

BEARCAT Brat Design Report

11TH INTELLIGENT GROUND VEHICLE COMPETITION

AT OAKLAND UNIVERSITY IN ROCHESTER, MICHIGAN; JUNE 2, 2003



Submitted by -

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Bearcat Brat Design Report 2003 – University of Cincinnati

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1. INTRODUCTION

The Bearcat Brat is an interactive, intelligent, Autonomous Guided Vehicle (AGV) designed to serve in unstructured environments. As our first step in reaching our objective, we have made steps to compete in the 11th Intelligent Ground Vehicle Competition at Oakland University, Rochester, MI. This contest provides active challenges in real world faced in most AGV applications. The design of the Bearcat Brat facilitates to perform all the tasks and obey all of the rules required for this contest. This report describes the evolution of the Bearcat Brat from its predecessor, the 2002 Bearcat III. The report organization is as follows. Section 2 gives detailed description of the team organization and design process. Section 3 gives design innovations, features and enhancements. System design and integration issues are described in Section 4 with emphasis on line following, obstacle avoidance, waypoint navigation, overall system integration, safety and reliability systems. Section 5 and 6 outlines the Performance prediction and the results. The appendix I shows the bill of materials.

2. TEAM ORGANIZATION

2.1 UC Robot Team

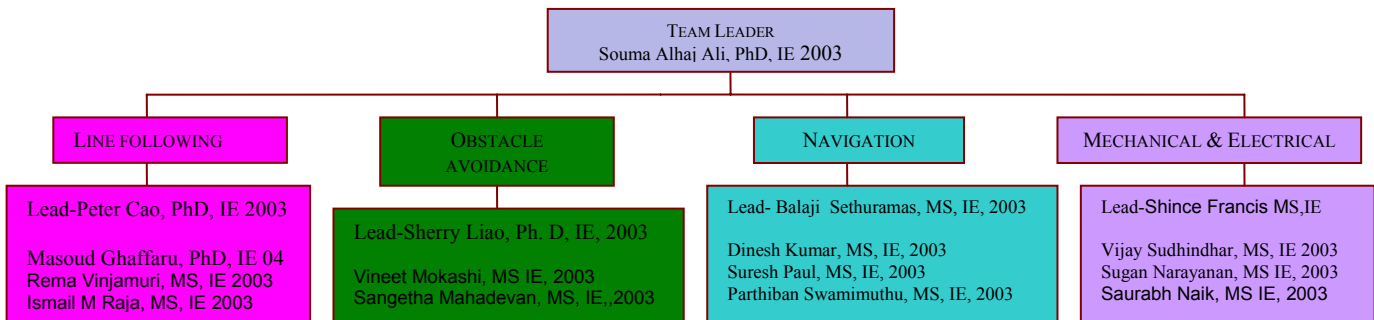


Figure 1: Year 2003 UC Robot Team

The UC robot team is a part of Center of Robotics Research at the University of Cincinnati and consists of undergraduate and graduate students from mechanical, industrial, systems and computer engineering fields. Starting from September 2002, students participated in the weekly meetings during the year, and actively contributed towards the progress of the design. The team members designed, constructed, tested and refined the individual subsystems of the vehicle, based on their areas of expertise and interests.

2.2 Design Process

Design approach followed Kaizen philosophy of continuous improvement. Our progress through several sessions of brainstorming issues related to the radical improvement of the system. A To-Do list required for the enhancements of the Brat including the reduction of I-Scan into a smaller unit. Our previous I-Scan tracker used was a 10-year-old model. Research on the structural changes and cameras showed sufficient reduction in size and in using newer cameras.

Project Schedule

	Days	Vision Calibration		GPS		Obstacle Avoidance		Testing	
		Estimated	Actual	Estimated	Actual	Estimated	Actual	Estimated	Actual
August	31	0	0	0	0	0	0	0	0
September	30	0	0	0	0	0	0	0	0
October	31	31	5	0	0	0	0	0	0
November	30	15	15	15	10	0	0	0	0
December	31	0	20	31	5	0	0	0	0
January	31	0	0	0	31	30	0	0	0
February	28	0	0	0	0	15	15	0	0
March	31	0	0	0	0	0	25	31	0
April	30	0	0	0	0	0	0	30	5
May	31	0	0	0	0	0	0	31	20

	Days	Market Study		Researching Options		Vendor Interactions		Fund Raising	
		Estimated	Actual	Estimated	Actual	Estimated	Actual	Estimated	Actual
August	31	15	0	15	31	0	0	10	20
September	30	0	18	0	12	0	0	10	15
October	31	0	2	0	0	0	0	10	0
November	30	0	0	0	0	15	10	10	0
December	31	0	0	0	0	0	0	10	25
January	31	0	0	0	0	0	0	10	15
February	28	0	0	0	0	0	0	10	0
March	31	0	0	0	0	0	0	10	0
April	30	0	0	0	0	0	0	0	0
May	31	0	0	0	0	0	0	0	0

