Design Report
Bearcat III
University of Cincinnati

The 13th Annual Intelligent Ground Vehicle Competition
At Grand Traverse Resort and Spa, Traverse City, Michigan
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1. INTRODUCTION

The Bearcat III is an interactive, intelligent, Autonomous Guided Vehicle (AGV) designed to serve in unstructured environments by following a desired path, avoiding obstacles and delivering a 20 pound payload to a goal location.[1] Several improvements have been made in the design since the 12th Intelligent Ground Vehicle Competition. One major enhancement is creating the dynamic model of the robot. With this model, a significant effort has been made in the control software to improve the execution, store data, and improve the navigation performance.

This report describes the evolution of the Bearcat III from its predecessor, the 2004 Bearcat III. The report is organized as follows. Section 2 gives a detailed description of the team organization and continuous improvement design process. Section 3 describes the 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 system reliability. Section 5 describes the design issues, the performance prediction, and preliminary results. Section 6 presents conclusions. Appendix I shows the bill of materials with vendor names.

2. TEAM ORGANIZATION

2.1 UC Robot Team

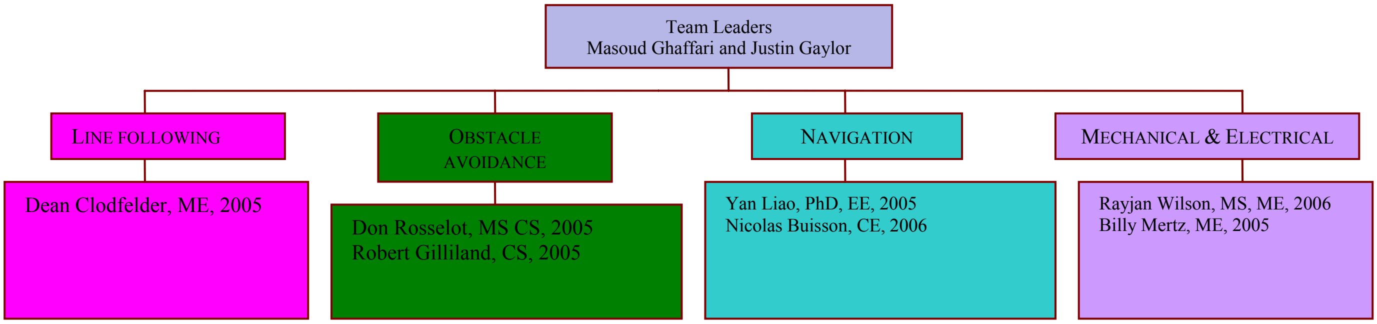


Figure 1. Year 2005 UC Robot Team

The UC robot team is a part of the Center for Robotics Research at the University of Cincinnati and consists of undergraduate and graduate students from mechanical, industrial, and computer science fields as shown in Figure 1. Starting from September 2004, students participated in weekly meetings during the year, and actively contributed towards the progress of the design. The team also conducted numerous demonstrations for visitors in their outreach effort. 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

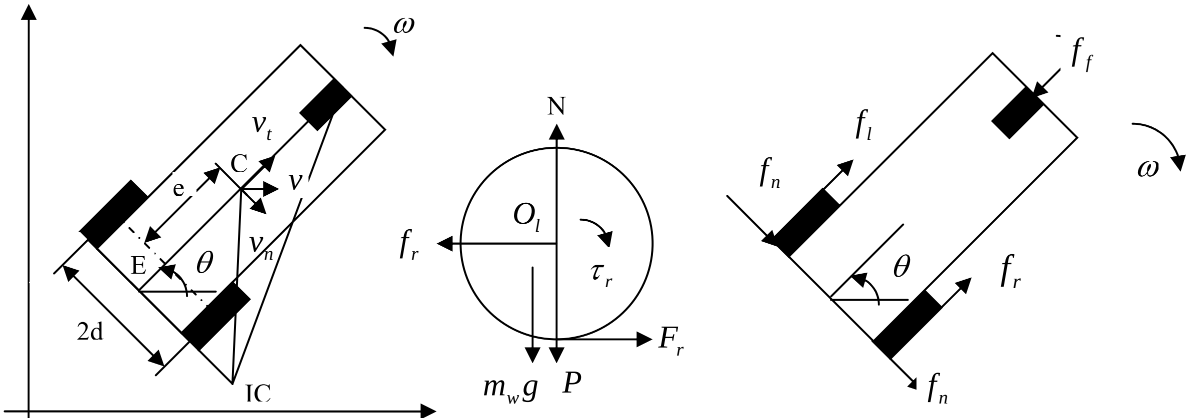
The design approach followed the Kaizen philosophy of continuous improvement. Our progress through several sessions of brainstorming issues resulted in a radical improvement of the system power and speed. A task list required for the enhancements of the robot was made and followed.

