BEARCAT III DESIGN REPORT – UNIVERSITY OF CINCINNATI

1. INTRODUCTION:

This report describes the design and fabrication of the Bearcat III – an enhancement to Bearcat II. The Bearcat III is an intelligent, automated, mobile robotic vehicle designed to compete in the 9th Intelligent Ground Vehicles Competition that is to be held June 2 – 4, 2001 at Oakland University, Rochester Hills, MI. The automated guided vehicle is an integration of numerous functional subsystems controlled by means of a high-level central computer that enables the vehicle to function as an intelligent machine. Each sub-system is designed to meet or assist with a specific contest requirement.

The report is organized as follows. A description of the design process and team organization is given in Section 2. The enhanced Bearcat III system is described in Section 3. A description of the integration of the changes into the overall design is given in Section 4. Several design issues are then described in Section 5. Results are given in Section 6. The technical specifications are tabulated and a bill of materials with manufacturers and prices are given in the appendices.

2. CONDUCT OF THE DESIGN PROCESS AND TEAM ORGANIZATION:

2.1 UC Robot Team

A team consisting of both undergraduate and graduate students from various disciplines was formed in September 2000. The team members are listed in Table 1. The work was divided among the team members for designing, constructing, testing and refining the individual subsystems of the vehicle, based on their areas of expertise and interests. However, every team member was trained to understand the safe operation of all the sub-systems of the vehicle. Communication was facilitated by means of a group mailing list and by means of regular updates on the official website of UC Center for Robotics.

Name	Year	Degree	Design Module
Mayank Saxena	2001	Industrial Eng. (MS)	Obstacle Avoidance
Mike Rivett	2001	Computer Science (BS)	Software Support
Trey Howard	2001	Computer Science (BS)	Software Systems
Xiaoqun Liao	2003	Industrial Eng. (PhD)	Fault Diagnosis
Ramya Ravindran	2001	Industrial Eng. (MS)	Design Report
Rahul Dhareshwar	2001	Industrial Eng. (MS)	Obstacle Avoidance
Rob Hicks	2001	Engineering (BS)	Vision and Sonar Systems
Steve Michalske	2003	Electrical Eng (BS)	Electrical Systems
Peter Cao	2003	Industrial Eng. (PhD)	System Support
Pravin Chandak	2002	Industrial Eng. (MS)	Obstacle Avoidance
Vidya Sagar Murty	2002	Industrial Eng. (MS)	Software Support
Sujan Balachandran	2002	Industrial Eng. (MS)	Mechanical Systems
Sachin Modi	2002	Industrial Eng. (MS)	Vision Systems
Maurice Tedder	2003	Information Technology (BS)	Power Systems