2.3 Design Strategy

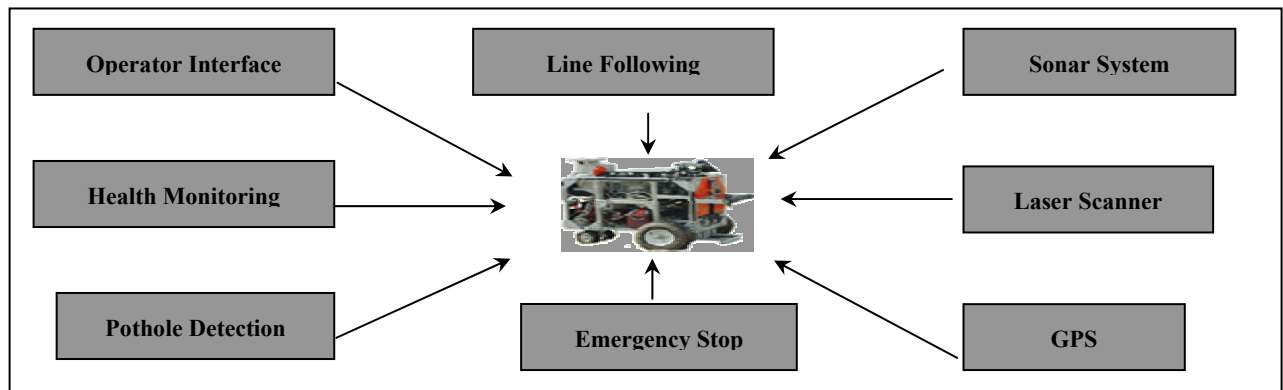


Figure 3: Major Sensor Control Systems

The design strategy was based on scheduling and working within progress deadlines. The system decomposition is carried on until all concerns reach the individual component level. These components were then designed,

integrated to form major sub-units and ultimately, on further integration, lead to the entire system. The vehicle can be broadly decomposed into a number of major sub-systems as shown in Figure 3. The basic criteria of simplicity, reliability, durability, safety and adherence to the rules of the contest were the guiding principles in the entire design process.

3. BEARCAT BRAT DESIGN ENHANCEMENTS

Bearcat Brat has several innovative design features. Like its predecessor, the 2002 Bearcat III is a modular design kit. The components used were off-the shelf and can be bought and assembled in a short time. Sufficient research was made to maintain the commercial aspect of the design, involving market key products, warranty issues of product life and quality concerns of products. We felt that the first step for marketability of an AGV is the reliability of the system and availability of fault diagnosis for the parts used. The new design innovations and features are as follows:

3.1 Navigation Systems:

The Navigation System of Bearcat Brat uses an innovative logic to process the global and local information simultaneously for accurate waypoint navigation. Global navigation data from a Differential GPS (Garmin-76) and local point-to-point navigation data from the wheel encoders are combined. The accuracy of the data from Differential GPS depends on the signal strength and that of the wheel encoder on the terrain. Mostly in open environment, the GPS signal strength is at its best and the terrain is uneven. Therefore, the Navigation Systems works largely on the data from Garmin76. Whereas in enclosed spaces like inside a building, the signal strength is, poor but the terrain is relatively even and hence the local encoders will play a larger role in navigating. Hence, the combined system provides accurate navigation capabilities to Bearcat Brat in most environments.

3.2 Automatic Video Tracking System:

Visual line following in Bearcat Brat's predecessor BearcatIII required manual operation for starting and setting modes on a video tracking system (Iscan). The manual part is now been eliminated with the addition of a new compact single target video tracking system, Iscan RK 446. RK446 is fully controlled using software to track lines from intense spots in the video stream supplied by the two cameras. The interface is RS232 between the robot control computer and Iscan, same as the earlier I-Scan. Therefore, integration of the Iscan was void of any hassles.

3.3 Structural Modifications:

The objective of structural modification was to reduce the load on the robot, improve the ergonomics of the unit and to fit all the components inside the frame. However, the ruggedness of the system was also kept in mind to safeguard the fragile components within the system and for physical stability during inclined and decline paths.

3.4 Waypoint Navigation Using Global Positioning System:

A differential GPS added to the Bearcat Brat gives accurate navigational ability. The Garmin 76 unit has a display that makes it easier to operate. In addition, an improved antenna detects from 9-12 satellites and improves the accuracy. The objective is to develop the ability to navigate to a given set of waypoints avoiding obstacles in the path. A laser sensing system detects and avoids obstacles en route to the target waypoints. On detecting an obstacle, the obstacle avoidance routine called negotiates the obstacle and then transfers the control back to the GPS navigational routine. The navigational system using the Differential GPS is described in detail in Section 4.3.1.

3.5 Point to Point Navigation Using Wheel Encoders:

This approach uses information from the wheel encoders for navigation. The GPS cannot detect signals inside buildings. Using information from the wheel encoders the vehicle can track the path navigated and make decisions about the distance to travel and angle to steer to reach a target point. This method however does not work very well outside due to the uneven terrain.

3.6 Software Modification

The 2002 Bearcat III used the Watcom compiler because of simplicity of interfacing the software and hardware. It works on 32-bit protected DOS mode. However, the team suggested for a multi-operating system for more versatility of the system and so we were looking for more standard package offering more OS adaptability and support. Upon researching, we concluded that we use the Turbo C++ compiler for quick and powerful compilation in the Bearcat Brat.

