# Bearcat II

## Design Report

## 8th Intelligent Ground Vehicle Competition

Submitted by
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University of Cincinnati

Faculty Advisor
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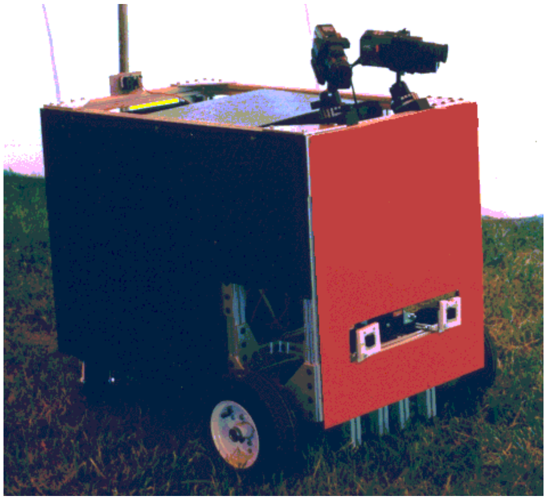


# *Table of Contents*

## 1. *Introduction*

This report describes the design and fabrication of the Bearcat II – an intelligent, autonomous, mobile robotic vehicle designed to contest in the 8th Intelligent Ground Vehicles Competition that is to be held between July 8 and July 10, 2000 in Orlando, FL. A multi-disciplinary team of engineers and scientists used a ‘divide-and-conquer’ approach to design the robotic vehicle. The design was divided into separate functional subsystems integrated with a high-level control logic that enables the vehicle to function as an integral system meeting all the performance requirements. Each sub-system is designed to meet a specific contest rule.

The strategy adopted for the designing the vehicle is described in Section 2. Section 3 gives the team involved in the design of the vehicle. Innovative design aspects are described in Section 4. The software design tools are designed in Section 5. The competition requirements are described in Section 6 with the analysis and the design solution for each specification. The road debris competition is described in Section 7. The follow the leader competition is described in Section 8. Fault diagnosis is described in Section 9. Preliminary results are described in Section 10. The vehicle specifications and bill of materials (BOM), manufacturers and cost are given in the appendices.

## 2. *Design Strategy*

The development of the Bearcat II 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 would be 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 vehicle can be broadly decomposed into six major sub-systems as shown in Figure 1.

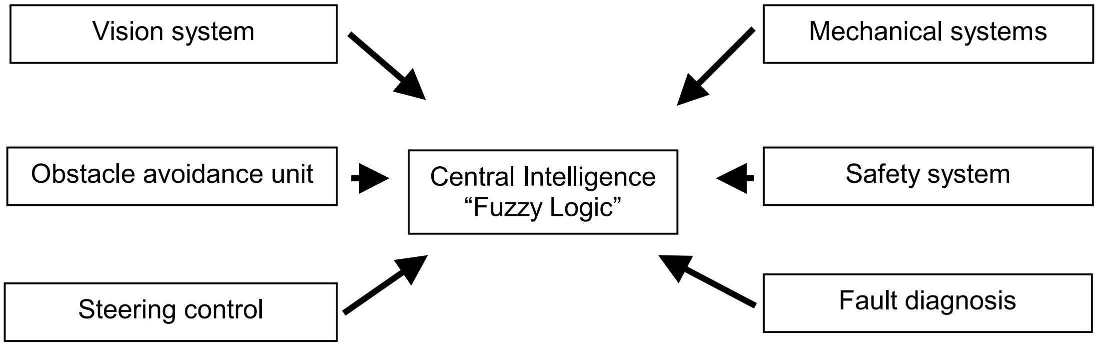


**Figure 1.Design Strategy**

## 3. *UC Robot Team*

A team consisting of both undergraduate and graduate students from various disciplines was formed in September 1999. 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 strength and interests. However, every team member was trained to understand the safe operation of all the sub-systems of the vehicle.

