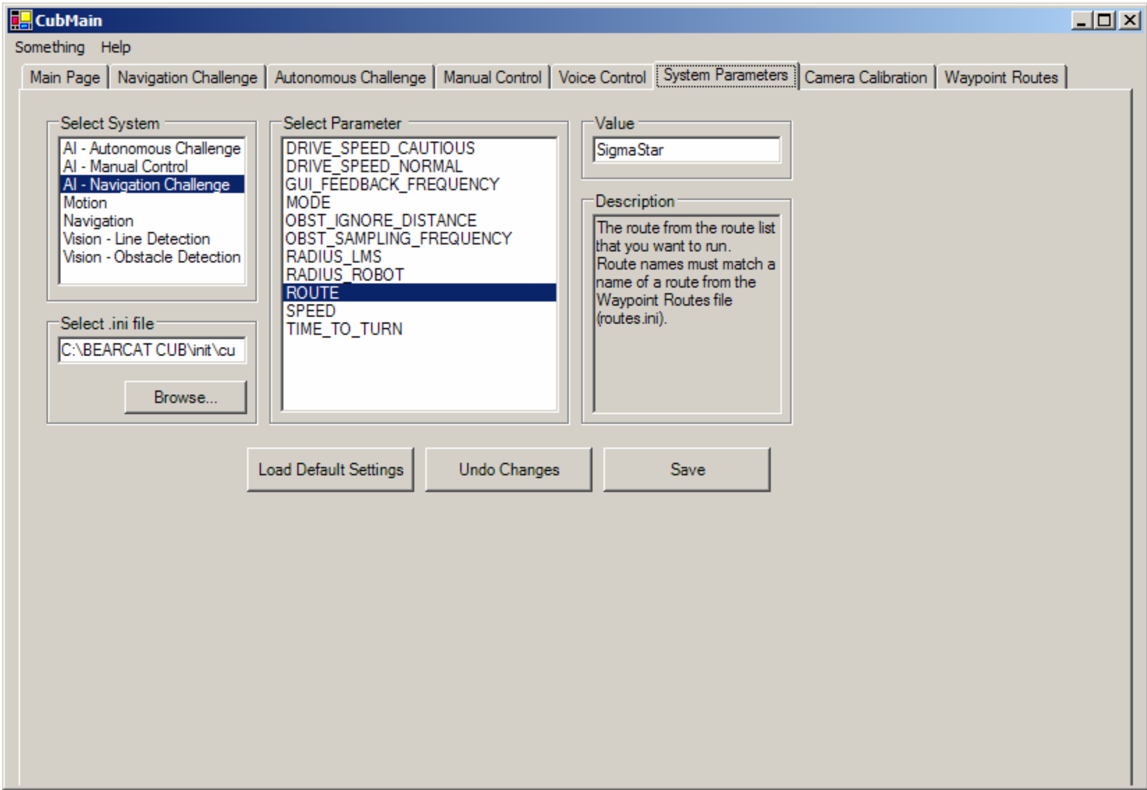


Figure 11. Screenshot of interface for conveniently initializing system parameters

7. Safety and Reliability

There are four different safety systems built in to stop the robot: manual e-stop, remote control e-stop system capable of stopping the robot from a range of 65 feet, joystick "full-stop" button, with a range of 30 feet and mechanical brakes. Joystick "full-stop" can be used to pause and continue software functionality, while use of the primary e-stop necessitates a manual reboot of the system. The drawbacks to the secondary e-stop are its range and its reliance on the software to be functioning properly in order to work. The primary remote e-stop will work regardless of the state of the software or any other device on the robot and controls engagement of the mechanical brake. A disconnect switch can also cut off all power to the robot. The generators have hazards from both internal combustion and electric powered systems but they come with built in overheat, over power and power surge protection.