3. BEARCAT III DESIGN ENHANCEMENTS

One major enhancement is creating the dynamic model of the robot. With this model, a significant effort has been made in the control software to improve the execution, store data, and improve the navigation performance.

3.1 Dynamic Model

For the Bearcat III robot, a kinematic and dynamic model was derived using the Newton-Euler method [11-14]. Bearcat III structure and dynamic analysis are shown in Fig. 2.



a. Robot Structure

b. Dynamic analysis for the right wheel

c. Dynamic analysis for the robot

Figure 2. Robot dynamic analysis

According to Fig. 2, the kinematic model with respect to the robot center of gravity (Point C in Fig. 4 a.) can be described as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ \sin\theta & -\cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_t \\ v_n \\ \omega \end{bmatrix} \tag{1}$$

Where v_t, v_n, ϖ can be defined in terms of the angular velocity of the robot left wheel ω_l and the angular velocity of the robot right wheel ω_r as follows:

$$\begin{bmatrix} v_t \\ v_n \\ w \end{bmatrix} = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{er}{2d} & \frac{-er}{2d} \\ \frac{r}{2d} & \frac{-r}{2d} \end{bmatrix} \begin{bmatrix} \omega_l \\ \omega_r \end{bmatrix} \tag{2}$$

However, Eq. 1 can be simplified by utilizing that $v_n = e\omega$ as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & e\sin\theta \\ \sin\theta & -e\cos\theta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_t \\ \omega \end{bmatrix} \tag{3}$$

The nonholonomic constraint can be obtained directly from Eq. 3 as:

$$\dot{x}\sin\theta - \dot{y}\cos\theta = \omega e \tag{4}$$

For the center of the wheel axes (Point E in Fig. 2 a.) $e = 0$ and hence Eq. 4 reduces to:

$$\dot{x}\sin\theta - \dot{y}\cos\theta = 0 \tag{5}$$

This means that there is no motion in the direction of the wheel axis.

Another constraint for the kinematic model comes from the inertial structure of the robot where the robot's path cannot exceed the minimum turning radius or the maximum curvature:

$$\rho \geq R_{\min imum} \text{ , or } k \leq K_{\max imum} \tag{6}$$

From Fig. 2 b., the Newton-Euler equation for the right wheel can be described as:

$$F_r - f_r = m_w \ddot{x}_r \tag{7}$$

$$\tau_r - F_r \cdot r = J_w \dot{\omega}_r$$

where:

F_r : is the reaction force applied to the right wheel by the rest of the robot;

f_r : is the friction force between the right wheel and the ground;

m_w : is the mass of the wheel;

τ_r : is the torque acting on the right wheel which provided by the right motor;

r : is the radius of the wheel;

J_w : is the inertia of the wheel.

Note that the Coriolis part had been deleted since it is negligible because the wheel inertia is much smaller than the robot inertia.

The dynamic model of the robot can be defined as:

$$M(\xi)\ddot{\xi} + J(\xi,\dot{\xi})\dot{\xi} + F = \tau \tag{8}$$

where:

$$M(\xi) = \begin{bmatrix} \frac{(mr^2\cos\theta + 2J_0\cos\theta)}{2r} & \frac{(mr^2\sin\theta + 2J_0\sin\theta)}{2r} & \frac{(mr^2ed\sin^2\theta - mr^2ed\sin\theta\cos\theta + J_cr^2 + 2J_0d^2)}{2rd} \\ \frac{(mr^2\cos\theta + 2J_0\cos\theta)}{2r} & \frac{(mr^2\sin\theta + 2J_0\sin\theta)}{2r} & \frac{(mr^2ed\sin^2\theta - mr^2ed\sin\theta\cos\theta - J_cr^2 - 2J_0d^2)}{2rd} \end{bmatrix}$$