3.7 Enhanced System Diagram

A block diagram of the system is shown in Figure 4.

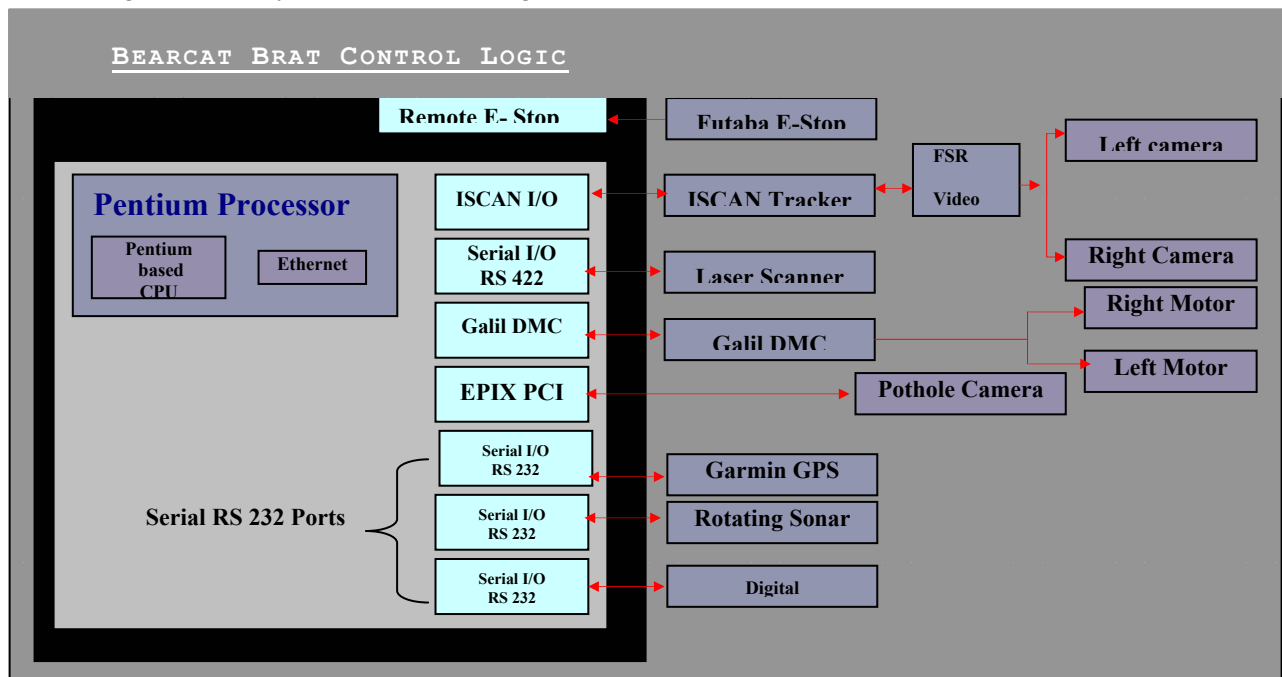


Figure 4: Bearcat Brat Block Diagram

4. SYSTEM DESIGN AND INTEGRATION

4.1 Line Following

The Bearcat Brat, designed to negotiate around an outdoor obstacle course in a prescribed time while staying within the 5 mph speed limit, raising itself in ramps not exceeding 10-degree incline and avoiding the obstacles on the track. However, the Brat can extend its speed capability up to a top speed of 10 mph, with incline angles up to 14 - 15 degrees.

4.1.1 Vision System

The Bearcat's vision system for the autonomous challenge comprises three cameras, two for line following and one for pothole detection. The vision system for line following uses 2 CCD cameras and an image tracking device (I-Scan) for the front end processing of the image captured by the cameras. I-Scan tracker processes the image of the line. The tracker finds the centroid of the brightest or darkest region in a captured image. The three dimensional world co-ordinates are reduced to two dimensional image coordinates using transformations between the actual ground plane to the image plane. A novel four-point calibration system was designed to transform the image co-ordinates back to world co-ordinates for navigation purposes. Camera calibration is a process to determine the relationship between a given 3-D coordinate system (world coordinates) and the 2-D image plane a camera perceives (image coordinates). The objective of the vision system is to make the robot follow a line using a camera. At any given instant, the Bearcat tracks only one line, either right or left. If the track is lost from one side, then the central controller through a video switch changes to the other camera.