Table-1. Year 2001 UC Robot Team

2.2 Design Process

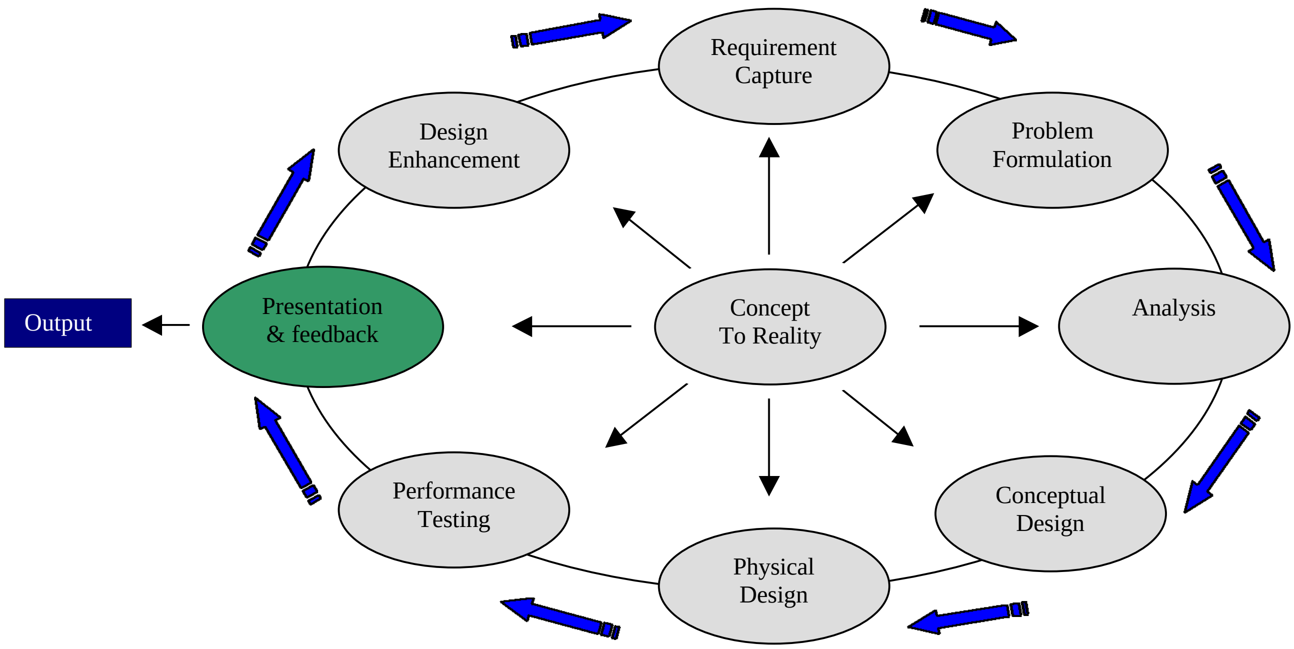

Figure-1. Design Process

The design process is the most critical issue in the development of any product and especially in designing a complex system like an automated guided vehicle. Given the critical nature of the design process the team decided to adopt a "divide and conquer" and "continuous improvement" approach. After the initial brainstorming session with the various members of the team it was decided to accomplish the design process in a systematic approach wherein the entire process of design was segmented into simpler units as shown in Figure 1. The various systems were designed using the above approach, iterating as many times as necessary to meet the performance criteria. The enhancements to the existing systems were also iterated. The process enabled us to design an intelligent autonomous vehicle for the autonomous ground vehicle competition.

2.3 Design Strategy

The development of the Bearcat III is based upon the realization that the design of a complex electro-mechanical system like an automated guided vehicle must be accomplished by a decomposition of the design problem into simpler units. This decomposition is carried on until all units reach the individual component level. These components can then be designed, integrated to form major sub-units and ultimately, on further integration, lead to the entire system. The basic criteria for design were simplicity, reliability, durability and adherence to the rules of the contest. The vehicle can be broadly decomposed into a number of major sub-systems as shown in Figure 2. A block diagram that shows the functional elements is given in Figure 3.

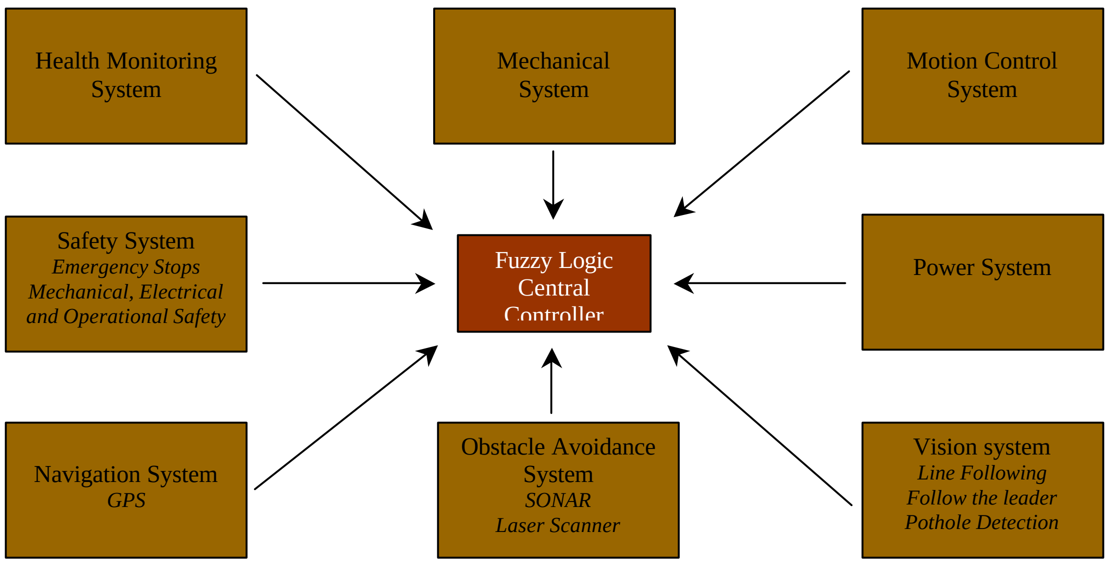

Figure-2. Major Subsystems

2.4 Design Tools

Various design tools, which were used in the design of Bearcat III, are shown in Table 2.

Mechanical design tools	Frame structure	2D model AUTOCAD Release 14
	FEA, stress analysis, moments and load analysis	IDEAS 6.0, MATHCAD
	BOM	AUTOCAD 80/20 libraries
Control system	Design and testing of control system	SIMULINK
	Calibration	MATHCAD and MATLAB 5.2
	Tuning	Galil WSDK
System Integration	Customized software Potential Failure Mode and Effects Analysis	TC ++ in DOS environment, HTML, ASP, MS SQL SERVER. Polakit, Watcom Compiler, Laser Scanner Simulator