| Name | Year | Degree | Design Module |
|---|---|---|---|
| Rahul Dhareshwar | 2001 | Industrial Eng. (MS) | Vision Systems |
| Meyyappa Ganesh | 2001 | Industrial Eng. (BS) | Software Support |
| Rob Hicks | 2001 | Engineering (MS) | Mechanical Systems |
| Sampath Kanakaraju | 2000 | Industrial Eng. (MS) | Fault Diagnosis |
| Jaiganesh Karuppuswamy | 2001 | Industrial Eng. (MS) | Vision Systems |
| Xiaoqun Liao | 2002 | Industrial Eng. (PhD) | Obstacle Avoidance |
| Nathan Mundhenk | 2000 | Psychology (BS) | Vision and Sonar Systems |
| Ramya Ravindran | 2001 | Industrial Eng. (MS) | Electrical Systems |
| Mike Rivett | 2004 | Computer Science (BS) | System Support |
| Mayank Saxena | 2001 | Industrial Eng. (MS) | Electrical Systems |
| Sathish Shanmugasundaram | 2000 | Industrial Eng. (MS) | Power/Mechanical Systems |
| Vishnuvardhanaraj Selvaraj | 2001 | Industrial Eng. (MS) | Mechanical Systems |
| Vijayakumar Sreekantan | 2001 | Industrial Eng. (MS) | Obstacle Avoidance |
| Ramesh Thyagarajan | 2000 | Industrial Eng. (MS) | Mechanical Systems |

**Table 1. UC Robot Team Members**

## 4. *Innovations in Design*

The major innovations in the Bearcat II design are summarized below:

1. Modularity – The vehicle can be disassembled and reassembled again in approximately 8 hours. The vehicle can be re-configured or transformed into another structure.
2. Off-the-shelf Design – All of the components are readily available “off the shelf”. A minimum amount of machining processes was needed to build this machine. With adequate resources and motivation, all the components can be bought and assembled in less than 5 days.

3. Zero Turning Radius – The vehicle has 2 drive wheels that are individually powered. This helps in realizing zero turning radius, which ensures maximum maneuverability. This is very critical in negotiating sharp turns or escaping dead ends. Also, the vehicle can move forward or reverse.
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. Also, power disconnect switches provide a backup safety device. These can also be turned off to prevent operation when the vehicle is unattended.
5. 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.
6. Obstacle Avoidance – The vehicle has a rotating and a stationary sonar transducer. These sensors can calculate the location, orientation and also the critical edges of the obstacles in real time.
7. Electrical Safety – The vehicle circuits are color-coded and protected with fuses.
8. Operational Safety – The remote emergency stop can operate from as far as 65 feet while the requirement is 50 feet.

## 5. *Design Tools*

To ensure that the vehicle is robust, easy to assemble and simple to maintain, several software design tools were used. The primary mechanical and power systems design calculations were designed with MathCAD 6.0[1] under the Windows NT environment. The advantage of using MathCAD is that it enables us to iterate through various design configurations with minimal effort.

When the team approved the initial design, a 3-D solid model of the kit was developed using AutoCAD Release 14[2]. After several iterations, the final “Bill of Materials” for the structure was developed using the 80/20 libraries[3] for AutoCAD. The control system was designed and tested using SIMULINK[4], while calibration was done using MathCAD and MATLAB 5.2[5].

The control system was tuned using Galil Windows Servo Design Kit (WSDK) 4.0[6]. The vehicle structure was examined for vibrations using IDEAS 6.0[7]. The structure was also analyzed using finite element analysis with IDEAS. Beam elements have been used to determine various stresses, moments and loads and to analyze the behavior of the frame under various conditions. The control software "Bearcat II" was developed in the Borland C++ 5.0[8] environment. A fault diagnostic expert system and another base design expert system was developed to support the vehicle. These were developed using Visual Basic 6.0[9] supported by Microsoft SQL Server[10].

## 6. *Autonomous Vehicle Challenge*

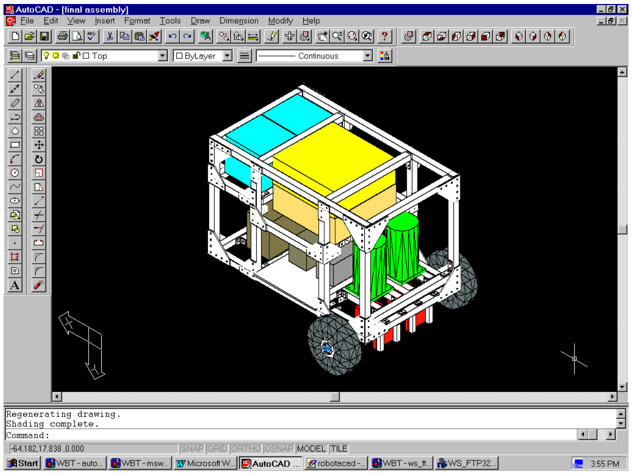
### 6.1 Vehicle Configuration

***Requirements Analysis:***

The vehicle is designed to be an outdoor vehicle capable of carrying a payload of at least 20 pounds, to fit the size requirements of the competition and with sufficient power for an 8-hour operation.