$$J(\xi,\dot{\xi}) = \begin{bmatrix} \frac{-J_0\dot{\theta}\sin\theta}{r} & \frac{J_0\dot{\theta}\cos\theta}{r} & \frac{-mre\dot{\theta}\cos\theta(\sin\theta + \cos\theta)}{2} \\ \frac{-J_0\dot{\theta}\sin\theta}{r} & \frac{J_0\dot{\theta}\cos\theta}{r} & \frac{-mre\dot{\theta}\cos\theta(\sin\theta + \cos\theta)}{2} \end{bmatrix}$$

$$F = \begin{bmatrix} \frac{-f_ner}{d} \\ \frac{-f_ner}{d} \end{bmatrix},\ \tau = \begin{bmatrix} \tau_r \\ \tau_l \end{bmatrix},\ \xi = \begin{bmatrix} x_c \\ y_E \\ \theta \end{bmatrix}$$

To customize the dynamic model for the Bearcat III, we need to substitute the values for $m, r, J_0, e, d, J_c, f_n$ in Eq. 8. According to Fig. 2 for Bearcat III, $m = 306.18kg$, $r = 0.2095m$, $e = 0.338m$, $d = 0.432m$, and J_0, J_c, f_n need to be calculated.

The value of the frictional coefficient μ between the ground and the wheel depend of the type of the surface of the ground; for grass, 0.6 is common, while for concrete 0.9 is usually used. Bearcat III usually moves on grass, therefore, 0.6 was used in the calculations. Substituting the parameters for Bearcat III into the normal force equation $f_n = \mu(\frac{1}{3}mg + m_wg)$, f_n is calculated to be 629.45 N.

The moment of inertia for the robot wheel is calculated as follows:

$$J_w = \frac{1}{2}m_t(r_{te}{}^2 - r_{ti}^2) + \frac{1}{2}m_r(r_{re}^2 - r_{ri}^2) = 0.055kgm^2 \tag{9}$$

Substituting the value of J_w from Eq. 9 for Bearcat III, J_0 is calculated to be $0.274kgm^2$.

Substituting these values into Eq. 8, the Bearcat III dynamic model is:

$$M_B(\zeta)\ddot{\zeta} + J_B(\zeta,\dot{\zeta})\dot{\zeta} + G_B(\zeta,\dot{\zeta},\ddot{\zeta}) = \tau \tag{10}$$

where:

$$\zeta = \begin{bmatrix} x_c \\ y_c \\ \theta \end{bmatrix}, \tau = \begin{bmatrix} \tau_r \\ \tau_l \end{bmatrix}$$

$$M_B(\zeta) = \begin{bmatrix} 33.454\cos\theta & 33.454\sin\theta & 10.866\sin^2\theta - 10.866\sin\theta\cos\theta + 11.014 \\ 33.454\cos\theta & 33.454\sin\theta & 10.866\sin^2\theta - 10.866\sin\theta\cos\theta - 11.014 \end{bmatrix}$$

$$J_B(\zeta,\dot{\zeta}) = \begin{bmatrix} -1.305\dot{\theta}\sin\theta & 1.305\dot{\theta}\cos\theta & -10.866\dot{\theta}\cos\theta(\sin\theta + \cos\theta) \\ -1.305\dot{\theta}\sin\theta & 1.305\dot{\theta}\cos\theta & -10.866\dot{\theta}\cos\theta(\sin\theta + \cos\theta) \end{bmatrix}$$

$$G_B(\zeta,\dot{\zeta},\ddot{\zeta}) = \begin{bmatrix} 11.308\dot{\theta}^2\sin^2\theta - 0.441\dot{\theta}^2\cos^2\theta - 11.308\ddot{\theta}\sin\theta\cos\theta - 103.422 \\ 11.308\dot{\theta}^2\sin^2\theta - 0.441\dot{\theta}^2\cos^2\theta - 11.308\ddot{\theta}\sin\theta\cos\theta - 103.422 \end{bmatrix}$$

4. SYSTEM DESIGN AND INTEGRATION

4.1 Line Following

The Bearcat III is 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 15 percent incline and avoiding obstacles on the track.

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 (Iscan) for the front end processing of the image captured by the cameras. The Iscan 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 determined from 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.

