# Motion Control Design of the Bearcat II Mobile Robot

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**ABSTRACT**

Motion control is one of the most critical factors in the design of a robot. The purpose of this paper is to describe the research for applying motion control principles for a mobile robot systems design, which is on going at the University of Cincinnati Robotics Center. The mobile robot was constructed during the 1998-1999 academic year, and called BEARCAT II. Its design has inherited many features of its predecessor, BEARCAT I, such as vision guidance, sonar detection and digital control. In addition, BEARCAT II achieved many innovative motion control features as rotating sonar, zero turning radius (ZTR), current control loop, and multi-level controller design (conventional control and fuzzy logic control). This paper will focus on the motion control design, development and programming for the vehicle steering control and rotating sonar systems. The systems have been constructed and tested at the 1999 International Ground Robotics Competition with the Bearcat II running an obstacle course for 153.5 feet and finishing fourth in the competition. The significance of this work is in the increased understanding of robot control and the potential application of autonomous guided vehicle technology for industry, defense and medicine.
Keywords: Motion control, motion behavior, compensation, mobile robots

## 1. INTRODUCTION

Motion control is one of the technological foundations of industrial automation. Whether the motion of a product, the path of a cutting tool, the motion of an industrial robot arm conducting seam welding, the motion of a parcel being moved from a storage bin to a loading dock by a shipping cart, or another application, the control of motion is a fundamental concern. Putting an object in the correct place with the right amount of force and torque at the right time is essential for efficient manufacturing operations. To be able to control a motion process, the precise position of objects needs to be measurable. Feedback comparison of the target and actual positions is then a natural step in implementing a motion control system. This comparison generates an error signal that may be used to correct the system, thus yielding repeatable and accurate results.

However, the use of feedback can lead to an unstable system whose output may oscillate or even go to infinity with a small input signal. Stability determination is therefore an important design consideration. One specification for absolute stability requires that the poles of the transfer function must be in the left half of the s-plane. Absolute stability, often specified in the frequency domain, is essential and necessary but not sufficient. Frequency domain specifications relating to relative system stability may also be given. For relative stability, a certain phase margin and gain margin may be specified to ensure that the system will remain stable although some parameters change due to temperature variations, aging or other environmental factors. If a system is stable, then other performance criteria specified in either the time or frequency domain may be considered to meet the performance requirements. Short-term, or transient, response specifications such as rise-time or percent overshoot to unit step function input may be given. Long term, or steady state, response such as zero steady state error may also be specified.

**Design Objectives:**

The desire for a super intelligent robot vehicle that can beat all other teams during the contest forces us to build a successful control mechanism that can drive the mobile robot along a changing contest course, such as steep ramp, sand, or over wet ground. This requires the robot have the ability to “see” its course. Another consideration of this design is that the robot must sense the obstacles in front of it. This indicates the design of separate systems that may generate different control signals, which may be integrated with certain method to drive the conventional motion system. The specific goals can be listed as follows:

1. It can automatically navigate around an outdoor course within a pre-defined time, and at the same time, avoid obstacles on the track.
2. Vehicles must be unmanned and autonomous. They must compete based on their ability to perceive the course environment and avoid obstacles. All computational power, sensing and control equipment must be carried on board the vehicle.
3. There are at least one manual E-Stop and at least one remote E-stop device built into the entire system.