***Design Solution:***

The solution was to design a modular robot kit that can be collapsed and assembled in a short period of time. Aluminum extrusions with joining plates and T-nuts were used to construct the main framework as shown in Figure 2. The initial design calculations were done using standard design procedures and the required components were selected from the corresponding manufacturers' catalogues. The principal advantage with this solution is that once the design is completed the required part can be bought with minimal lead-time.



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Regenerating drawing.
Shading complete.
Command:
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**Figure 2. AutoCAD 3D Solid Model of Bearcat '00**

A 3-D solid model was then developed featuring the selected components. The novelty in this part of the design was the use of the 80/20 part libraries. Using the 3D model, we were able to get the bill of materials for the vehicle main frame, as soon as we completed the design.

The base was also subjected to a post-design vibration testing and finite element analysis, as shown in Figure 3, to study the behavior of the vehicle under various load conditions[11].

All the above steps were done in an iterative process. If the components did not fit, the whole process was repeated.

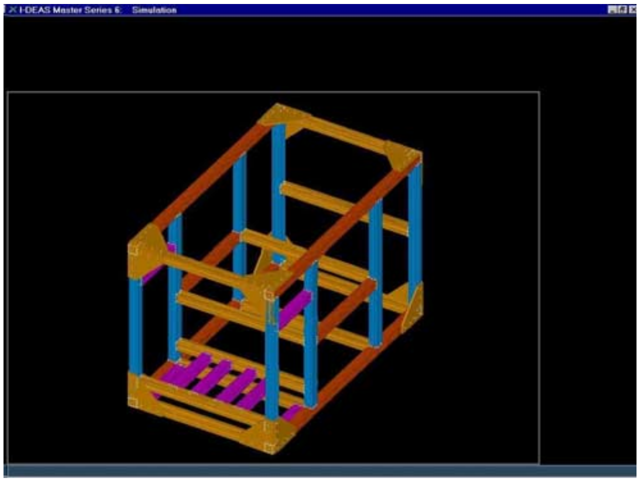

Figure 3. Structural Beam Model in IDEAS

***Safety Considerations:***

All the components were rigidly tightened to the base, properly cleated and the CPU hard drive of the control computer was shock-mounted to tolerate shocks and vibrations. All the circuits are color coded to ensure proper re-connection, in case they need to be rewired. To prevent the destruction of any component, the main frame has been consciously designed such that the aluminum frame forms the boundary on all sides. A front bumper was added to protect the cameras in case of a collision.

## 6.2 Vehicle Motion Control

***Requirements Analysis:***

The vehicle should be propelled by direct mechanical to ground contact with a maximum speed of 5 mph. The vehicle should also be able to confront natural or artificial inclines of about 15% gradient.

***Design Solution:***

Two individually driven front wheels powered by two 36-volt, 15-amp motors are used as shown in Figure 4. The motors drive the left and the right wheel separately through two independent gearboxes, which increase the motor torque by a factor of 40. This enables a zero turning radius by rotating one wheel in the forward direction and the other in the reverse direction. This unique design offers the ability to make a turn about the center of axis of the drive wheels thereby providing the vehicle exceptional maneuverability. The power to each motor is delivered from an AMC DC 48A amplifier that amplifies the signal from the Galil DMC Motion Controller. To complete the control loops, a position encoder is mounted on each of the drive motors. A castor wheel at the back of the vehicle balances the load.

Steering the vehicle is achieved by varying the speed of the left and the right wheels while negotiating a curve. This enables the vehicle to make a curved turning 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.

