Comparison of three obstacle avoidance methods

for an autonomous guided vehicle

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Abstract

Obstacle avoidance is one of the most critical factors in the design of autonomous vehicles such as mobile robots. One of the major challenges in designing intelligent vehicles capable of autonomous travel on highways is reliable obstacle avoidance. Obstacle avoidance may be divided into two parts, obstacle detection and avoidance control. Numerous methods for obstacle avoidance have been suggested and research in this area of robotics is done extensively. Three different methods for obstacle detection and avoidance are available on the BEARCAT III. These include fixed mounting of sonar sensors, a rotating sonar sensor and a laser scanner. The fixed mounting system uses two sonar sensors which are mounted at the outer front edges of the vehicle. The rotating sonar system consists of a Polaroid ultrasound transducer element mounted on a micro motor with an encoder feedback. The motion of this motor is controlled using a Galil DMC 1000 motion control board. It is possible to obtain range readings at known angles with respect to the center of the robot. The laser range scanner system consists of a SICK Optics laser scanner which returns a two dimensional profile of the horizontal region in front of the vehicle. The data from these systems can be used to detect and avoid obstacles.   The systems were tested in July 2002 at the International Ground Robotics Competition. The BEARCAT III placed third in the autonomous challenge contest. This test bed system provides experimental evaluation of the tradeoffs among the systems in terms of resolution, range and computation speed as well as mounting arrangements. The significance of this work is in the increased understanding of obstacle avoidance for robot control and the applications of autonomous guided vehicle technology for industry,
 defense and medicine.

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Chapter 1

Introduction

1.1 Motivation

There has been a great amount of research devoted to the obstacle avoidance problem for mobile robot platforms and intelligent vehicle s. Any mobile robot that must reliably operate in an unknown or dynamic environment must be able to perform obstacle avoidance. As road following and off road systems have become more capable, more attention has been focused on obstacle detection problem.

Several sensors are capable of obstacle detection. Two considered in this paper are: sonar and laser scanner. Sonar systems in various mounting arrangements have been used for many years for obstacle detection for mobile robots. Sonar systems are an excellent low cost obstacle detection solution. Laser scanners are more recent but have also been used widely for obstacle detection and are found to be reliable and provide accurate results. They operate by sweeping a laser beam across a scene and at each angle, measuring the range and returned intensity. The Center for Robotics Research at the University of Cincinnati has built an unmanned, autonomous guided vehicle (AGV); named Bearcat III for the International Ground Robotics Competition conducted each year by the Association for Unmanned Vehicle Systems (AUVS). Previously, ultrasonic transducers were used on Bearcat II to detect and avoid unexpected obstacles, which did not provide us with accurate data. This year there was an enhancement in obstacle avoidance system using a laser scanner. The vehicle senses its location and orientation using the integrated

vision system and a high-performance laser scanner is used for the obstacle detection system of Bearcat III. It provides fast single-line laser scans and is used to map the location and size of possible obstacles. With these inputs the fuzzy logic controls the steering speed and steering decisions of the robot on an obstacle course 10 feet wide bounded by white/yellow/dashed lines. Several promising methods have been developed for obstacle detection. The payoff to obstacle detection research may be in safer automobiles as pointed out in the survey conducted by Florida International University[1]. One approach developed at the University of Florida[2] noted that the obstacle avoidance problem could be divided into two sub-areas, i.e. obstacle detection and mapping, followed by vehicle control to avoid the detected obstacles. Various methods including neural networks have been used on the Navlab project at CMU[3]. Obstacle detection and avoidance thus poses an important challenge in the field of unmanned vehicle systems.

1.2 Objective

Three different methods for obstacle detection and avoidance are available on the BEARCAT III. These include fixed mounting of sonar sensors, a rotating sonar sensor and a laser scanner. The fixed mounting system uses two sonar sensors which are mounted at the outer front edges of the vehicle. The rotating sonar system consists of a Polaroid ultrasound transducer element mounted on a micro motor with an encoder feedback. The motion of this motor is controlled using a Galil DMC 1000 motion control board. It is possible to obtain range readings at known angles with respect to the center of the robot. The laser range scanner system consists of a SICK Optics laser scanner which returns a two dimensional profile of the horizontal region in front of the vehicle. The data from these systems can be used to detect and avoid obstacles. These three methods used

on the Bearcat are described and compared, and an experimental evaluation of the tradeoffs among the systems in terms of resolution, range and computation speed as well as mounting arrangements is made, stating the advantages and disadvantages of each method.