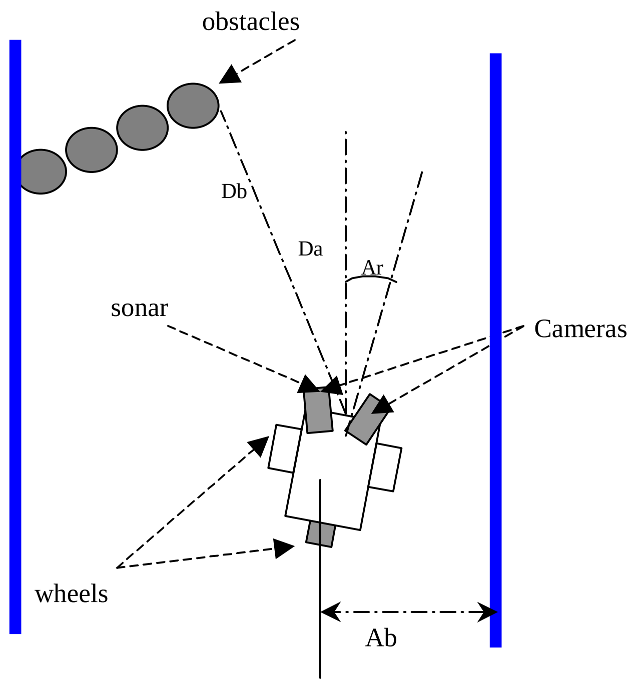



Figure 1. Bearcat II and its working environment

**Specific goals:**
Our approach to achieve the above goals is based upon our previous design experiences and the devices available. The specific aim of the proposed research can be stated as follows:

1. Define the steering mechanism of the robot, which can meet the specific challenges of the International Ground Robotics Competition contest.
2. Select and construct equipment that has the desired functional and operational features and also the proper ability to drive the vehicle to the desired direction at the desired speed.
3. Program to achieve the motion behavior under the control of central computer.

The paper outline is as follows. The system development is described in Section 2. The motion control problem is stated in Section 3. In Section 4, the motion control systems modeling and compensation method is described. The motion programming is described in Section 5. Finally, results and conclusions are given in Section 6.

## 2. SYSTEMS DEVELOPMENT

### 2.1 Bearcat II subsystems description:
Digital control, vision guidance, ultrasonic distance sensors and emergency stop characterize the physical structure of Bearcat II. The main components of the robot include: the central CPU, Iscan vision tracker and two CCD cameras for vision sensing, Polaroid ultrasonic sonar, two 12V batteries as the motor power source, Galil digital controller and two DC motors, as shown in Figure 2.