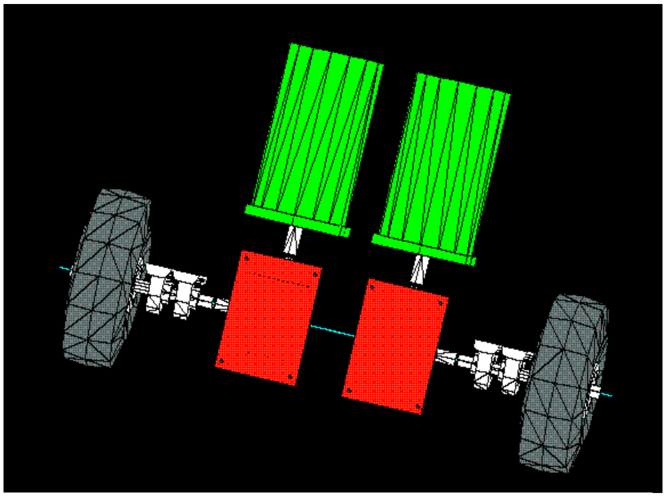

Figure 4. 3D Model of the Power Train

Velocity of Vehicle, $V = (V_L + V_R)/2$

Orientation of Vehicle, $\theta = (V_L - V_R)/WT$

where, $V_L$ = Velocity of the left wheel

$V_R$ = Velocity of the right wheel

W = Distance between the center of the two wheels

T = Sampling time

The design objective in selecting the motor control parameters was to obtain a stable control over the steering system with a good phase and gain margin and a fast unit step response. For this purpose a Galil Motion Control Board with a Proportional Integral Derivative controller (PID Controller) was used. The system was modeled in MATLAB using SIMULINK and the three parameters of the PID controller were selected using a simulation model to obtain optimum response. The unit step response values for the PID controller were tested on the actual vehicle and were fine tuned using the software supplied by Galil Motion, Inc. – WSDK 1000.

Safety Considerations:

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, which is designed to operate to a maximum of 65 feet. The advantage of using this is that the transmitter need not be in the line of sight with 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.

The manual emergency stop unit consists of a red manual push button located on the easily accessible rear surface of the vehicle. When pushed, the power to the motors is cut off and the self-locking mechanism of the gearbox brings the vehicle to a rapid halt. This self-locking mechanism ensures that the vehicle does not move when it is not powered, and serves as a safety measure against any possible runaway situation for the vehicle.

To prevent short-circuits between the aluminum frame and the power units, the batteries, connections and switches were insulated. The monitors were shielded to prevent their interference with the remote emergency stop.

## 6.3 Line Following System

### *Requirements Analysis*

The vehicle has to track white or yellow, solid or dashed, lane markers that are 3 inches wide.

### *Design Solution*

Two JVC CCD cameras[12] are used to view and follow the left or the right lane marker. Only one lane marker is followed at any instant. A CCSU-8BW video switch device from FSR, Inc. alternates between the two cameras depending on the visibility of the lane marker. The video switch is controlled from the software through the Galil DMC.

An ISCAN[13] RK-446-R image-tracking device processes the image from the camera. The device finds the centroid of the brightest or darkest region in a computer controlled window, and returns the X, Y co-ordinates of its centroid and the size information of the blob. If no object is found, a loss of track (LOT) signal is generated. The cameras are angled downward at 32° and panned to the front at 30°. This setup gives a 4-foot wide view of the ground and 6-foot view ahead.

Image co-ordinates are two-dimensional while actual world co-ordinates are three-dimensional. In an autonomous situation, the problem is to determine the three-dimensional coordinates of a point on the line given its image coordinates. A new algorithm[14] was developed to establish the mathematical and geometrical relationships between the physical 3-D world coordinates of the line to be followed and its corresponding 2-D digitized image coordinates. The mean square error between these measured and computed points was 0.242 inches for the X-axis and 0.295 inches for the Y-axis, which established the accuracy of the algorithm. A new simpler vision calibration method has also been designed which uses only four 3-D points.

## 6.4 Pothole Detection

***Requirements Analysis:***

The vehicle should be capable of detecting and avoiding simulated potholes represented by two feet diameter white circles randomly positioned along the course.

***Design Solution:***

A monochrome Panasonic RS170 camera was used to detect simulated potholes. The data from the camera is passed into an Imaging Board from EPIX Inc. The formatted data from the EPIX Imaging Board is then processed to detect the presence of a simulated pothole and the centroid location of the pothole, in case one is present.