1.3 Organization of the Thesis

The thesis is organized into 6 chapters. Chapter 1 is an introduction and gives the motivation and objective of the thesis. Chapter 2 describes the test bed on which the systems in discussion were tested. Chapter 3 presents the literature overview of the theory of navigation and obstacle avoidance. Chapter 4 describes the three obstacle avoidance systems in detail along with the algorithms used for obstacle avoidance, the advantages and limitations of the systems. Chapter 5 presents the conclusion and comparison of the systems. Finally, Chapter 6 concludes the thesis with recommendations for improvement and areas for further development.

Chapter 2

Test Bed - The Bearcat III

Bearcat III is an Autonomous Guided Vehicle being built at the University of Cincinnati Center for Robotics Research. The vehicle is capable of following line tracks and avoiding obstacles on the path. It also has navigational capabilities using a global positioning system (GPS). The specifications and performance of the vehicle is tabulated below.

Table 2.1: The predicted performance of the bearcat

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

2.1 Major Systems and Components of Bearcat III

The figure 2.1 shows the major subsystems of the Bearcat III According to the functionality Bearcat III has been categorized into the following major units[4] as –

a. Vision system

b. Motion control system

c. Sonar system

d. Laser scanner system

e. Mechanical system

f. Navigation system

g. Electrical system

h. Health and Safety systems
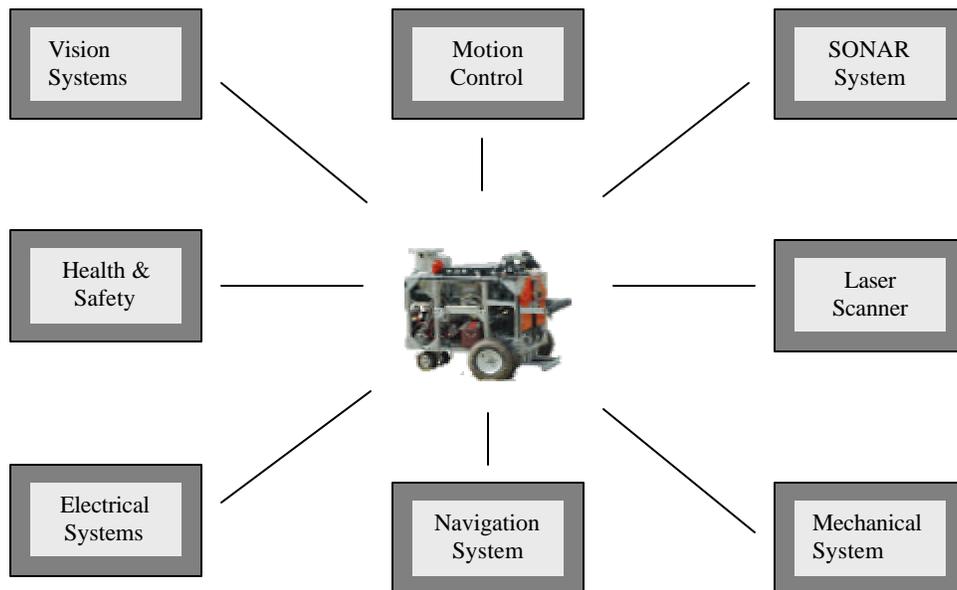
Figure 2.1: The major subsystems of the Bearcat

2.2 Vision System

The Bearcat III was designed to negotiate around an outdoor obstacle course in a prescribed time while staying within the 5 mph speed limit and avoiding the obstacles on the track. 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 is used to process the image of the line. The tracker finds the centroid of the brightest or darkest region in a captured image. The three dimensional world co-ordinates are reduced to two dimensional image coordinates using transformations between the 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. In order to obtain accurate information about the position of the line with respect to the centroid of the robot, the distance and the angle of the line with respect to the centroid of the robot has to be known. When the robot is run in its auto-mode, two Iscan windows are formed at the top and bottom of the image screen as shown in Figure 2.2. The centroids of the line segments are returned by the Iscan tracker these are shown as points