Table-2. Design Tools

3. BEARCAT III SYSTEM DESIGN AND ENHANCEMENTS:

3.1 Enhanced System Diagram

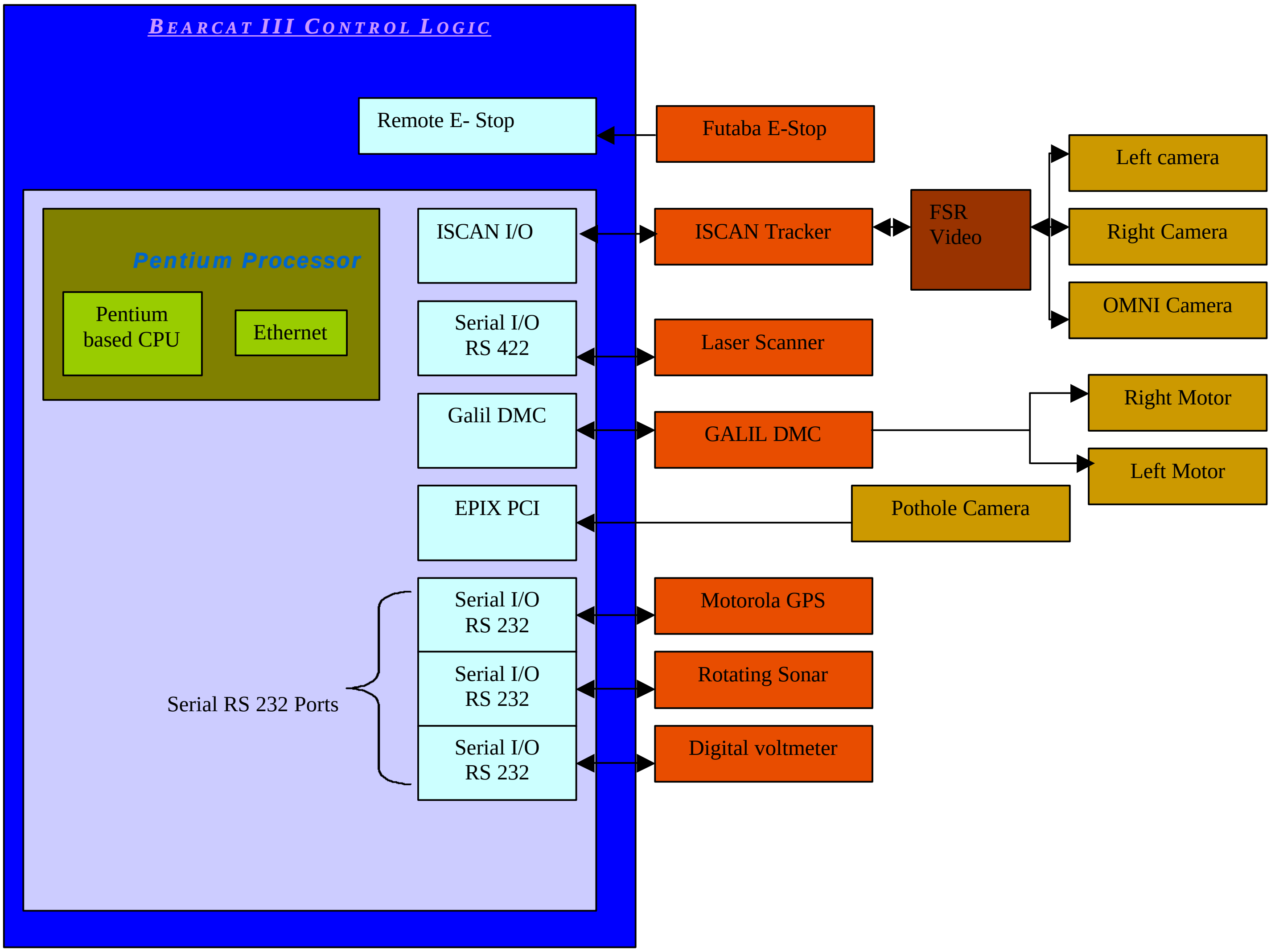

Figure-3. BEARCAT III Block Diagram

3.2 Mechanical System

The Bearcat III is an outdoor vehicle designed to carry a payload of 100 pounds. The vehicle frame has been designed to meet indoor and outdoor conditions. Standard design procedures were used for initial calculations and CAD software such as AutoCAD Release 14 and IDEAS were used in the final design process for stress and load analysis. The bill of materials was developed. The parts were acquired through local, national and international manufacturers. Aluminum extrusions with joining plates and T-nuts were used to construct the main framework.

Two separate gearboxes are used to individually power the wheels. Worm gears with a ratio of 40:1 are used to transmit power to the wheels through a mechanical coupling. The self-locking mechanism of the worm gears does not require the vehicle to have a separate mechanical breaking system. The front wheels are powered. The rear wheel is a castor wheel. This design gives the robot a zero turning radius (ZTR) capability. The two motors are driven at 36 Volts and 10 Amps. This design supplies sufficient power to negotiate a 10% slope.