First, a threshold operation is performed on the image to obtain a binary image. Then, the noise from the environment is removed by analyzing the blobs in the image. The noise-removed image is then processed with a circular regression procedure. The XCOBJ/PXIPL Image Processing libraries[16] provided by EPIX were used extensively for developing the control software.

## 6.5 Central Intelligence

***Requirements Analysis:***

The various sub systems have to be integrated to make decisions like the speed and steering angle of the vehicle, and switching between the left and the right cameras.

***Design Solution:***

The control logic was built into the custom developed software written in C++. A central computer running in MS-DOS operating system, hosts the control program. Sensor fusion is achieved through the high-level control logic that takes in the data from the various sensors and makes sensible decisions. The line following system is given the greatest weight and the data from the sonar (for obstacle avoidance) and the front camera (for pothole detection) are fused with the line following data. The input from all these sensors are used to take decisions to control the velocity and the orientation of the wheels as mentioned in Section 6.2: Vehicle Motion Control.

Driver software was written for the Galil Motion Control Board in C language, and for the other sensors the drivers supplied with the hardware were used. In the case of the EPIX Imaging Board, the libraries supplied were used extensively for writing the control software.

## 7. *Road Debris Competition*

***Requirements Analysis:***

The vehicle should be capable of detecting and avoiding 5-gallon white pails and full-size orange and white construction drums.

***Design Solution:***

The obstacle avoidance system consists of a Polaroid ultrasonic transducer[15] in fixed and rotating mounts. In operation, the system uses a "Time of Flight" (TOF) approach to compute the distance from any obstacle. The system transmits sound waves towards a 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. Knowing the speed of sound in air, the system can convert the elapsed time into a distance measurement and hence compute the distance. The distance value is returned through a RS 232 port to the control computer.

An Intel 80C196 microprocessor and a circuit board with a liquid crystal display are used for processing the distance calculations. The system requires an isolated power supply: 12 Volts DC, 0.5 Amps. The two major components of the ultrasonic ranging system are the transducer and the drive electronics. The range of the system depends on system parameters as well as outdoor operating conditions, but is approximately 40 feet.

System parameters include: internal frequency, blanking time and signal frequency. Environment parameters include: humidity, temperature and external noise. A drive signal of 16 pulses @ 52 kHz is used. The digital electronics generate the ultrasonic frequency of the transmitted signal and the Polaroid integrated circuit provides a variable gain for the received signal. Using a closed loop DC servomotor, the transducer is made to sweep an angle depending on the horizon. The control loop is closed by an encoder, which measures position for feedback. The sonar pings (firing time) are controlled in the software.

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. The main advantage in using one rotating sonar is that, when it runs in conjunction with the logic, the vehicle can not only detect an obstacle and find its distance, but also calculate its orientation and shape.

To detect dead-ends and trap corners, the control software computes the distance between the obstacle and the nearest boundary line and stops when three successively smaller distances are encountered. The vehicle then backs up 7 feet and tracks the opposite line.

## 8. *Follow the Leader Competition*

***Requirements Analysis:***

The vehicle must be capable of following a lead vehicle by targeting a wooden sign of size 15 cm high by 30 cm wide.

***Design Solution:***

A unique omni-directional vision system with a 180-degree view wide-angle fish eye lens was used to achieve the design goal as shown in Figure 5. 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.