(x1, y1) and (x2, y2) in Figure 2.2. These data-points are used to determine the angle and distance of the line to the robot as shown in Figure 2.3. The calculated distance and angle are used as inputs for the motion control system.
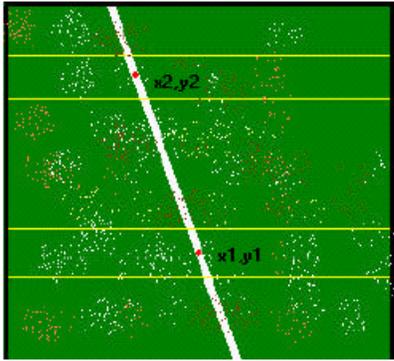
Fig 2.2: Two windows are used to capture two points on the boundary line.
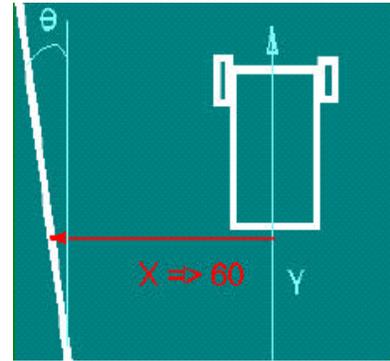
Fig 2.3: Robot in relation to the line

2.3 Motion Control System

The motion control system shown in Figure 2.4 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 left and 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.
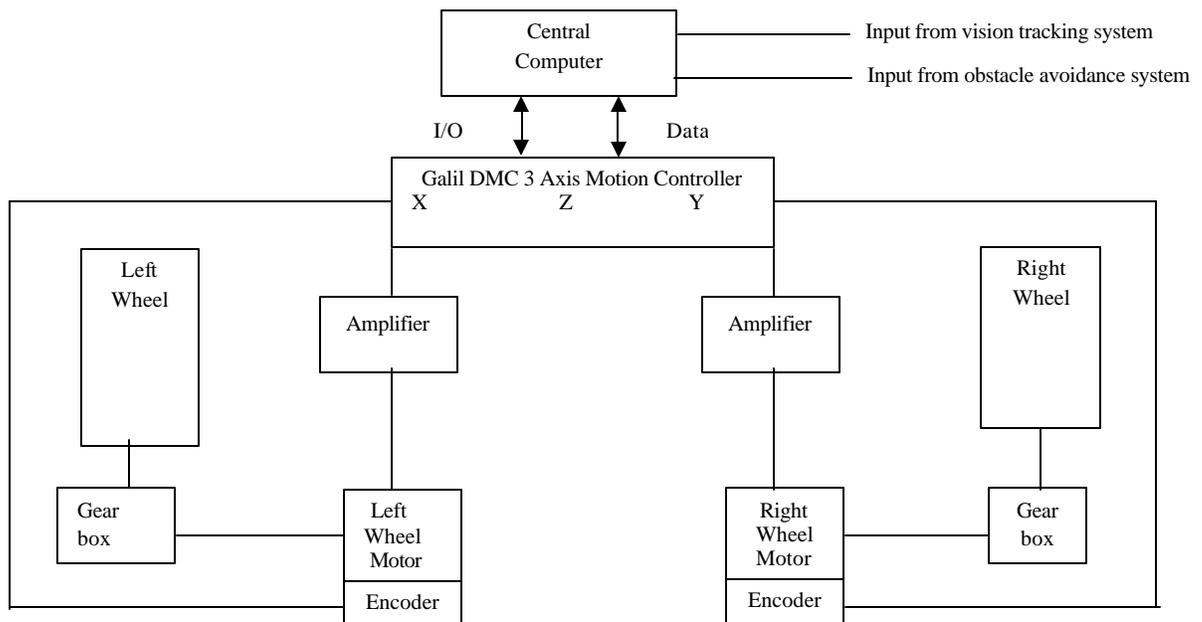
Figure 2.4: Motion control system block diagram

2.4 Sonar System

The two main components of the ultrasonic ranging system are the transducers and the drive motor . A 12 Volts DC, 0.5 Amps unit powers the sonar. The "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.