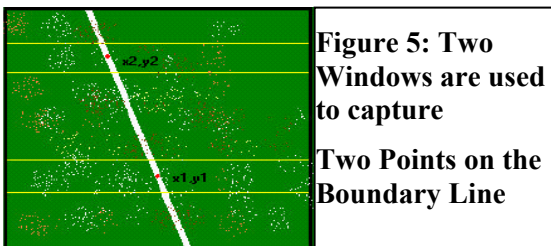


Figure 5: Two Windows are used to capture Two Points on the Boundary Line

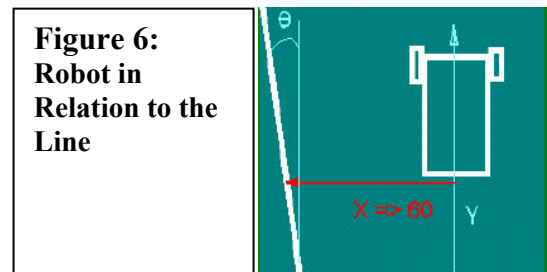


Figure 6: Robot in Relation to the Line

In order to obtain accurate information about the position of the line with respect to the centroid of the robot, the distance and the angle of the line with respect to the centroid of the robot has to be known. When the robot is run in its auto-mode, two I-Scan windows are formed at the top and bottom of the image screen as shown in Figure 5. The centroids are shown as points (x_1, y_1) and (x_2, y_2) in Figure 5. The angle and distance of the line to the robot are determined.

4.1.2 Motion Control System

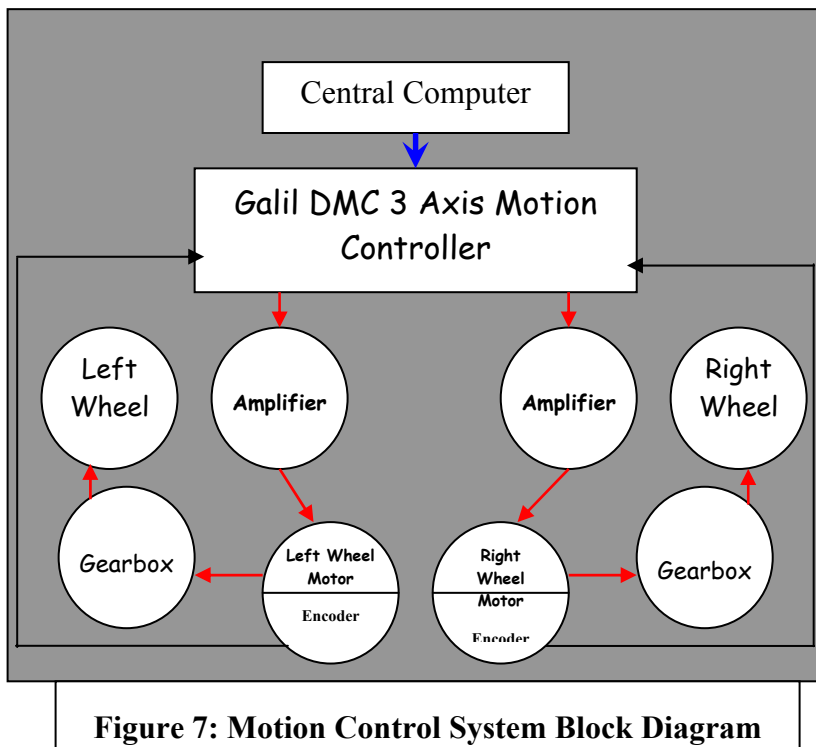


Figure 7: Motion Control System Block Diagram

The motion control system shown in the Figure 7 enables the vehicle to move along a path parallel to the track and to negotiate obstacles. Steering is achieved by applying differential speeds to the left and right wheels. Manipulating the sum and difference of the speed of the right wheels, the velocity and orientation of the vehicle can be controlled at any instant. Two motors power the gear trains. The motor torque is increased by a factor of 40 using a worm gear train. The power to each motor is delivered through an amplifier that amplifies the signal from the Galil DMC motion controller. The data from the vision and obstacle avoidance systems work as an input to the central controller to give

commands to the motion control system to drive the vehicle.

4.1.3 Mechanical System

Figure 8 shows the frame assembly view of the mechanical system.



Figure 8: The Mechanical System

The Bearcat Brat is designed to be an outdoor vehicle able to carry a payload of 100 pounds. Optimal design was achieved using good design practices and tools during the basic design. CAD software such as AutoCAD R14 and IDEAS Master series 7.0 was used in the final analysis phase for stress and load analysis. The basic structure is built with aluminum extrusions, joining plates and T-nuts.

4.2 Obstacle Avoidance

The obstacle avoidance system detects an obstacle on the navigational course and then calls the appropriate software routine to negotiate it. Two alternative solutions one using a laser scanner and one with the sonar sensors are used on the Bearcat for obstacle detection and avoidance. Both approaches are explained below.

4.2.1 Design Solution using Laser Scanner for Fine Detection

The Bearcat uses the SICK laser scanner (LMS 200) for sensing obstacles in the path. The power supply to the unit is through a 24Volt, 1.8 Amp adapter. The unit communicates with the central computer using a RS422 serial interface card. The maximum range of the scanner is 32 meters. For the contest, a range of 8 meters with a resolution of 1° has been selected. The scanner data is used to get information about the distance of the obstacle from the robot. This can be used to calculate the size of the obstacle. The scanner is mounted at a height of 8 inches above the ground to facilitate the detection of short as well as tall objects. The central controller performs the logic for obstacle avoidance and the integration of this system with the line following and the motion control systems. Figure 9 shows the field of view of the laser scanner.