3.3 Motion Control System

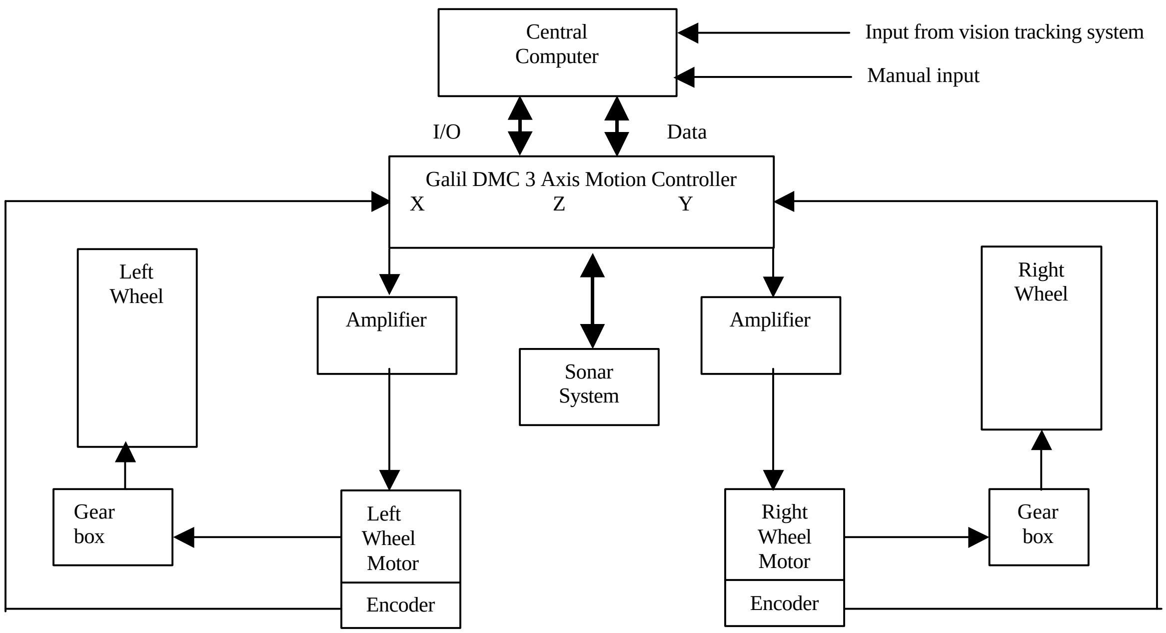

Figure-4. Motion Control System Block Diagram

While negotiating a curve, steering of the vehicle is achieved by differential speeds of the left and the right wheels using the motion control system shown in Figure 4. This enables the vehicle to move along a curved path parallel to the track lines. By manipulating the sum and difference of the speed of left and the right wheels, the velocity and the orientation of the vehicle can be controlled at any instant. Two motors power the gear train and drive the left and the right wheel separately through two independent gearboxes. The gear train increases the motor torque by a factor of 40. The power to each motor is delivered through an AMC DC 48A amplifier that amplifies the signal from the Galil DMC Motion Controller. The central controller gives the input to the motion control system. The central controller processes information received from the vision and obstacle avoidance sensors and gives an input to the motion control system to drive the Bearcat III.

3.4 Power System

The Bearcat's electrical system consists of a DC battery power system that supports an AC power system through an inverter. The main power is supplied by three 12-Volt DC, 130 Amp hour, deep-cycle marine batteries connected in series, which provide 4680 Amp hours. 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. 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 411.3 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 amp hours available. Based on these estimates the Bearcat III 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.

3.5 Vision System

The Bearcat's vision system for the autonomous challenge comprises three cameras. Two cameras are used for line following. This permits following a dashed line. One additional camera is used for simulated pothole detection. The placement of the cameras is shown in Figure 5.

3.5.1 Line Following

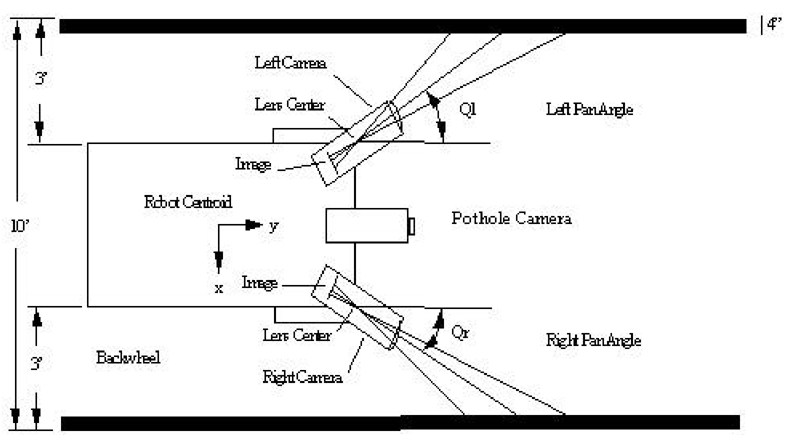

Figure-5. Line Following System

Point or line tracking is achieved through two digital CCD cameras. At any instant, only one camera is used. In case if the track is lost from one camera, the vision is switched to the other camera. This is accomplished using a video switch. Image processing is done by the Iscan tracking device. This device finds the centroid of the brightest or darkest region in a computer-controlled window, and returns its X, Y centroid image coordinates as well as size information. This information is updated every 16 ms, however the program must wait 10 ms after moving the window to get new data. This results in a 52 ms update time for tracking two points in sequence. Since image coordinates are two-dimensional while actual world coordinates are three-dimensional, a three-dimensional measurement algorithm is used. A four-point camera calibration method is used to find a matrix of “camera co-efficients.” These are used in an algorithm to convert the image data that is received to the real world distances used by the central controller. In controlling the robot to follow the obstacle course, the angle of the line and the distance from the centroid of the robot is measured. The perpendicular distance from the line to the robot centroid is measured with respect to the x-axis. The goal of the central controller is to maintain the robot in the center of the track while avoiding the obstacles.