2.5 Laser Scanner System

The Bearcat uses the SICK Optics laser scanner (LMS 200) for sensing obstacles in the path. The power supply to the unit is through a 24 Volt, 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 Bearcat III, 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.

2.6 Waypoint Navigation

Bearcat-III is also designed to autonomously travel from a starting point to a number of target destinations and return to home base, avoiding obstacles in the course, knowing the coordinates of those targets. The waypoint navigation is achieved by using a differential GPS as explained below.

2.6.1 Waypoint Navigation Using Global Positioning System

The methodology behind the Bearcat navigational challenge problem was to select a commercially available GPS unit and utilize the built in features of the unit to provide a

solution to the GPS navigational problem. This approach relies on the GPS unit's navigational processing features and reduces the computational load that the robot CPU must perform to navigate the course. The basic criteria used in the selection of the GPS unit are WAAS (Wide Area Augmentation System) capability, RS-232 serial port input/output ability, external antenna, external power capability, and embedded navigation features. Based on these selection criteria the Garmin GPS 76 was chosen as the unit to provide GPS navigational ability to the robot. The major navigational features of the GPS unit used in the solution of the GPS navigational problem are the ability to input/output NMEA (National Marine Electronics Association) messages, set target waypoints, and calculate bearing/range information to the target waypoint.

The physical implementation of GPS navigation feedback control loop consists of the Garmin 76 GPS unit, the robot 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 coordinates are 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 relation:

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 0 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. The robot computer handles the communications interface with the Garmin 76, laser scanner, and motion control system devices. It is also responsible for running the digital feedback control algorithm code and sending the correction commands to the robot motion control system. The obstacle avoidance in integrated into the navigation system and is achieved by using a laser scanner.

2.7 Mechanical System

The mechanical system as a whole serves as steering control for the robot. Bearcat III is an outdoor vehicle designed to carry a payload of 100 pounds. The frame of the vehicle has been designed keeping in mind the outdoor conditions. Standard design procedures were used for initial calculations. CAD software i.e. AutoCAD Release 14 and IDEAS were used for the final design process for stress and load analysis. The components include 40:1 reduction gearbox, two pairs of flexible couplings, two 36 volts servomotors and two sets of wheels with shafts, couplings and keys. The computer, through Galil motion controller, controls the servomotors, which supply power to the gear train for the mechanical motion transmission. 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. Power is transmitted

to the front wheels. The rear wheel is a castor wheel and this gives the Bearcat III a zero turning radius.

2.8 Power System

The Bearcat III's electrical system consists of a DC battery power system that supports an AC power system through an inverter. Three 12-Volt DC, 130 Amp hours, deep-cycle marine batteries connected in series provide a total of 36 Volts DC, 4680 Amp hours for the main electrical power. A 36-Volt, DC input, 600-Watt inverter provides 60 Hz pure sine wave output at 115 Volts AC. The inverter supplies AC electrical power for all AC systems including the main computer, cameras, and auxiliary regulated DC power supplies. An uninterruptible power source (UPS) interfaces the robot main computer with the AC power system. The UPS provides 3 minutes of emergency power to the main computer during AC power system interruptions. The UPS allows the main computer to be properly shutdown or connected to an external power source if the main robot AC power system is offline. 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 III 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 Watt hours available. Based on these estimates the Bearcat III power system has an estimated endurance of 3.34 hours at full load.

2.9 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. Two voltage threshold trip points can be set that will trigger a low voltage 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 robot 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 power system voltage display is also visible to the operator and provides a constant indication of the robot electrical voltage.

2.10 Safety System

2.10.1 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.

2.10.2 Remote Controlled Emergency Stop

The mobile robot can be de-activated by a remote unit from a distance of 65 feet in compliance with the rules for autonomous challenge of the international ground vehicle 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.