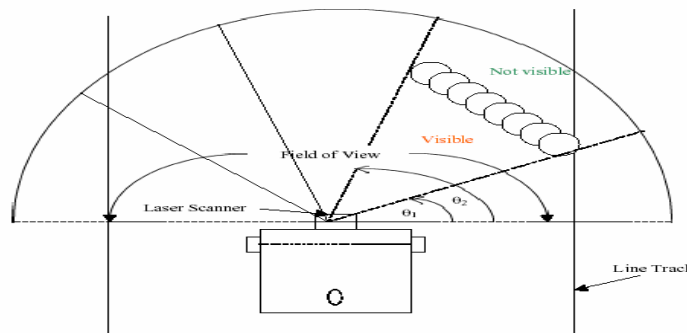


Figure 9: Field of View of the Laser Scanner

4.2.2 Design Solution using Sonar System for Coarse Detection

Figure 10 shows the setup for obstacle avoidance using a rotating sonar sensor.

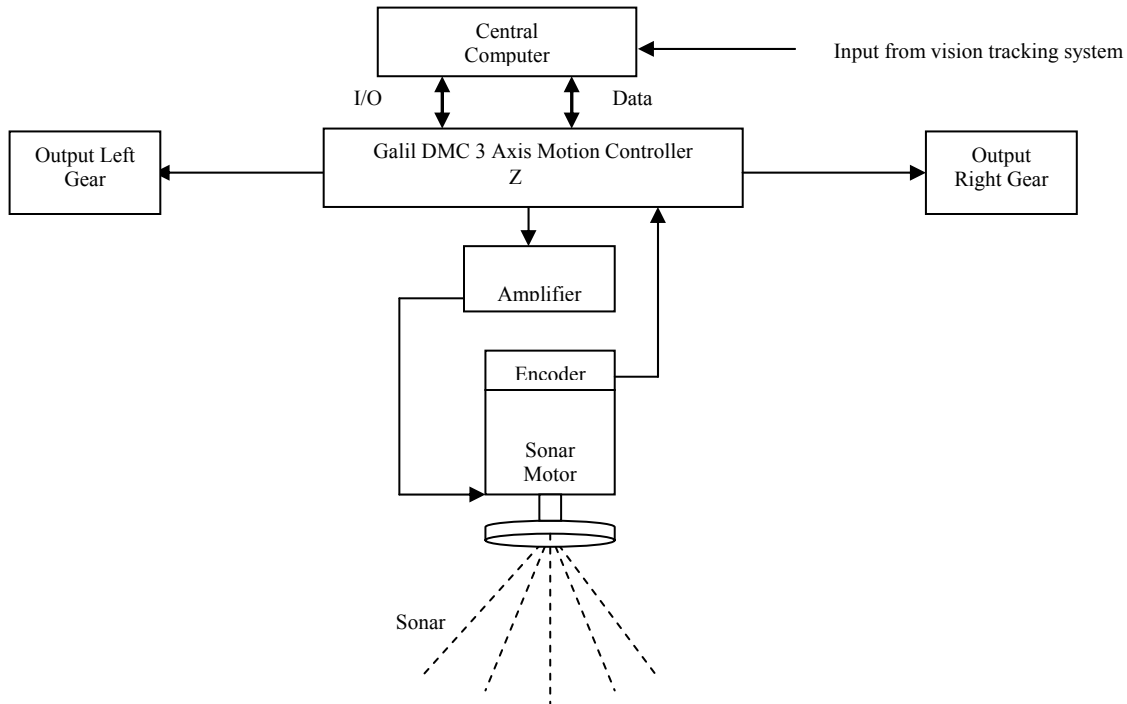


Figure 10: Sonar Obstacle Detection System

The two main components of the ultrasonic ranging system are the transducers and the drive motor as shown in Figure 10. A 12 Volts DC, 0.5 Amps unit powers the sonar. A “time of flight” approach is used to compute the distance from any obstacle. The sonar transmits sound waves towards the target, detects an echo, and measures the elapsed time between the start of the transmit pulse and the reception of the echo pulse. The transducer sweep is achieved by using a motor and Galil motion control system. Adjusting the Polaroid system parameters and synchronizing them with the motion of the motor permits measuring distance values at known angles with respect to the centroid of the vehicle. The distance value is returned through an RS232 serial port to the central controller. The central controller uses this input to drive the motion control system. The range of this system is 40 feet.

4.2.2 Pothole Detection

The robot has the ability to detect and avoid simulated potholes represented by two-foot diameter white circles randomly positioned along the course. A non-contact vision approach has been taken since simulated potholes are significantly different visually from the background surface. A monochrome Panasonic CCD camera is used to capture an image of the course ahead of the robot. The data from the camera is fed to the Epix imaging board. The control software for the imaging board processes the formatted data. This software makes extensive use of the XCOBJ/PXIPL Image Processing libraries provided by EPIX to detect the presence of a simulated pothole and determine the location of the centroid of the pothole. The line following, obstacle avoidance and pothole detection systems are integrated for pothole detection and avoidance. The obstacle avoidance system takes precedence over the pothole avoidance system. Figure 11 shows view of simulated potholes that can be detected.