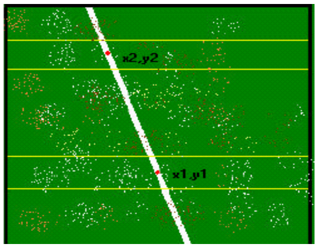


Figure 3. Two Windows Used to Capture Points on Boundary Line

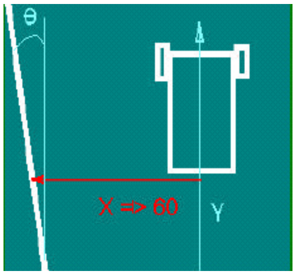


Figure 4. Robot in Relation to the Line

In order to obtain accurate control 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 3. The centroids are determined as shown by points (x_1, y_1) and (x_2, y_2) in Figure 3. The angle and distance of the line to the robot are determined and used by the motion controller to follow the line as shown in Figure 4.

4.1.2 Motion Control System

The motion control system shown in the Figure 5 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.

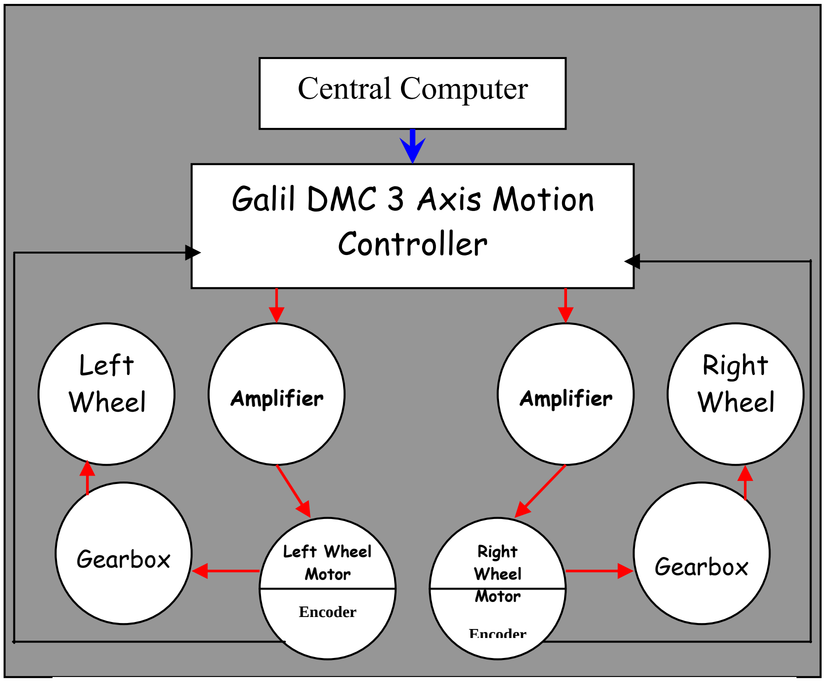


Figure 5. Motion Control System Block Diagram

4.1.3 Mechanical System

Figure 6 shows the frame assembly view of the mechanical system.

The Bearcat III was designed to be an outdoor vehicle able to carry a payload of more than 20 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.

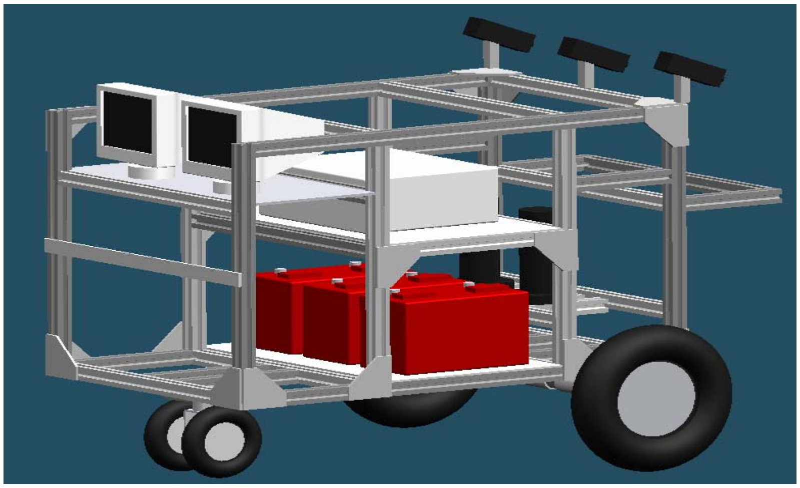


Figure 6. Mechanical System

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 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 7 shows the field of view of the laser scanner.