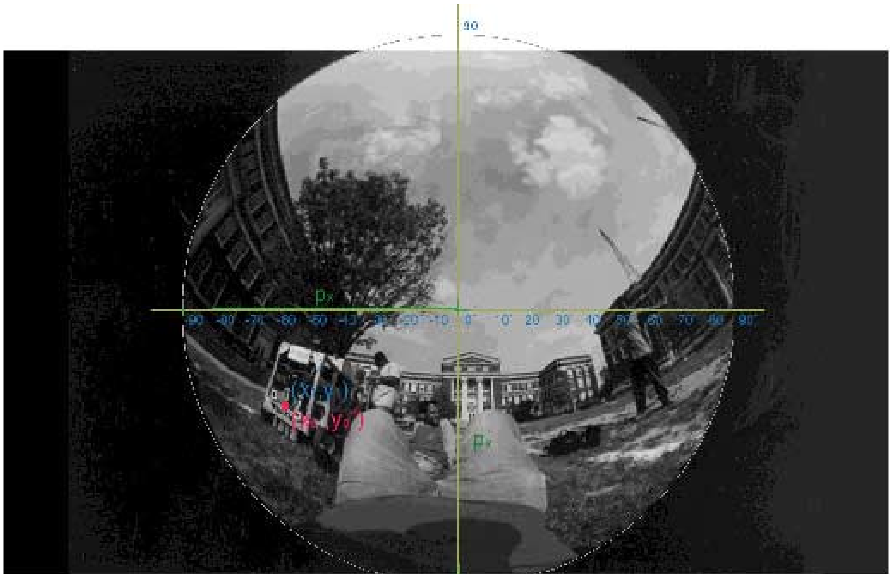

**Figure 5. Wide Angle Image**

First, the distortions from the fish-eye lens are removed. Using an innovative custom equation combined with circular regression, the resulting information is processed to get the target world co-ordinates. The two dimensional data is also used to determine the distance of the lead vehicle from the robotic vehicle.

## 9. *Fault Diagnosis*

***Requirements Analysis:***

The reliability of the various sub-systems is critical to the successful functioning of the vehicle. Also quick fault fixing is a key element in successful functioning of the vehicle. To achieve this we need a tool that can monitor the various faults occurring in the system and can suggest corrective actions.

***Design Solution:***

A computer aided Robot Fault Diagnostic System (RFDS) was developed. Using a top-to-bottom approach the vehicle is divided into major functional units. These are analyzed in depth in terms of potential failures and their effects on the vehicle as a whole. The possible causes of failures and their corresponding remedies were explored through the technique of Potential Failure Modes and Effects Analysis (PFMEA).

## 10. *Results*

A robotic kit has been designed, constructed and tested. A comprehensive list of Bill of Materials (BOM), along with supplier details, unit cost and total cost has been generated as shown in the appendix.

The vehicle has been tested outside under various conditions in the sun and rain. Flat surfaces have been used of various materials including asphalt, concrete and grass. Inclined ramps with slopes up to 30% have been tested. The vehicle was found to behave well under these conditions but each test has led to improvements.

## 11. *Acknowledgements*

Our team would like to thank the following contributors:

- Our previous team members especially: Karthikeyan Kumaraguru, Sameer Parasnis, Tayib Samu, Nikhil Kelkar, Umesh Nikham, Bradley Matthews, David Perdue, Mike Ruthemeyer, Alan Lewis, Malik Spencer, Sanjeev Gupta, Fred Reckelhoff, Todd Brehm, Dhyana Chandra, Raymond Ande, Scott Pawlikowski, Kalyan Kolli, Krishnamohan Kola, Kay Shastry, and Randy Smith.
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- Our generous individual and corporate sponsors whose contributions enabled us to build this robotic vehicle – Bearcat II. All our sponsors are listed at our web page at: http://www.robotics.uc.edu/Y2KSponsorslist.htm/

## *Appendix 1: Technical Specifications of the Vehicle*

| | | | |
|---|---|---|---|
| 1 | **Construction** | Structure | Aluminum 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 | 49 inches |
| | | Breadth | 33 inches |
| | | Height | 44 inches |
| | | 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<br>2. Vision |
| 8 | **Safety** | Number of emergency stops | 2 |
| | | Range of remote E-stop | 65 feet |
| | | Stopping mechanism | Power/mechanical locking |
| 9 | **Appearance** | Color | Red and black |
| | | Shape | Prismatic Solid |
| 10 | **Software** | Operating system | MS-DOS and Windows |
| | | Development environment | Borland C++ v3.0, Watcom C++ v11.0 |
| | | Control software | Bearcat II version 3.0 |
| 11 | **Special Features** | Pothole Detection | EPIX Frame Grabber |
| | | Follow the leader | 180 degree view - fish eye lens and control logic |
| | | Dead end detection | ZTR, reversing ability |
| | | Construction | A kit design - made of off-the-shelf components |
| 12 | **Material Costs:** | | $24,928.84 |