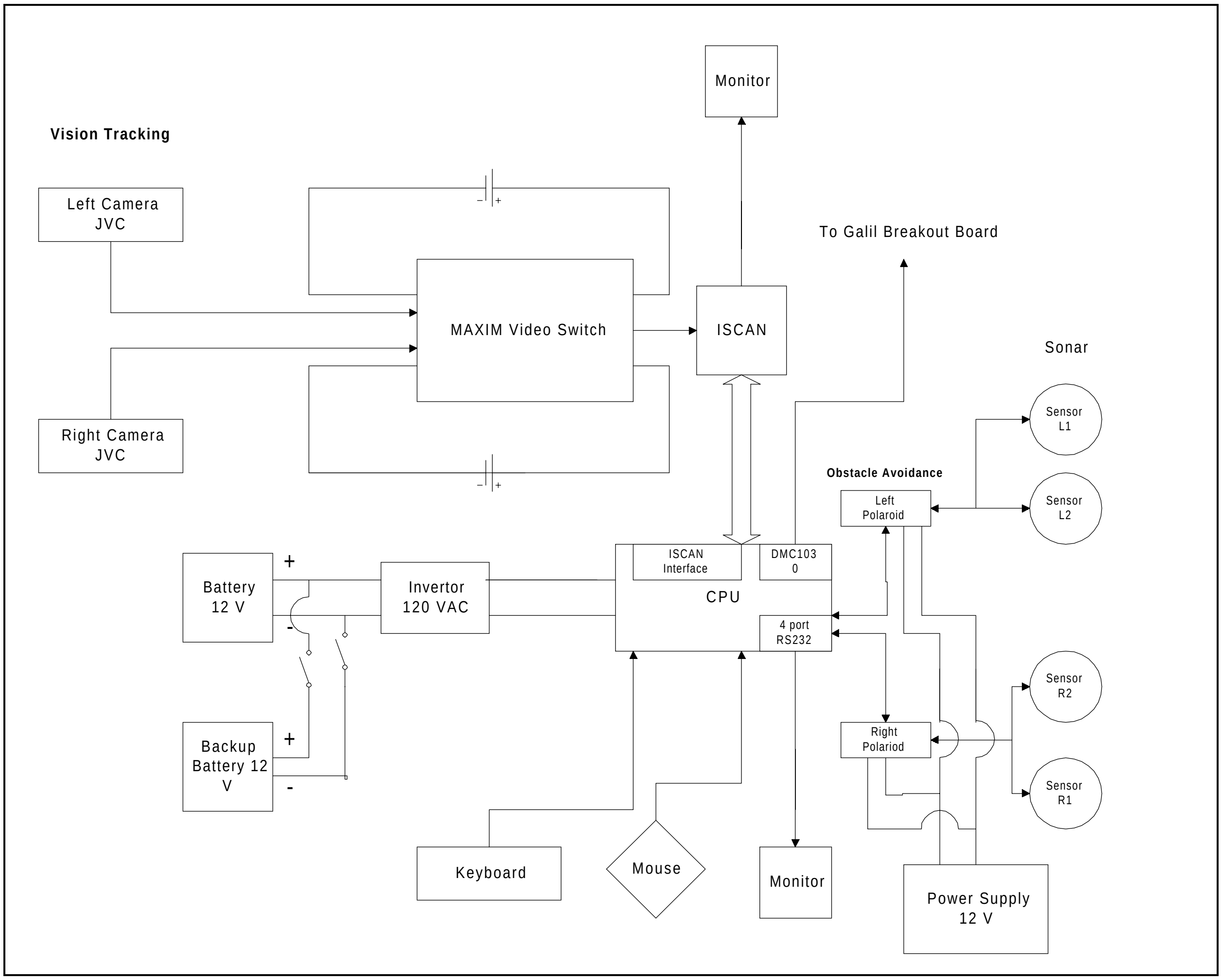



Figure 2. Block diagram of the functional components of Bearcat II

- **Vision Systems**
  The vision guidance system helps the vehicle to know its current position along the road. It needs to be calibrated before its real functioning. The purpose of calibration is to transform the camera coordinates into robot coordinates. Two CCD cameras are used to judge the current position of the robot.

- **Obstacle Avoidance System**:
  The sonar system reliably detected obstacles between 0.5 meter and 6 meters within an accuracy of 0.02 meter. The system interfaces between the Polaroid unit, Galil controller and the supervisory controller were found to be successful. The fuzzy logic controller computed correction angles. To drive the robot around the obstacles going downslope on a ramp, it was observed that the sonars detected the ground as an obstacle. Modifying the sonar algorithm such that if sonars on either side gave identical readings, the obstacle shall be ignored solved this problem.

- **Steering control system**:
  The steering mechanism worked satisfactorily. Implementing the PID controller to control two identical motors on both sides of the robot. The action of turning is achieved with the speed variations

of the two motors. Encoders that are attached to the motors continuously report the working status (velocity and position).

- **Safety and Emergency Stop Braking System**:

A safety switch and a remote safety switch are in serial connection into the motor power control circuit. When an emergency situation appears, one can press the emergency stop button or remote stop button to stop the robot immediately.

**2.2 Motion control systems introduction**

In general the robot motion includes moving forward and backward, turning left and right or stopping. It often happened during the Bearcat I operation that the robot will miss the control line when there is a small radius turn on the track. This requires a built in mechanism that can move the robot in a sharp turn and motivated the ZTR design.

The motor amplifier drives the motor. The motor amplifier gets its control signal from a control board, which is connected to the control computer. The control board is an information center. It gets the motor rotation condition via the encoder. Then, it transfers the encoder signal into a proper data format and then sends it to the main computer. The computer is the final decision-maker on the machine. It gets information from both vision systems and the sonar system, integrates the information, make decisions based on those signals and then send the command to the control board. The commands are then transferred into voltage (analog) control signal that is applied to the amplifier.

The sonar system is used to detect obstacles in front of the robot. This requires another important motion behavior, that is, the rotation of the sonar sensor. This requires a high speed, accurate motor to rotate sonar to the desired angle.