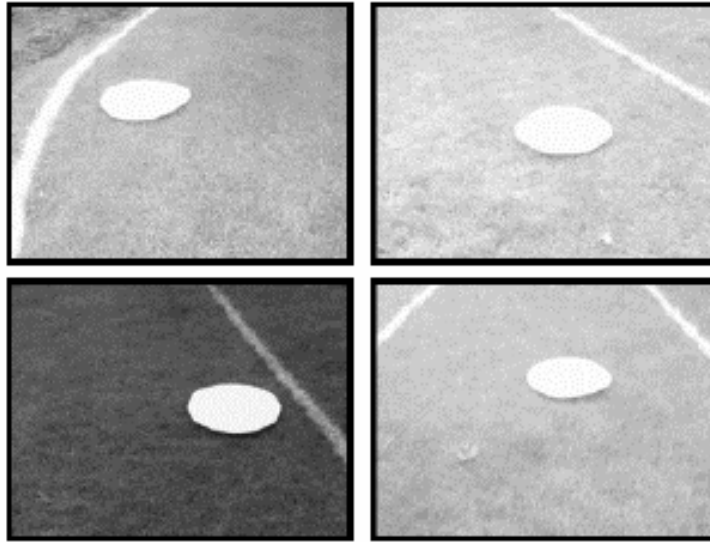


Figure 11: View of Simulated Potholes

4.3 Navigational Challenge Problem and Solution

The goal is to navigate Bearcat Brat to a series of predefined waypoints while avoiding obstacles. For this the GPS is used to get the original robot position, then tracking is used to move the robot from one point to the next, updating the new base with every pass. A laser sensing system is used to detect and avoid obstacles en route to the target waypoints. Wheel encoders on the vehicle are used to track the path navigated and make decisions about the distance to travel and angle to steer to reach a target point

4.3.1 GPS Selection

The basic criteria used in the selection of the GPS unit are:

- Embedded navigation features
- Waas capability to improve accuracy of standard GPS signal to 3meters
- RS-232 serial port input/output to interface with robots computer
- External antenna for accurate reception and
- External power capability to ensure constant source of regulated power

Based on the above selection criteria the Garmin-76 GPS was chosen as the unit to provide GPS navigational ability to the robot. The Garmin-76 unit provides all of the above-mentioned features in addition to other features not used in the current navigation algorithm.

4.3.2 Description of Navigational Challenge Algorithm

The basic solution selected to solve the navigational challenge problem is to model the problem as a basic closed feedback control loop. This model has an input command (target waypoint destination), feedback signal (GPS unit position information), error signal, and transfer function of the output characteristics. The GPS unit uses the current position information (latitude, longitude, height and velocity information at the rate of 1 to 255 second/output) and calculates the bearing and range from the target waypoint to determine the error. Correction signals are generated to reduce the error to a certain tolerance based on the bearing angle error signal generated by the GPS unit. The correction signals consist of turn right, turn left, forward motion, or stop. These corrective

commands are sent to the motion control system, which translates these commands into motor control voltages that steer and propel the robot on the course. Once the bearing angle error and target range have been reduced to the required tolerance the command is considered complete and the robot arrives at its target destination waypoint. At this point, the next target waypoint is selected and the process is repeated until all target waypoints in the database have been reached. The GPS signal is very poor inside buildings. However, the terrain is relatively flat and even. Here the data from wheel encoders provide data for the motion control. This system is also used at the start until the velocity reaches a point that provides accurate GPS data.

4.3.3 Point to Point Navigation using Wheel Encoders

An encoder translates motion into electrical pulses, which are feed back into the Galil motion controller. The feedback is used to calculate the distance traversed. Steering is achieved by differential motion of the two wheels. The problem is modeled as a closed feedback control loop. The input command is the target waypoint destination relative to the robot position. The wheel encoder provides the feedback signal. The motion from the origin A to target B is achieved by two motions. The program calculates Angle “ α ” and distance “d”. The robot first steers “ α ” units and it then traverses “d” units to reach the target. Figure 12 shows the concept of navigation using wheel encoders.

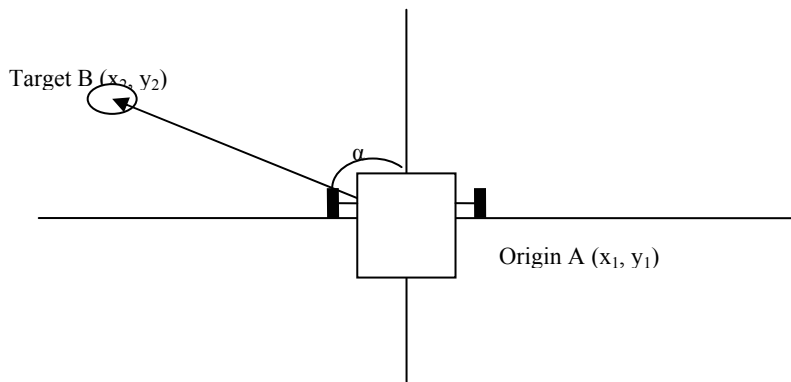


Figure 12: Concept of Point-to-Point Motion

4.3.4 Obstacle Avoidance

A laser scanner is used to detect and avoid obstacles. If an obstacle is detected, an obstacle avoidance routine, similar to the feedback control loop used for the GPS navigation, is used to navigate the robot around the obstacle. Once the robot avoids the obstacles, the original target waypoint is restored and the navigational feedback control loop is resumed.