Reliability of an autonomous robot can sometimes be difficult to predict. However, we have tried to be as thorough as possible in our testing strategies, and the Cub has performed very well. The emergency stop systems are available to quickly and reliably stop the robot if it starts to misbehave. Front bumpers are present which reduce the impact of physical shocks from reaching the stereo vision and cameras mounted on the robot. All circuits have been color coded to ensure proper reconnection with the black wires used for ground.

8. Performance

The performance for key requirement is shown in Table 2.

	Task	Requirement	Measured
1	Line following	Solid and dashed lines, white or colored, left or right	Accuracy 0.5 inch
2	Obstacle avoidance	Detect and turn	Detect and turn
3	Pothole detection	2 foot diameter	2 foot diameter
4	Waypoint detection	5 foot radius	3 foot radius
5	Emergency stop	50 foot range	65 foot range
6	Turning radius		0 degrees
7	Maximum speed	5 mph	5 mph
8	Ramp climbing ability	15 degrees	20 degrees
9	Braking distance	6 feet	3 feet

Table 2. Comparison of requirements and measured performance

9. Conclusion

The Bearcat Cub avoids obstacles successfully with our laser scanner and stereo vision. The robot is also able to use the GPS to recognize and find given waypoints. The vision system allows the robot to detect the brightest spot from images and drive within the boundaries between two lines. All functionalities have been tested repeatedly to meet the contest requirements. The robot hardware cost $23,135 and a bill of materials is shown in Appendix 1. This cost does not include travel costs or the cost of the more than 1200 person-hours spent designing and building the robot.

Acknowledgement

The team is grateful to the industry sponsors: Student Organization & Activities, Graduate Student Association, Control Think, Society of Manufacturing Engineers, General Electric, Procter & Gamble, UC Alumni Association, Little Tikes, ROV Technologies, Cincinnati Test Systems and the MINE Department; the College of Engineering and the University Vice President for Research and individual sponsors: Karen Davis, Ernie Hall, Larry Ruess, Randy Allemang, Doug Smith, Robert Hous, Jack Judge, Ron Tarvin, Sandra Degen, Larry Genskow, Joe Nurre, Don Rosselot, Sherry Liao, Kavita Sastry, Dinesh Manthena, Peter Cao, James Fraley and many individuals for their efforts in making this robot design and building process a success.

CERTIFICATION

I certify that the engineering design in the vehicle Bearcat Cub (original and changes) by the current student team identified in this Design Report has been significant and equivalent to what might be awarded credit in a senior design course.

Ernest L. Hall, Paul E. Geier Professor _________________________

Faculty Advisor to the UC Robot Team

APPENDIX 1

Part	Manufacturer	Model No	Price
Frame	80/20 Inc.	Custom design	$1,100
Generator	Honda	EU 2000i	$778.00*2=$1556
Motors	Pacific scientific	PMA43R-00112-00	$970.00*2=$1940
Amplifiers	Copley Controls Corp.	Xenus Servo Drives XSL-230-36	$768.00*2=$1536
Drive Wheels	Segway	Enhanced Traction	$188*2=$376
Gearboxes	Segway gear-box	HT design, 25:1 gear ratio	$688*2=$1376
Castor wheel	Borne	8 inch, 90 series, castor wheels	$100
Laptop & accessories	Dell	2.2 GHz P4 HD: 60GB4 Ultra ATA/100 7200RPM 512MB DDR SDRAM	$2,500
ISCAN image processor	ISCAN Inc.	RK447-BMP	$3,200
Camera switcher	FSR Inc.	CCSU-8 BW	$1,541.00 Donated
Cameras	Sony	PV-DV51	$419*2=$838
E-stop	Futaba	FRF-0302U	$321
Motion controller	Galil Inc.	DMC-2130 web based	$3,900
Camera mounts	Pelco	PS7-24,PT270P	$300
GPS	Garmin	Garmin 76	$251
Stereo vision	PointGrey Research	Bumblebee	$2,000
Cover	Sheet Metal	Square D	$300
Digital Compass	Honeywell	HMR3300 demo-232	$400
TOTAL			**$23,535**