**2.3 General descriptions of the motion systems design**

One solution to effect vehicle motion control is to drive two wheels with independent motors. These motors drive the left and right wheel respectively through two independent gearboxes, which increase the motor torque by forty times.

**2.4 Motion systems architecture and descriptions**

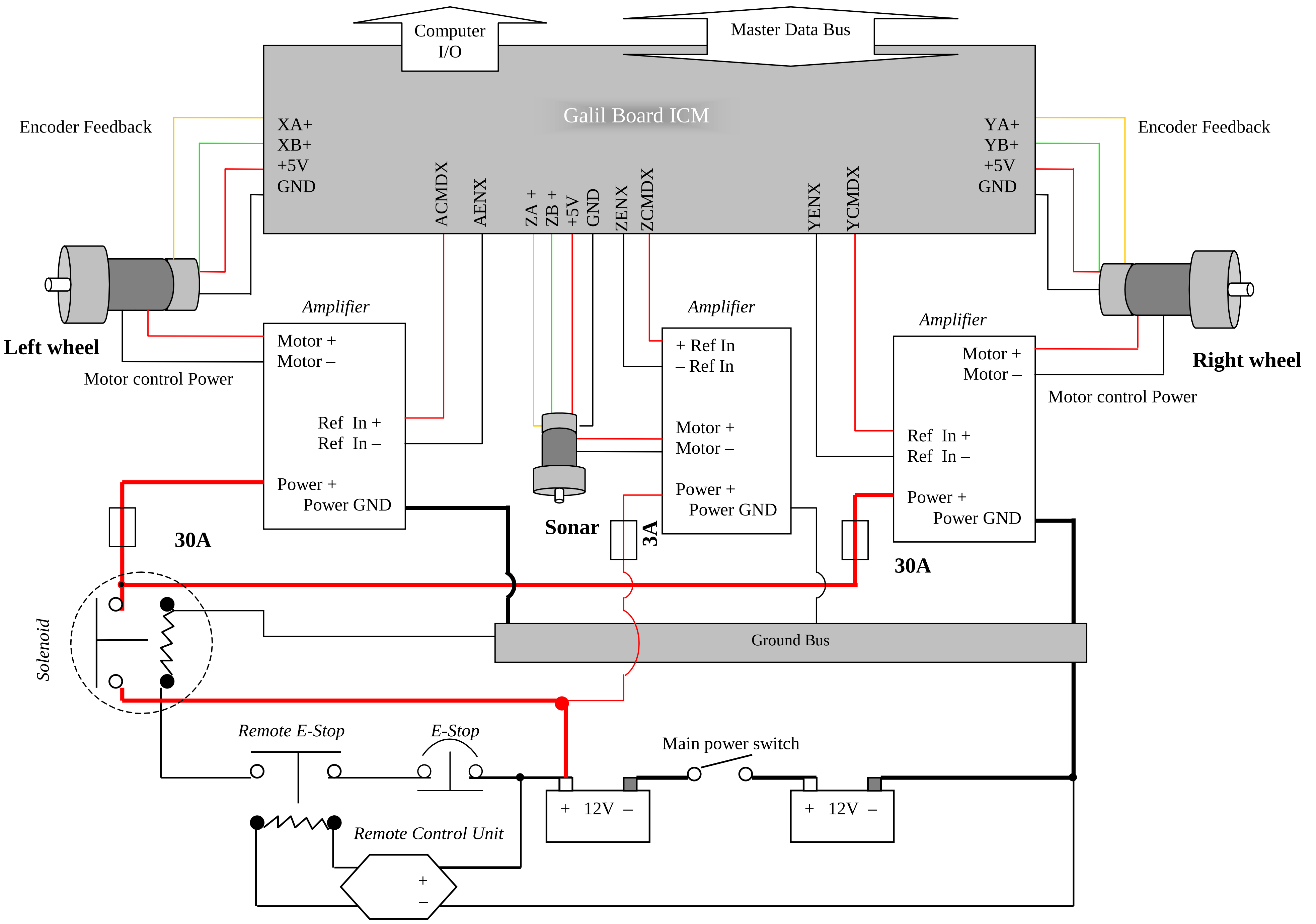
- Amplifier mode settings

There are generally 3 modes of operation for each amplifier: the current mode (torque mode), voltage mode and velocity mode. The current mode will provide the largest torque while the voltage mode will provide the fastest speed. During the field test, the robot will always have to encounter ramps, high friction grass surfaces, sand, etc. So the two wheel motors were configured as current mode for high torque. The only load on the sonar motor is the quarter-pound sonar head. So, the load for the sonar amplifier is small. Voltage mode is selected to support a prompt response for the sonar motor.