4.3.5 Algorithm Implementation

The physical implementation of feedback control loop of the GPS navigation consists of the Garmin 76 GPS unit, the motion control system, laser scanner, and the robot computer. Waypoint coordinates are read from the waypoints file during the initialization stage of the program and stored in an array in memory. A NMEA message is sent to the Garmin 76 GPS unit via the RS 232 port, which sets the active target waypoint in the GPS unit’s memory. This is the command signal. Once set, the waypoint coordinate is used by the GPS unit to calculate bearing, track, and range to the target waypoint. The Garmin 76 GPS unit transmits ASCII data output via the RS232 port containing the bearing, track, and range to the destination waypoint. The turn angle (angle

error) is related to the track angle and bearing angle by the equation: $\text{Turn Angle} = \text{Track Angle} - \text{Bearing Angle}$. This equation gives the turn angle in the 0 to 360 degree reference frame but this angle is transformed to zero to 180 degrees (left turn angle) or 0 to -180 degrees (right turn angle) for the robot turning subroutine. The robot turns to the commanded correction turn angle if the turn angle is greater than 6 degrees or less than -6 degrees and then moves forward until the GPS position data are updated. When the robot arrives within 5 feet of the destination waypoint, the next target waypoint is selected and this process is repeated until all targets have been reached. This process defines the discrete feedback control loop algorithm used for the robot GPS navigation course.

4.4 Power System

The Bearcat's electrical system consists of a DC battery power system that supports an AC power system through an inverter. Three 12-Volt DC, 130 Amp hours, deep-cycle marine batteries connected in series provide a total of 36 Volts DC, 390 Amp hours for the main electrical power. A 36-Volt, DC input, 600-Watt inverter provides 60 Hz pure sine wave output at 115 Volts AC. The inverter supplies AC electrical power for all AC systems including the main computer, cameras, and auxiliary regulated DC power supplies. An uninterruptible power source (UPS) interfaces the robot main computer with the AC power system. The UPS provides 3 minutes of emergency power to the main computer during AC power system interruptions. The DC system provides 36 volts unregulated DC electrical power to the motors at a maximum of 10 Amps. The total power required by the Bearcat is approximately 735 Watts for the DC systems and 411 Watts for the AC systems. Thus, 1146-Watts total power is required to operate the Bearcat Brat. A loss of 10 percent was estimated for the required power to yield 1261 Watts actually required. A 10 percent loss can also be assumed for power supplied by the batteries to yield 4212-watt hours available. Based on these estimates the Bearcat Brat power system has an estimated endurance of 3.34 hours at full load. A spare set of batteries is available and will be needed during the contest runs.

4.5 Safety System

4.5.1 Manual Emergency Stop

The manual emergency stop unit consists of a red manual push button located on the easily accessible rear surface of the vehicle. When pressed, the power to the motors is cut off and the self-locking mechanism of the gearbox brings the vehicle to an instant halt. The self-locking mechanism ensures that the vehicle does not move when it is not powered, and serves as a safety measure against any undesirable motion such as rolling when parked on a slope.

4.5.2 Remote Controlled Emergency Stop

The mobile robot must be de-activated by a remote unit from a distance of no less than 50 feet in compliance with the rules for this contest. The remote controlled emergency stop consists of a Futaba transmitter, a receiver, an amplifier and a relay. The advantage of using this is that the transmitter need not be in a line of sight of the receiver. The Futaba transmitter uses a 6V DC and transmits FM signals at 72.470 MHz over a range of 65 feet. This amplified current activates the contacts of the relay that in turn activates the emergency stop solenoid and cuts power to the motors.

4.6 Health Monitoring System

The Bearcat Brat is equipped with a self-health monitoring system. A RS 232 serial port is used to take input from a digital multi meter, which can be accessed from C++ code to check the total DC voltage of the batteries. The health monitoring is implemented as a C++ class module that has methods that can monitor battery voltage and display warning messages to the computer screen. There are two threshold trip points, which are set to trigger a low and a critical low voltage-warning message. The low voltage warning indicates that the battery voltage is below the first threshold trip point and that preparations should be made to change or charge the batteries. The critical low voltage warning indicates that corrective actions must be taken immediately because power system shutdown is eminent. The voltmeter class can also be used in code to sound an audible alarm or activate the robot strobe light at the specified threshold point. The voltage display is also visible to the operator and provides a constant indication of the robot electrical voltage.