Chapter 3

Literature review

3.1 The Sense-Plan-Act Paradigm

Sense	World Model	Planning	Control	Execution
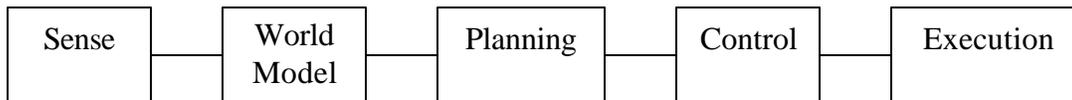
Figure 3.1: The sense-plan-act paradigm

The general approach taken for mobile vehicle navigation is shown in Figure 3.1. The vehicle has a set of sensors which provide data for modeling the environment. The world model interprets the sensor data and processes it until logical prepositions about the state of the world are produced. These prepositional accounts of the world state serve as inputs along with goals and possibly user preferences, to the planning process. The planning process would evaluate the set of possible actions and determine the desired action. Each step of this plan is passed to the control level for execution, which means that the plan includes actions down to the actuator level. This model for mobile navigation is a reactive model, when a vehicle is moving it will detect a change in the world map - for example a new obstacle - and then will react to the new information by developing a new plan for navigation.

This approach gave way to that of mapping and navigation control. There are three basic questions that define the mobile robot mapping and navigation.
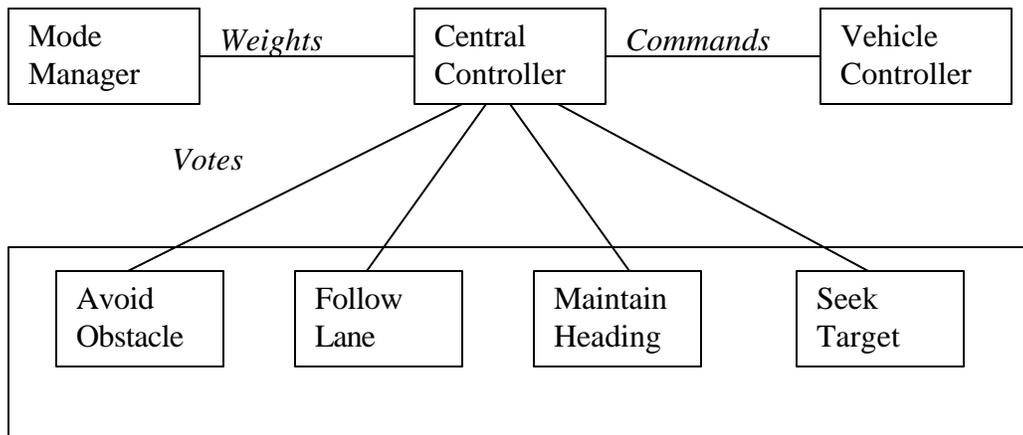
- Where am I?

- How do I get to other places from here?

- Where are the other places relative to me?

There are different approaches to representing and using spatial information. As such they span a spectrum of options for mapping and navigation[5]. On one side of this are purely metric maps. In these the robot's environment is defined by a single global coordinate system in which all mapping takes place. Typically the map is a grid with each cell of the grid representing some space in real world. These approaches work well in environments with little consistent structure. Here it is easy for the robot to realign itself with the global coordinates by using external markers. On the other side of the spectrum are qualitative maps; these represent the robot's environment as places and connection between places. These maps do not contain geometric information but have only information about proximity and order. Qualitative maps can be more compact in their representation of the space. They work well in structured environments where there are distinctive goals that the vehicle must achieve.