- Control board and amplifier configuration

The basic configuration between the motor and the Galil controller is shown in Figure 3. The Galil motion controller plugs into the PC bus and accepts several high level, ASCII commands. Analog motor commands in the ±10 V range give a signal for driving the servo amplifiers. The 16-bit resolution of the Galil board is the main interface to transfer data to the computer and also the commands to the amplifiers. It gets motor status information from the encoders and then reports the data to the computer. The computer command is first sent to the Galil board and then transferred into the analog control signal, which is between +/- 10 V via a 16-bit D/A converter (resolution 0.003 Volts). This signal is a reference voltage that is applied to the amplifier reference in +/- pins to control the motor direction and speed. Depending on the amplifier mode, the control signal controls current, voltage or speed. The two wheel motor amplifiers are powered by two 24V DC power (2--12 volt batteries in series connection). These amplifiers get control signals from Reference in + and Reference in -, then the output voltage/current power is supplied to the motor accordingly. The variation of the error between the reference and feedback will determine the strength of the power output to the motor.

**Figure 3 BEARCAT II Motion Control Systems Architecture**



The encoder is mechanically attached to the motor to read and give negative feedback information of motor motion position. The negative feedback will cause a difference between the command signal and feedback signal. This difference is called the error signal. The amplifier compares the feedback signal to the command signal to produce the required output to the load by continually reducing the error signal to zero. The encoder gets +5V DC power directly from the Galil board. The encoder signal is transferred to the Galil board via pin *A+ and pin *B+. The motor amplifiers get control signals from the Galil controller pin ACMD* and pin AEN* (* means X or Y or Z, depend on the axis). For safety, the motor amplifier was protected by a 30A fuse and sonar amplifier by a 3A fuse. The motion systems are shown in Figure 3.

**2.5 Amplifier parameter adjustments**

There are 4 potentiometers to be adjusted built into the amplifier, loop gain, current limit, reference gain and offset. The loop gain adjustment in voltage & velocity modes. Voltage to current scaling factor adjustment in current mode; The current limit adjusts both continuous and peak current limit by maintaining their ratio (50%); The Reference gain adjusts the ratio between input signal and output variables (voltage, current, velocity); The offset/test is used to adjust any imbalance in the input signal or in the amplifier. Before operation, these potentiometers need to be tuned to gain an optimum performance.

**2.6 Motion control factor identification**

The control of the vehicle movement in a two dimensional space can be reduced to the control of two variables: the vehicle speed and the orientation of the vehicle

The speed of the vehicle refers to the speed of the mid-point of the vehicle. It can be defined as

$$V = ds / dt \qquad (1)$$

Where V is the motion speed
s is the change of the moving distance of the robot.

This velocity may also be expressed in terms of the velocities of the left and right wheels as:

$$V = (V_L + V_R) / 2 \qquad (2)$$

Where $V_L$ is the speed of the left wheel
$V_R$ is the speed of the right wheel

The speeds of these two wheels would determine the speed and orientation of the vehicles.
When $V_L > V_R$ The vehicle would move towards the right
When $V_L = V_R$ The vehicle would move straight
When $V_L < V_R$ The vehicle would move toward the left
When $V_L + V_R = 0$ and $V_L != 0$, the vehicle is making a ZTR turn

The orientation angle of the vehicle is also determined by the left and right speeds as

$$d\theta / dt = ( V_L - V_R ) / W \qquad (3)$$

Where W is the width of the axle or distance between the wheels.

The most common methods of turning a wheeled vehicle are with the steering wheel or with differential left and right wheel drives.