3.5.2 Follow the Leader

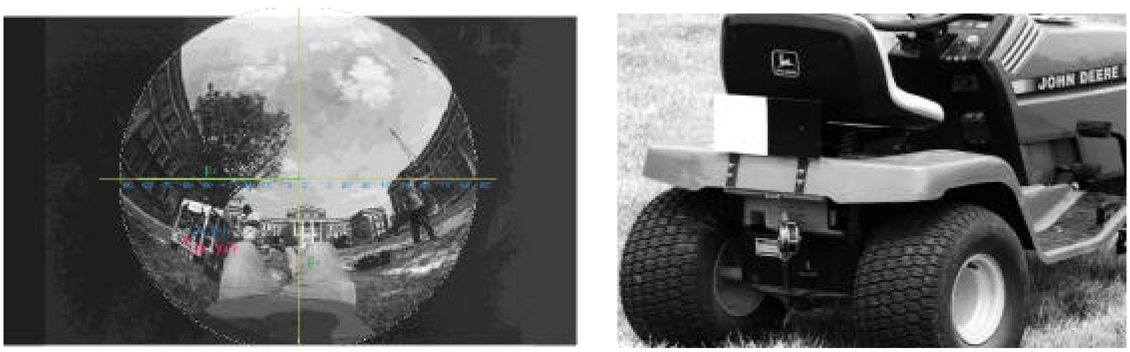

Figure-6. Wide Angle Image and Target

The vehicle must be capable of following a lead vehicle by targeting a wooden sign of size 15 cm high by 30 cm wide. A unique omni-directional vision system with a 2π steradian view is used to track the target as shown in Figure 6. The raw image data from the camera is fed into an ISCAN image-tracking device. The ISCAN finds the centroid of the targeted area and returns the X, Y co-ordinates of the area that is being tracked. The two dimensional data is also used to determine the distance of the lead vehicle from the robotic vehicle. This data is then used by the central logic system to guide the robot motion. A sunshade is used to block out the sunlight.

3.5.3 Pothole Detection

For the autonomous challenge event, the vehicle should be capable of detecting and avoiding simulated potholes represented by two feet diameter white circles randomly positioned along the course. Pothole avoidance may be considered similar to other obstacle avoidance except that the potholes are depressions rather than extrusions from a surface. A non-contact vision approach has been taken since potholes are significantly different visually from the background surface. A monochrome Panasonic CCD camera is used to capture the course ahead of the robot. The data from the camera is fed into the video switch. The data from the Panasonic camera is passed through the video switch to an 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 fused to permit the robot to follow a path around the pothole.