3.2 The Distributed Architecture for Mobile Navigation.

Figure 3.2 shows a representation for the distributed architecture for mobile navigation. This architecture considers the actions taken by the robot as behaviors. For example each action producing module such as – road following or obstacle avoidance is considered as a separate behavior and is responsible for a particular aspect of vehicle control or achieving some particular task. These behavior modules operate in parallel and asynchronously send the output to the arbiter or the central controller. The central

controller uses weights assigned by the mode manager to send commands to the vehicle controller to take the desired actions for navigation. This architecture offers several advantages such as greater reactivity, robustness, and flexibility. However, unlike reactive systems the perception and planning components are not prohibited for maintaining complex internal representations of the world[6].

```
┌──────────┐  Weights  ┌────────────┐  Commands  ┌────────────┐
│ Mode     │───────────│ Central    │────────────│ Vehicle    │
│ Manager  │           │ Controller │            │ Controller │
└──────────┘           └────────────┘            └────────────┘
                Votes

┌──────────┐   ┌────────┐   ┌──────────┐   ┌────────┐
│ Avoid    │   │ Follow │   │ Maintain │   │ Seek   │
│ Obstacle │   │ Lane   │   │ Heading  │   │ Target │
└──────────┘   └────────┘   └──────────┘   └────────┘
```

Figure 3.2: The distributed architecture

3.3 Structure of the Vehicle Navigation System

Figure 3.3 shows the structure of the vehicle navigation system, the data from the position sensors – this can be information from the DGPS or from the vision systems while lane following- and the obstacle avoidance sensors is fused together to obtain an environment map and sense the position and orientation of the vehicle. The position and orientation of the obstacles is also known at this point. Using this information the path generation module develops a path for the vehicle to follow the central controller, then plans the motion and velocity of the vehicle, and appropriate commands are issued for vehicle control.
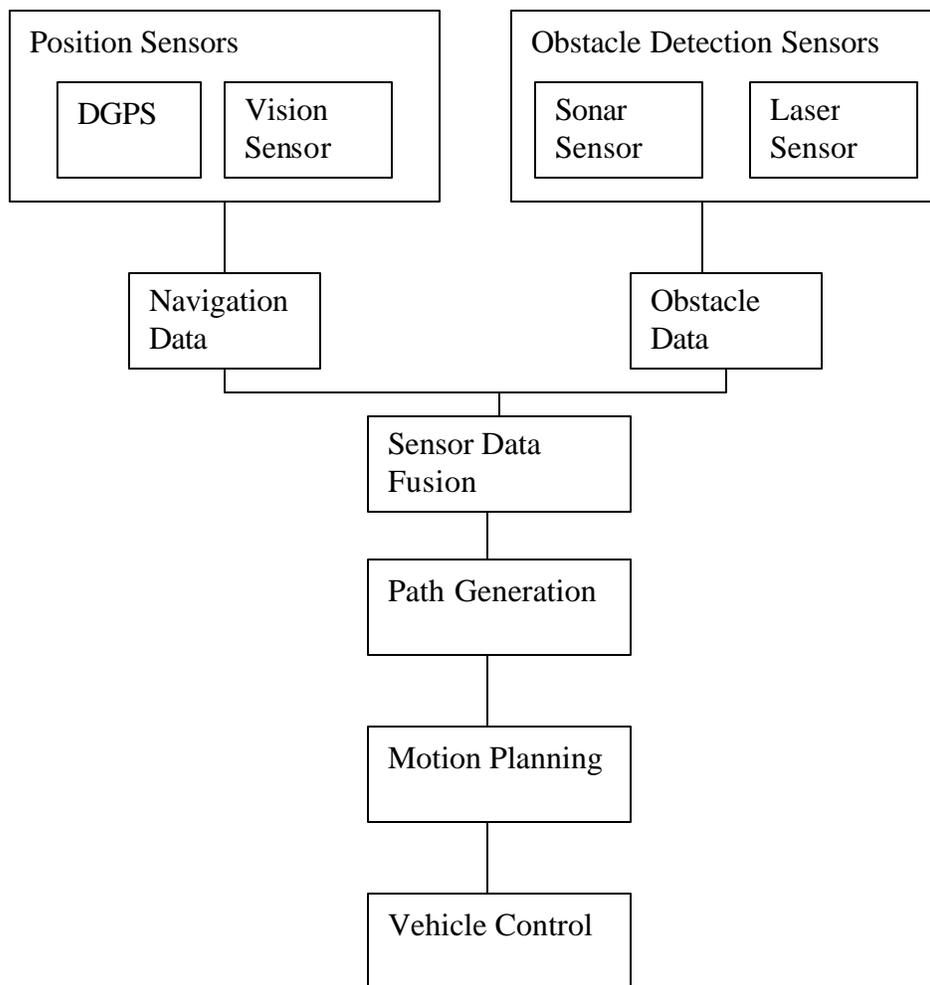
Figure 3.3: Structure of the vehicle navigation system