4.7 Overall System Integration

For the autonomous challenge and line following, the inputs comes from the vision system as image coordinates of the track to be followed or from the obstacle avoidance system as laser scanner/sonar data and pothole detection data. The central controller to give commands to the motion control system, which drives the mechanical drive train, processes these inputs. For the navigational challenge, data comes from the navigation system as GPS data or from the obstacle avoidance system as laser scanner/sonar data. These data are used as inputs by the central controller to give commands to the motion control system, which drives the mechanical drive train.

5. DESIGN ISSUES

5.1 Predicted Performance

The predicted performance for the major tasks required of the contest is shown in the Table 1.

Table 1: Predicted Performance

	Task	Predicted Performance
1	Line Following	Tracks lines with an accuracy of 0.3 inches
2	Obstacle Avoidance	Detects obstacles 8 inches and higher in a range of 24 feet
3	Pothole Detection	Detects simulated potholes across the 10 feet track and a distance of 4 feet
4	Waypoint Detection	Navigates waypoints with an accuracy of 5 feet
5	Emergency Stop	Has a remote controlled emergency stop that can be activated from a distance of 65 feet
6	Dead End Detection	Detects dead ends and avoids traps by backing up and following alternative route
7	Turning Radius	Vehicle has a zero turning radius
8	Maximum Speed	5 miles per hour
9	Ramp Climbing Ability	Can climb inclines up to 10 %
10	Braking Distance	Vehicle comes to a dead stop as soon as the power is cut off

5.2 Safety Reliability and Durability

All the components are rigidly tightened to the base. The CPU and the hard drive of the control computer are shock-mounted to tolerate shocks and vibrations. All the circuits are color coded to ensure proper re-connection with black for ground. To prevent damage to any component during a collision, the main frame has been designed with the aluminum frame forming a boundary on all sides. A front bumper protects the cameras, sonar and laser scanner.

6. CONCLUSION

Bearcat Brat has been designed constructed and tested. The component cost for upgrading the Bearcat Brat from 2002 Bearcat III was about \$3,000. Now the market value of the Brat is approximately \$30,000 (including depreciation). A bill of materials is shown in Appendix I. The vehicle has been tested outside under various conditions. A protective cover is needed during rain. Flat surfaces of various materials including asphalt, concrete and grass have been traversed. It has been tested on inclined ramps with slopes of 10%. The vehicle was found to behave well under the contest conditions. Bearcat Brat is capable of meeting all the performance specifications of the contest.

ACKNOWLEDGMENT

The team is grateful to the industry sponsors: ROV Technologies, P&G, GEAE, Zybron, Krogers, SME, Mr. Jims; University sponsors: SOA, GSGA, MINE Department; and individual sponsors: Dr. Joseph H. Nurre, Mr. John J. Judge, Dr. Richard L. Shell, Dr. Ronald Huston, Mr. Ronald Tarvin, Mr. Jin Cao, Mr. Dinesh Kumar Dhamodarasamy, Dr. Eugene Merchant, Mr. Ed Barnes, Mr. Hank Deardurff and Mr. John Clock and many individuals for their efforts in making this robot design and building process a success. We ate a lot of pizza, made friends and remembered to have fun.

References

1. Ka C. Cheok, Ernest Hall, David Ahlgren, William Agnew, and Gerald R. Lane, "The Intelligent Ground Vehicle Competition (IGVC): A Cutting-Edge Engineering Team Experience," Proceeding of the ASEE Annual Conference, 2003, Nashville, TN.
2. Nick Gartner and Scott Bailey, "Bearcat Cub UC Design Clinic Report," June 2002.

APPENDIX I:
BILL OF MATERIALS

Bearcat Brat		Units	Manufacturer/Vendor
Mechanical System Subassembly		1	
Frame		1	
Aluminum Bars	24	80/20 Inc	
90 degree Joint Plate		40	80/20 Inc
Plexiglas Sheets	2	Cincinnati Plastics	
Transmission Subsystem		1	
Gearbox		2	Cincinnati Belting
Couplings		2	Grainger
Shafts		2	Grainger
Bearings		2	Cincinnati Beltings
Wheel Assembly		2	Borne & Co
Electrical System Subassembly	1		
Motors		2	Reliance Electric
Amplifiers		2	
Power System Subassembly		1	
Battery		3	Michael Tire Co
Inverter	1	Triplet	
UPS		1	Hosefelt Inc
Adapter	2	Michael Tire Co	
Central Controller System Subassembly	1		
Computer		1	UC Bookstore
Hardware			
CPU		1	UC Bookstore
Monitor		1	UC Bookstore
Keyboard		1	UC Bookstore
Touch Pad		1	UC Bookstore
Software			
Watcom C++ Compiler	1	Watcom	
Galil Controller	1	Galil Inc	
Sensory System Subassembly		1	
Sonar Subassembly		1	
Sonar System		1	Reliance Electric
Pola Kits		1	Polaroid System
Motor		1	Reliance Electric
Differential GPS Unit		1	Garmin
Vision System		1	
Video Camera		2	JVC Inc
Video Switch		1	FSR Inc
I-Scan Tracker		1	I-Scan Inc
Pothole Detection System		1	
Video Camera		1	Panasonic Inc
Epix Frame Grabber		1	Epix Inc
Laser Scanner		1	Sick Optics