3.6 Obstacle Avoidance System

3.6.1 Design Solution Using Sonar

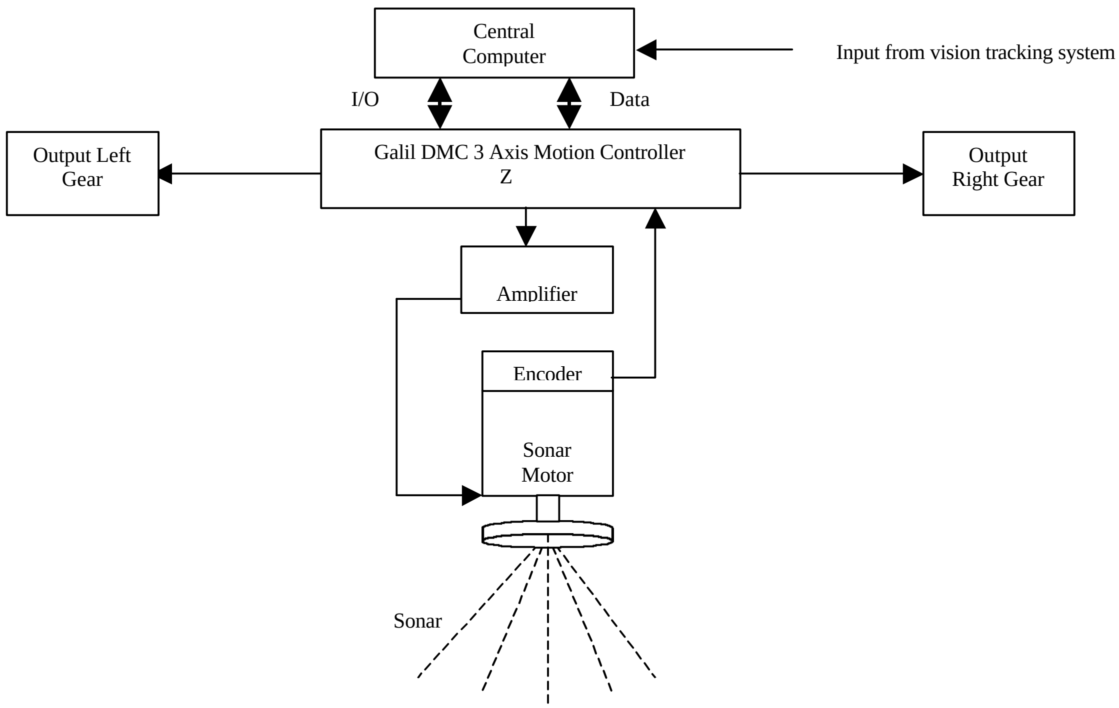

Figure-7. Sonar obstacle detection system

A 12 Volts DC, 0.5 Amps power unit powers the Sonar. The two main components of the ultrasonic ranging system are the transducers and the drive motor as shown in Figure 7. A “time of flight”, approach is used to compute the distance from any obstacle. The Sonar transmits sound waves towards the target and detects an echo, and measures the time that elapses between the start of the transmit pulse and the reception of the echo pulse. The digital electronics generate the ultrasonic frequency of the transmitted signal and the Polaroid IC provides a variable gain for the receiver signal. The transducer sweep is achieved by programming the 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. Knowing the speed of sound in air permits the measurement of the distance to the obstacle. 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 to avoid obstacles and detect dead ends. This system gives a range of approximately 40 feet.

3.6.2 Design Solution Using Laser Scanner

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 0.25^o has been selected. The scanner data is used to get the information about the profile shape and size of the obstacle. It 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 interface between the line following and the motion control program.

3.7 Navigation System

3.7.1 Global Positioning System

A Motorola GPS system is used that includes a custom integrated radio frequency circuit: MRFIC 1504 board and a 32 bit RISC computer MMC 2003. The GPS tracks the NAVSTAR GPS constellation of satellites. The satellite signals received by an active antenna are tracked with 12 parallel channels of L1, C/A code 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 through an RS 232 serial link. For the navigation contest, a fixed base point is set as the home position. Then the GPS is used to get the original position in MAS. Then tracking is used to move from one point to the next, updating the new “base” with every pass. The algorithm is shown in the following pseudo code:

```
Procedure moveCar( X, Y)
Input (desired position X, Y)
Output move the car from current position to the desired position (X, Y)
Begin:
        (curX, curY)=readGPS(timenow)  // (curX, curY) is the current position
        diffX=X-curX
        diffY=Y-curY
        while( sqrt(diffX^2+diffY^2)>0.1) meter then  // if current position is 0.1 meter off its way
                vX=vX+0.01*diffX // change X speed
                vY=vY+0.01*diffY// change Y speed
        endwhile
End moveCar
```

3.8 Safety System

3.8.1 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 a rapid 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. Disconnect switches also permit disconnecting all power for a final safety measure.

3.8.2 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 line with the 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.

3.9 Health Monitoring Systems

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 continuously checks the voltage of the batteries. An audible alarm is sounded when the voltage is less than a threshold to inform the operator to shut down the system and change batteries. Several other meters and LED displays are included to assist in operation. A fault diagnosis system is available on-line for anticipated problems.

4. DESCRIPTION OF INTEGRATION OF CHANGES INTO OVERALL DESIGN:

4.1 Central Controller

The central controller or the Brain of the Bearcat III processes the inputs it receives from the various sensing systems. The reaction i.e. the behavior of the Bearcat III is decided by using a series of algorithms, which after processing its sensory inputs define a navigational path to travel.

The control logic is custom developed software written in C++. A central computer running on both MS-DOS and Windows operating systems, hosts the control program. The principles of SDLC (Software Development Life Cycle) were followed while developing the code for the software. Since a major part of Bearcat's lifetime is spent in testing and adding enhancements to the current system, the software was developed in such a way to be easily managed, tested and upgraded.

The fusion of the sensor inputs with the algorithms is achieved through the high-level control logic that takes in the data from the various sensors and makes high level, intelligent decisions to determine the optimal course. In normal operation, the line following system is given the greatest weight. However, when the lines disappear, an obstacle is encountered or conflicting sensor signals are received, a fuzzy logic approach is used to provide the path control. The data from the vision system (the line following data) and the obstacle avoidance system (sonar, laser scanner and pothole detection camera) are used to make decisions to control the velocity and the orientation of the wheels with reference to the direction of the line being followed. The various sub systems are integrated to make decisions about the speed and steering angle of the vehicle, and switching between the left and the right cameras.

The central controller also uses separate algorithms to integrate the data from the GPS to guide the Bearcat III in a pre-determined path for the navigation challenge event. The omni-vision system used for follow the leader contest is integrated with the motion control system, as is the GPS. A wireless modem setup gives the Bearcat the ability to be controlled from a remote computer and is integrated with the logic for the manual motion control.

The remote emergency stop overrides the commands of all the other system and causes the computer to shut off the power thus bringing the vehicle to a complete stop. The overall system structure has been developed to allow enhancements and integration of new systems in to the current system.

5. DESIGN ISSUES:

5.1 Innovations and Features

Several innovative design features have been included in the design of Bearcat III. The innovations achieved in Bearcat III are the outcome of team effort and co-operation. Like its predecessor, the Bearcat III is a modular design that can be assembled and reassembled within a period of 8 hours. The components used in the design are off-the shelf. They can be bought and assembled in a short time. Changes were also made in control software to incorporate the newly implemented systems - the GPS and the laser scanner. The software written in C++ is object oriented with special emphasis on comments at appropriate places to ensure that the code is understandable. Guidelines about the code and information about the various systems are available online at www.robotics.uc.edu .The various design innovations are as follows:

1. Navigation Systems: To accommodate the changes in the navigation contest a GPS unit is installed to facilitate point-to-point navigation. To ensure accurate line following an innovative vision algorithm that converts the 2-D image co-ordinates into the 3-D real world co-ordinates has been used. The mean square error between these measured and computed points was 0.242 inch for the x-axis and 0.295 inch for the y-axis. A new, simpler vision calibration method was also designed which uses only four calibration points.