## *Appendix 2: Bill of Materials, Manufacturers and Price*

| Sl. # | Mfr. Part # | Qty. | Description | Vendor | Price | Total |
|---|---|---|---|---|---|---|
| 1 | 1515LITE | 2 | Aluminum extrusion -- 43.5" long | 80/20 Inc. | $20.33 | $40.66 |
| 2 | 1515LITE | 4 | Aluminum extrusion -- 26.3" long | 80/20 Inc. | $13.90 | $55.60 |
| 3 | 1515LITE | 4 | Aluminum extrusion -- 22.5" long | 80/20 Inc. | $11.51 | $46.04 |
| 4 | 1515LITE | 4 | Aluminum extrusion -- 17.22 " long | 80/20 Inc. | $9.41 | $37.64 |
| 5 | 1515LITE | 2 | Aluminum extrusion -- 10.07" long | 80/20 Inc. | $6.47 | $12.94 |
| 6 | 1515LITE | 2 | Aluminum extrusion -- 9.88" long | 80/20 Inc. | $6.05 | $12.10 |
| 7 | 1010LITE | 4 | Aluminum extrusion -- 8.33" long | 80/20 Inc. | $3.74 | $14.96 |
| 8 | 3320 | 14 | 15 Series 90 deg joining plate | 80/20 Inc. | $8.25 | $115.50 |
| 9 | 4350 | 4 | 15 Series 90 deg joining plate | 80/20 Inc. | $5.30 | $21.20 |
| 10 | 4351 | 22 | 15 Series 90 deg joining plate | 80/20 Inc. | $6.75 | $148.50 |
| 11 | 3320 | 344 | Flanged BHSCS - economy T-Nut | 80/20 Inc. | $0.57 | $196.08 |
| 12 | 3321 | 48 | Flanged BHSCS - economy T-Nut | 80/20 Inc. | $0.47 | $22.56 |
| 13 | 4101 | 12 | 10 series inside corner bracket | 80/20 Inc. | $3.90 | $46.80 |
| 14 | 4302 | 60 | 15 series 2 hole inside bracket | 80/20 Inc. | $2.80 | $168.00 |
| 15 | 0728-39-003 | 2 | Electro-craft motor model E728 | Reliance Electric | $900.00 | $1,800.00 |
| 16 | DC48A | 2 | Advanced motion controls | Reliance Electric | $300.00 | $600.00 |
| 17 | RK446R | 1 | ISCAN video tracker | Iscan Inc. | $9,000.00 | $9,000.00 |
| 18 | JVC-1520 | 2 | JVC solid state cameras | JVC Inc. | $400.00 | $800.00 |
| 19 | MT1CCD72G | 1 | Fish eye lens and adapter | Nikon Inc. | $475.00 | $475.00 |
| 20 | (Assembled) | 1 | 442 video switch | Maxim Inc. | $20.00 | $20.00 |
| 21 | Power supply | 1 | 5 Volt video power supply | Radio Shack | $50.00 | $50.00 |
| 22 | DMC1030 | 1 | Galil DMC 1030 | Galil, Inc. | $900.00 | $900.00 |
| 23 | ICM1100 | 1 | Galil breakout board ICM 1100 | Reliance Electric | $150.00 | $150.00 |
| 24 | Computer | 1 | Pentium II computer | UC Bookstore | $1,200.00 | $1,200.00 |
| 25 | C++ | 1 | Turbo C++ | UC Bookstore | $100.00 | $100.00 |
| 26 | 8000 series | 1 | RS 232 interface – 4 port | Black Box Corp. | $250.00 | $250.00 |
| 27 | Trojan | 5 | 12 volt marine batteries | Michael Tire Co. | $65.00 | $325.00 |
| 28 | PV750FC | 1 | 750 watt inverter | Triplite | $600.00 | $600.00 |
| 29 | F721-40 | 2 | Boston gearboxes, worm gear, 40:1 | Cincinnati Belting | $340.00 | $680.00 |
| 30 | P2BSCM100 | 4 | Bearing blocks | Cincinnati Belting | $31.56 | $126.24 |
| 31 | 6L019, 6L016 | 4 | Shaft couplings | Grainger | $6.00 | $24.00 |
| 32 | ZF720, ZF768 | 4 | Shaft key | Grainger | $4.28 | $17.12 |
| 33 | 90 Series 6S | 2 | Castor wheels 8" dia. overall | Borne & Co. | $27.75 | $55.50 |
| 34 | 10 series | 2 | Drive wheels, pneumatic | Borne & Co. | $30.00 | $60.00 |
| 35 | Cables | 8 | Battery connecting cables | Michael Tire Co. | $2.00 | $16.00 |
| 36 | End caps | 10 | Battery connecting insulators | Michael Tire Co. | $1.50 | $15.00 |
| 37 | Switch | 10 | Switches | Home Depot | $1.50 | $15.00 |
| 38 | Connectors | 30 | Connectors and lugs | Home Depot | $0.15 | $4.50 |
| 39 | 10SWG | 30 | Wires - red, blue, black | Home Depot | $30.00 | $90.00 |
| 40 | 16 SWG | 15 | Wires – red, blue, black | Home Depot | $15.00 | $225.00 |
| 41 | FRF03-01U | 1 | Remote switch - Futaba | Futaba Inc. | $520.00 | $520.00 |
| 42 | F721 base | 2 | Gearbox base | Cincinnati Belting | $30.00 | $30.00 |
| 43 | Plexiglas - Bronze | 3 | 10'x10' | Cincinnati Plastics | $60.00 | $180.00 |
| 44 | Fasteners | 84 | Butterfly bolts and nuts | Home Depot | $0.25 | $21.00 |
| 45 | Keels | 30 | Plastic keels | Cincinnati Plastics | $1.00 | $30.00 |
| 46 | Solenoid | 1 | Relay switch | Tektron Corp. | $24.00 | $24.00 |
| 47 | 7000 series | 2 | Polaroid Polakits | Polaroid Systems | $295.00 | $590.00 |
| 48 | MG-PS10AD | 1 | Power supply | Hosefelt Inc | $350.00 | $350.00 |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| 49 | 0723-39 | 1 | Electrocraft motor with encoder | Reliance Electric | $651.90 | $651.90 |
| 50 | Frame Grabber | 1 | EPIX SV4 Imaging Board | EPIX Inc | $395.00 | $395.00 |
| 51 | Video Switch | 1 | CCSU-8BW | FSR Inc | $2000.00 | $2000.00 |
| 52 | Video Camera | 1 | Panasonic RS170 | Panasonic | $400.00 | $400.00 |
| 53 | C++ Compiler | 1 | Watcom C++ ver 11.0 | Watcom | $200.00 | $200.00 |
| 53 | Miscellaneous |  | Miscellaneous resins, tapes, tools. | Grainger |  | $1,000.00 |
|  |  |  |  | **Total** |  | **$24,928.84** |