With Equations 3.1 and 3.3, the wheel speeds can be controlled by the sum and the difference of the two wheel speeds.

$$V_L + V_R = 2V_m \qquad (4)$$

$$V_L - V_R = W ( d\theta/dt ) \qquad (5)$$

Or

$$\omega_L + \omega_R = ( V_m / \pi R ) \quad (6)$$

$$\omega_L - \omega_R = ( W / 2\pi R ). (d\theta / dt) \quad (7)$$

## 3. Control problem

The control problem can now be identified. Let $V_m$ and $\Delta V$ are now identified as the inputs to the computer.

Where $V_m$ is the speed for the middle point of the wheel shaft and
$\Delta V$ is the difference between the two wheel speeds.

The outputs are $V_L$ and $V_R$, the speeds of the two wheels respectively.

From Equations 3.6 and 3.7, we can get

$$\omega_L = ( 2V_m + \Delta V ) / 2\pi R \quad (8)$$

$$\omega_R = ( 2V_m - \Delta V ) / 2\pi R \quad (9)$$

and

$$V_L = V_m + ( \Delta V / 2 ) \quad (10)$$

$$V_R = V_m - ( \Delta V / 2 ) \quad (11)$$

To track a straight line, two error variables have been defined, namely the distance error Y and the orientation error $\theta$. The distance error is the perpendicular distance from the vehicle centroid to the track center. The orientation error is the angle enclosed by a tangent drawn to the track line at the position of the vehicle and the direction to which the vehicle is heading or the angle enclosed between two consecutive co-ordinates picked by the vision tracking system of the vehicle.

A control algorithm is now needed to permit the robot to follow the path.

## 4. MOTION CONTROL SYSTEMS MODELING AND COMPENSATION

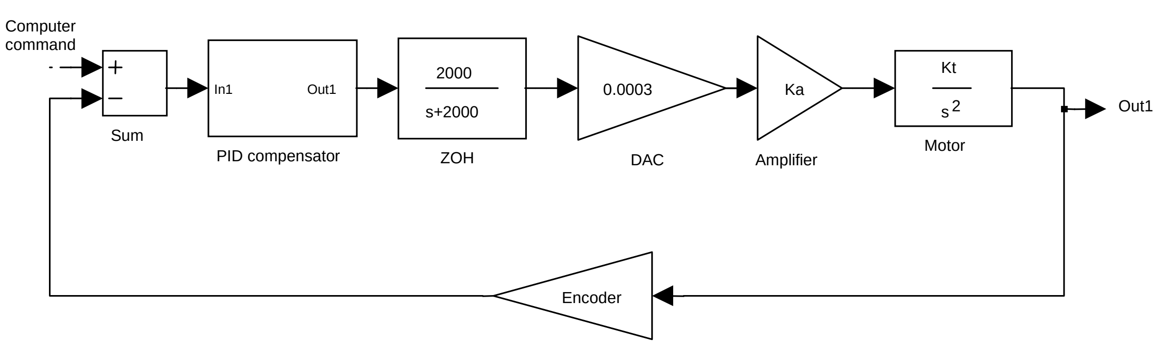



*Figure 4. Block Diagram of the motion control system*

The control systems were modeled as shown in Figure 4. One important feature of this design is the application of digital PID controller that is built into the Galil controller. The Galil controller permits the implement of a PID (Proportional, Integral, and Derivative) controller through an equivalent digital filter. The digital filter is defined as:

$$D(z) = K*(z-A)/z + C*z/(z-1) \tag{12}$$

The filter parameters K, A and C are related as follows:

$$K = KP+KD \tag{13}$$

$$A = KD/(KP+KD) \tag{14}$$

$$C = KI/8 \tag{15}$$

Where KI, KP and KD are the parameters of a continuous time PID controller.