2. Obstacle Avoidance: An indoor laser scanner for obstacle avoidance empowers us with the ability to avoid obstacles more efficiently. The indoor laser scanner has a reaction time of and is a more accurate way of identifying obstacles. In addition to the laser scanner the vehicle has the rotating sonar transducer to determine the location of obstacles in real time. Both the systems can be used interchangeably for obstacle avoidance.

3. Durability: A new 36 Volt inverter was added to increase the running time of the robot.

4. Safety: The self-locking mechanism of the gearbox eliminates the need for an external brake to bring the vehicle to a halt. The vehicle comes to a rapid stop after the power is cut off. Both manual and remote controlled emergency stops are used. In addition, power disconnect switches provide a backup safety device. These can also be turned off to prevent operation when the vehicle is unattended.

5. Appearance: A new cover was added to improve the appearance of the robot.

5.2 Problems and Solutions

One of the main problems encountered was the interfacing of the laser scanner with the central controller. This required the use of a RS 422 serial interface card. The installation of the additional PCI card posed problems due to interrupt conflicts between the COM ports. The solution was to use one RS 232 Serial port and assign the interrupt of the other COM port to the PCI slot on which the RS 422 serial interface card is mounted.

5.3 Predicted Performance

In accordance with the contest rules, the maximum speed of the Bearcat III is limited to 5mph. The software is capable of slowing the speed for navigating the obstacle course. The vehicle is also capable of climbing a ramp with a 10% incline. Three 12 Volt, 130 Amp batteries can operate the vehicle for over 3 hours. Sonar and laser scanner sensors are capable of recognizing dead ends and traps in the course. In these cases, the vehicle could come to a stop or backup to try another route. The laser scanner, which is mounted at a height of 8 inches from the ground, can detect low-lying debris and obstacles as well as taller supported obstacles. It would not detect tree limbs or other unsupported obstacles.

5.4 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. RESULTS:

An autonomous robot has been designed, constructed and tested. The technical specifications are shown in Appendix 1. A comprehensive list of bill of materials with supplier details, unit cost and total cost is shown in Appendix 2. The vehicle has been tested outside under various conditions in the sun and rain. In the rain, a protective cover must be used. Flat surfaces of various materials including asphalt, concrete and grass have been traversed. It has been tested on inclined ramps with slopes up to 10%. The vehicle was found to behave well under these conditions but each test has led to improvements. The nature of the autonomous vehicle is that continuous improvements can be made each year.

APPENDIX I. TECHNICAL SPECIFICATIONS OF BEARCAT III

1.	Construction	Structure	Aluminium extrusions - 1.5" x 1.5"
		Design	A kit design - made of off-the-shelf components
		Assembling time	8 hours (approximate assembly time)
2.	Size	Length x Breath x Height	49'' x 33'' x 44''
		Wheel span	28 inches
		Weight	630 lbs.
		Design Payload	100 lbs.
3.	Power	Peak current drawn	15 amps
		Peak voltage	36 volts
		No. of batteries	3, 12 volt marine
		Run time between recharges	At 36 volts continuous, 7 hours
		Charging time needed	8 hours
4.	Motion Control	Direction of motion	Forward and reverse
		Turning Radius	0 (zero turning radius)
		Maximum Speed	5 mph
		Acceleration	0-5 mph in 5 sec
		Braking distance	< 1 inch (at maximum speed)
5.	Sonar Data	Number of sonars	One/two (rotating sonar)
		Obstacle sensing distance	8-14 feet
		Sonar sweep	100-120 degrees
		Reaction time	49 milliseconds
		Cycle time	20 milliseconds
6.	Vision Data	Distance viewed ahead	2.5 to 8.5 feet
		Number of cameras	4 (3 for main contest, 1 for follow the leader)
		Size of vision window	6 feet x 4 feet
		Capture cycle time	52 milliseconds
		Number of lines tracked	One at a time – two in total
7.	Control Logic	Principal cycle time	0.5 seconds
		Sensor fusion	Fuzzy logic
		Sensor hierarchy	1. Sonar
			2. Vision
8.	Safety	Number of emergency stops	2
		Range of remote E-stop	65 feet
		Stopping mechanism	Power/mechanical locking
9.	Software	Operating system	MS-DOS and Windows
		Development environment	Borland C++ v3.0, Watcom C++ v11.0
		Control software	Bearcat III version 1.0
10.	Special	Pothole Detection	EPIX Frame Grabber
	Features	Follow the leader	180 degree view - fish eye lens and control logic
		Dead end detection	ZTR, reversing ability
		Construction	A kit design - made from off-the-shelf components
11.	Laser Scanner Data	Number of Scanners	One
		Obstacle sensing distance	> 8 meters
		Laser sweep	180 degrees
		Resolution	.25°, .5°, 1°
		Reaction time	60 milliseconds
12.	GPS	Accuracy	10 meters with relative algorithm
13.	Material Costs:		$29,385.84