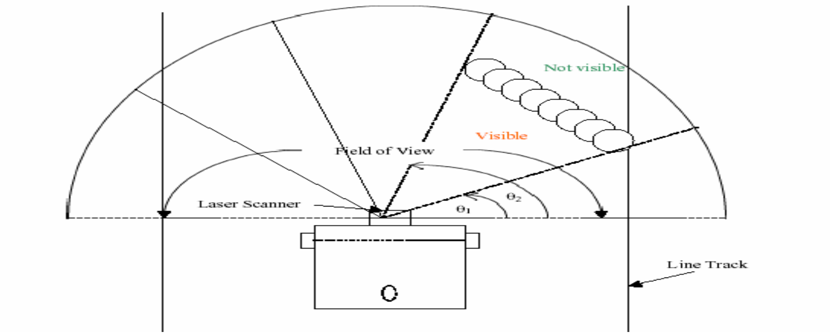


Figure 7. Field of View of the Laser Scanner

4.2.2 Design Solution using Sonar System for Coarse Detection

Figure 8 shows the setup for obstacle avoidance using a rotating sonar sensor.

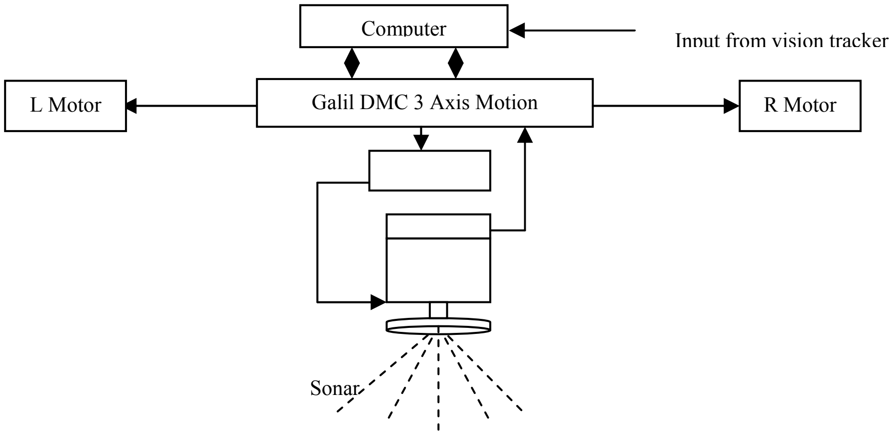


Figure 8. Sonar Obstacle Detection System

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.

4.2.3 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 9 shows view of simulated potholes that can be detected.

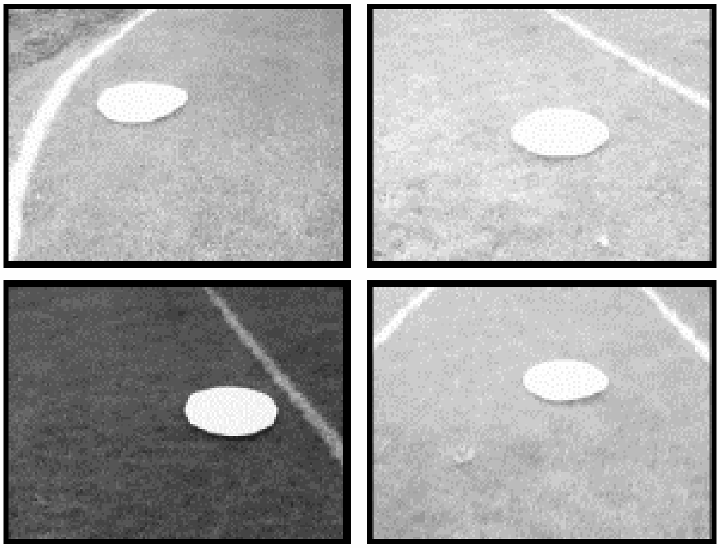


Figure 9. View of Simulated Potholes

4.3 Navigational Challenge Problem and Solution

The goal is to navigate Bearcat III 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 Navigation

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.

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.

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 10 shows the concept of navigation using wheel encoders.