## *References*

1. MathCAD is the registered trademark of MathSoft, Inc.
2. AutoCAD is the registered trademark of AutoDesk, Inc.
3. “80/20 AutoCAD libraries,” 80/20, Inc., Industrial Erector Set, Columbia City, IN, 1998.
4. SIMULINK is the registered trademark of Math Works, Inc.
5. MATLAB the registered trademark of Math Works, Inc.
6. “DMC-1000 Technical Reference Guide Ver 1.1,” Galil, Inc., Sunnyvale, CA, 1993.
7. IDEAS is the registered trademark of SDRC, Inc.
8. Borland C++ is the registered trademark of Borland Systems, Inc.
9. Visual basic 6.0 is the registered trademark of Microsoft, Inc.
10. Microsoft SQL Server is the registered trademark of Microsoft, Inc.
11. “Finite Element Analysis of Vehicle Structure,” Jaideep Karnik, UC Graduate Student, Mechanical Eng.
12. “Camera Users Manual,” JVC, Inc., Indianapolis, IN, 1985.
13. “RK-446-R Video Tracking System Manual,” ISCAN, Inc., Cambridge, MA, 1993.
14. “Vision System for Three Dimensional Line Following of an Unmanned Autonomous Mobile Robot,” MS Thesis by Tayib Samu, University of Cincinnati, 1996.
15. “DMC-1000 Technical Reference Guide Ver. 1.1,” Galil Inc., Sunnyvale, CA 1993.
16. “XCOBJ/PXIPL Image Processing Libraries,” EPIX Inc. Buffalo Grove, IL, 1999.