APPENDIX II. BILL OF MATERIALS

S.No	Part	Qty.	Description	Vendor	Price	Total
1	1515LITE	22	Aluminum extrusion – 43.5" long	80/20 Inc.	$9.96	$219.17
2	90 deg joining plate	40	15 Series - 3320, 4350, 4351	80/20 Inc.	$7.13	$285.2
3	Flanged BHSCS	394	Flanged BHSCS 3320, 3321	80/20 Inc.	$0.55	$218.64
4	4101	12	10 series inside corner bracket	80/20 Inc.	$3.90	$46.80
5	4302	60	15 series 2 hole inside bracket	80/20 Inc.	$2.80	$168.00
6	0728-39-003	2	Electro-craft motor model E728	Reliance Electric	$900.00	$1,800.00
7	DC48A	2	Advanced motion controls	Reliance Electric	$300.00	$600.00
8	RK446R	1	ISCAN video tracker	Iscan Inc.	$9,000.00	$9,000.00
9	JVC-1520	2	JVC solid state cameras	JVC Inc.	$400.00	$800.00
10	MT1CCD72G	1	Fish eye lens and adapter	Nikon Inc.	$475.00	$475.00
11	(Assembled)	1	442 video switch	Maxim Inc.	$20.00	$20.00
12	Power supply	1	5 Volt video power supply	Radio Shack	$50.00	$50.00
13	DMC1030	1	Galil DMC 1030	Galil, Inc.	$900.00	$900.00
14	ICM1100	1	Galil breakout board ICM 1100	Reliance Electric	$150.00	$150.00
15	Computer	1	Pentium II computer	UC Bookstore	$1,200.00	$1,200.00
16	C++	1	Turbo C++	UC Bookstore	$100.00	$100.00
17	8000 series	1	RS 232 interface – 4 port	Black Box Corp.	$250.00	$250.00
18	Trojan	5	12 volt marine batteries	Michael Tire Co.	$65.00	$325.00
19	PV750FC	1	750 watt inverter	Triplite	$600.00	$600.00
20	F721-40	2	Boston gearboxes, worm gear, 40:1	Cincinnati Belting	$340.00	$680.00
21	P2BSCM100	4	Bearing blocks	Cincinnati Belting	$31.56	$126.24
22	6L019, 6L016	4	Shaft couplings	Grainger	$6.00	$24.00
23	ZF720, ZF768	4	Shaft key	Grainger	$4.28	$17.12
24	90 Series 6S	2	Castor wheels 8" dia. Overall	Borne & Co.	$27.75	$55.50
25	10 series	2	Drive wheels, pneumatic	Borne & Co.	$30.00	$60.00
26	Cables	8	Battery connecting cables	Michael Tire Co.	$2.00	$16.00
27	End caps	10	Battery connecting insulators	Michael Tire Co.	$1.50	$15.00
28	Switch	10	Switches	Home Depot	$1.50	$15.00
29	Connectors	30	Connectors and lugs	Home Depot	$0.15	$4.50
30	10SWG	30	Wires - red, blue, black	Home Depot	$30.00	$90.00
31	16 SWG	15	Wires – red, blue, black	Home Depot	$15.00	$225.00
32	FRF03-01U	1	Remote switch - Futaba	Futaba Inc.	$520.00	$520.00
33	F721 base	2	Gearbox base	Cincinnati Belting	$30.00	$30.00
34	Plexiglas - Bronze	3	10'x10'	Cincinnati Plastics	$60.00	$180.00
35	Fasteners	84	Butterfly bolts and nuts	Home Depot	$0.25	$21.00
36	Keels	30	Plastic keels	Cincinnati Plastics	$1.00	$30.00
37	Solenoid	1	Relay switch	Tektron Corp.	$24.00	$24.00
38	7000 series	2	Polaroid Polakits	Polaroid Systems	$295.00	$590.00
39	MG-PS10AD	1	Power supply	Hosefelt Inc	$350.00	$350.00
40	0723-39	1	Electrocraft motor with encoder	Reliance Electric	$651.90	$651.90
41	Frame Grabber	1	EPIX SV4 Imaging Board	EPIX Inc	$395.00	$395.00
42	Video Switch	1	CCSU-8BW	FSR Inc	$2000.00	$2000.00
43	Video Camera	1	Panasonic RS170	Panasonic	$400.00	$400.00
44	C++ Compiler	1	Watcom C++ ver 11.0	Watcom	$200.00	$200.00
45	Miscellaneous		Miscellaneous resins, tapes, tools.	Grainger		$1,000.00
46	Laser Scammer	1	LMS 200	SICK Optics	$3890	$3890
47	GPS	1	MRFIC 1504 board	Motorola	$300	$300
48	Serial Interface Card	1	RS 422 Serial interface PCI Card	Black box	$267	$267
					Total	$29385.84

Table-3. Bill of materials, manufacturers and prices