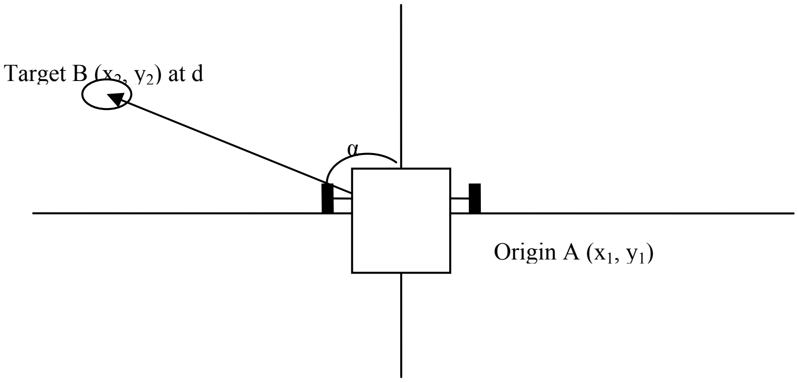


Figure 10. Concept of Point-to-Point Motion

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: Turn Angle = Track Angle – 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 24 volt and one 12 volt battery are now used to provide 80 volts to the motors. One 24-Volt and one12-Volt DC, 130 Amp hours, deep-cycle marine battery are connected in series to provide a total of 36 Volts DC for the inverter AC 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 80 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 III. 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 III power system has an estimated endurance of 0.5 hours at full load. A spare set of batteries is available and are changed as 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 III 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 and Actual Performance

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

Table 1. Predicted and Actual Performance

	Task	Predicted and Actual 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 III has been designed constructed and tested. The component cost for upgrading the Bearcat III from 2003 Bearcat III was about $600. Now the market value of the Bearcat III is approximately $20,000. A bill of materials is shown in Appendix I. The student man hours expended this year was about 120. The vehicle has been tested outside under various conditions. A protective cover is available for operation in the rain. Flat surfaces of various materials including asphalt, concrete, and grass have been traversed. It has been tested on inclined ramps with slopes of 15%. The vehicle was found to behave well under the contest conditions. Bearcat III is capable of meeting all the performance specifications of the contest.

ACKNOWLEDGMENT

The team is grateful to all the industry and individual sponsors for their efforts in making this robot design and construction process possible.

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. Masoud Ghaffari, et. al., "Design of an Unmanned Ground Vehicle, Bearcat III, Theory and Practice, " **Journal of Robotic Systems**, Special Issue on the IGVC, Wiley, 2004.

CERTIFICATION

I certify that the engineering design in the vehicle Bearcat III (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 I:
BILL OF MATERIALS

Bearcat III		Units	Manufacturer/Vendor	
Mechanical System Subassembly		1		
Frame ($1700)		1		
Aluminum Bars	24	80/20 Inc		
90 degree Joint Plate	40	80/20 Inc		
Plexiglas Sheets	2	Cincinnati Plastics		
Transmission Subsystem		1		
Gearbox ($400)		2	Cincinnati Belting	
Couplings		2	Grainger	
Shafts		2	Grainger	
Bearings		2	Cincinnati Beltings	
Wheel Assembly		2	Borne & Co	
Electrical System Subassembly	1			
Motors ($2000)		2	Reliance Electric	
Amplifiers ($600)			2	
Power System Subassembly		1		
Battery ($400)		3	Michael Tire Co	
Inverter ($600)	1	Triplet		
UPS ($50)		1	Hosefelt Inc	
Adapter	2	Michael Tire Co		
Central Controller System Subassembly	1			
Computer ($1000)		1	UC Bookstore	
Hardware				
CPU		1	UC Bookstore	
Monitor		1	UC Bookstore	
Keyboard		1	UC Bookstore	
Touch Pad		1	UC Bookstore	
Software				
Turbo C++ Compiler	1	Microsoft		
Galil Controller ($1000)	1	Galil Inc		
Sensory System Subassembly		1		
Sonar Subassembly ($300)			1	
Sonar System		1	Reliance Electric	
Pola Kits		1	Polaroid System	
Motor		1	Reliance Electric	
Differential GPS Unit		1	Garmin	
Vision System ($3000)		1		
Video Camera		2	JVC Inc	
Video Switch		1	FSR Inc	
I-Scan Tracker		1	Iscan Inc	
Pothole Detection System ($300)			1	
Video Camera		1	Panasonic Inc	
Epix Frame Grabber		1	Epix Inc	
Laser Scanner ($3000)			1	Sick Optics