Although it is possible to calculate proper PID values, it is difficult to find real life model parameters characters such as friction on different lands. One good solution is to perform field ground step response testing and approximate the PID value by reading its step response. This task could be done with the Galil Windows Servo Design Kit (WSDK). The WSDK software can do an automatic close-loop test to see if the system is stable. There are various tuning options available on the software. The system overshoot and settling times were seen in the tuning test module of the software. Once it is stable the corresponding PID values and crossover frequency as well as the system step response may be observed and acceptable response selected.

# 5. MOTION BEHAVIOR PROGRAMMING

## 5.1 Motion behavior identification

In order to give the BEARCAT II ideal ability to handle its motion during the contest, the robot should have at least three motion status, i.e. turn left, turn right and stop. In addition to that, the robot should also have the ability to go backwards whenever it has found no way to proceed. Also, one important feature of this design is its ability of making zero turning radiuses (ZTR), which is gaining popularity in the U.S. mowing market. ZTR means the ability to turn around the center of the axis of the drive wheels. This design offers exceptional maneuverability with sharp turns. For the sonar system, the rotation required of the sonar is limited to several positions at a limited range. In this design, the robot needs to sense an area of +/-30 degree in front of it. Five positions were selected as the sonar sensor reading.
All in all, the robot should have the following motion abilities:

1) Left turn
2) Right turn
3) ZTR_left
4) ZTR_right
5) Reverse
6) Sonar positioning

## 5.2 The Galil motion control mode selection

The motion controller plugs into the PC bus and accepts a language consisting of several high level ASCII commands and motion profiles. A terminal emulator program is provided enabling the designer to send commands from the PC keyboard. The Galil controller has its own programming language to control the motors. In general there are three positioning strategies to follow:

**Independent Axis Positioning**: In this mode, the desired absolute position (PA) or relative position (PR), along with the acceleration rate (AC), deceleration rate (DC), and slew speed (SP) are specified.

**Jogging**: The jog mode allows the user to command each motor to run at a prescribed jog speed until a stop command is assigned. During its operation, the wheel motor motion is a continuous process; **jogging** mode was selected for this kind of motion.

**Sonar**: For the sonar motion, it requires the motor to move the motor to a specified position to sample obstacle distance, so the **independent axis-positioning** mode is a good solution.

The master program was programmed in Turbo C++ that serves as the decision-maker as well as the interface between the Galil control board, vision system and the sonar system. The architecture of the system is a distributed computer since the motion control, vision and sonar systems each have their own microprocessors. The programs that achieve these motion behaviors are listed in reference 4

## 6. RESULTS AND CONCLUSIONS

The robot was transported to Oakland University in Detroit to participate the AUVS competition in the early June of 1999. Extensive field tests were performed on the contest track. The motion system was tested on a variety of ground conditions including dry and wet grass, sand, plywood ramps and asphalt. The performance of motion systems is as following

1. It can successfully follow the computer command, demonstrated all five motion behaviors as defined before. The accuracy of the motion behavior is between 90% ~95%.
2. Both the remote E-stop and manual E-stop can stop the motion of the robot. The effective distance for the remote E-stop is about 65 feet.
3. No run away situation occurred.
4. The overall quality of the motion system was proved by its performance during the contest. During the Vehicle Performance Competition, the robot successfully followed the track and avoided obstacles and also traveled over 153 feet. This score ranked 4$^{th}$ among 14 competitors. Also, during the ROAD DEBRIS competition, the robot moved 65 feet without breaking rules, which is the 3$^{rd}$ best performance.

In conclusion, the design of motion controls systems for a mobile robot is a challenging task. A reliable and powerful motion control system is the basic requirement for the robot to perform accurately for any action. In this design, a digital motion control system was configured, designed, implemented, tested and evaluated. The adaptation of PID compensation and computer controller gives the system maximum flexibility. Safety was emphasized as an important factor in the design. In the future, higher level controller could be developed which integrates control signals from more than one subsystem, such as vision system and sonar system in many other ways. One such controller may employ both fuzzy logic and neural network knowledge.

Further research on autonomous guided vehicles is needed. One great testing ground for such vehicles is the International Ground Robotics Competition sponsored by the Autonomous Unmanned Vehicle Society. The next contest is scheduled for July 8, 2000 at Disney World in Orlando.

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