3.4 Obstacle Avoidance for Mobile Robots

Robots require a wide range of sensors to obtain information about the world around them. These sensors detect position, velocity, acceleration, and range to objects in the robots workspace. There are many different sensors used to detect the range to an object. One of the most common rangefinders is the ultrasonic transducer[7]. Vision systems are also used to greatly improve the robot's versatility, speed, and accuracy for its complex

tasks. For many experimental automated guided vehicles (AGV), ultrasonic transducers, or sonar, are frequently used as a primary means of detecting the boundaries within which the vehicle must operate. W. S. H. Munro, et al.[8] developed a vehicle guidance system using ultrasonic sensing. The unit used by them comprises of a separate array of transducers and gives a field of view of 60 degrees. J. P. Huissoon and D. M. Moziar[9] overcame the limited field of view of a typical sonar sensor by creating a cylindrical transducer which employs 32 elements. Z Yi, et al.[10] have developed an algorithm to fuse outputs from multiple ultrasonic sensors on a mobile robot, filter the noise and reduce errors.

Laser range scanners provide both two-dimensional reflectance and three-dimensional range images. J Gonzalez, et al.[11] have used a 2D laser rangefinder to build a map of the environment. They use an algorithm to build smaller maps of the region the robot navigated which are again integrated to a large global map later. L. Podsedkowski, et al.[12] present a way for using a laser range finder and building a map of the environment. This map is then used to compare against previously memorized maps to estimate the location of the robot. A novel method for obstacle detection has been presented by J Hancock, et al.[13]. They have used laser intensity as a measure to detect obstacles. The scanner on the Bearcat III produces a two-dimensional floor map by integrating knowledge obtained from several range images acquired as the robot moves around attempting to find a path for navigation.

Chapter 4

The Obstacle Avoidance Systems on Bearcat

4.1 Stationary Sonar System

4.1.1 Sonar Theory and System

The first obstacle avoidance system consists of multiple ultrasonic transducers mounted in fixed locations. The two major components of an ultrasonic ranging system are the transducer and the drive electronics. The drive electronics have two major categories - digital and analog. The digital electronics generate the ultrasonic frequency. The system requires an isolated power supply: 10-30 VDC, 0.5 amps. A drive frequency of 16 pluses at 52 kHz is used in this application. In the sonar ranging system[4] a short acoustic pulse is first emitted from a transducer. The transducer then switches to the receiver mode where it waits for a specified amount of time before switching off. If a return echo is detected, the range R, can be found by multiplying the speed of sound by one half the time measured[14]. The time is halved since the time measured includes the time taken to strike the object, and then return to the receiver, where c is the speed of sound and t is the time in seconds.

$$R = \frac{ct}{2}$$

---------------------------- (4.1)

The speed of sound, c, can be found by treating air as an ideal gas and using the equation,

$$c = \sqrt{nR_1 T} \ \ m/s$$

---------------------------- (4.2)

Where n = 1.4, R_1 = 287 m^2/ (s^2K), and the temperature T, is in Kelvin.

Substituting in the values, the equation reduces to:

$$c = 20\sqrt{T} \text{ m/s}$$ ------------------------------   (4.3)

The speed of sound is thus proportional to the temperature. At room temperature (20°C, 68°F) the values are:

$$c_m = 343.3 \text{ m/s}, c_f = 1126.3 \text{ f/s}$$

An Intel 80C196 microprocessor and a circuit were used to process the distance calculations. The distance value was returned through a RS232 port to the control computer. A pulse of electronically generated sound is transmitted toward the target and the resulting echo is detected. The system converts the elapsed time into a distance value. The digital electronics generates the ultrasonic frequency and all the digital functions are generated by the Intel microprocessor. Operating parameters such as transmit frequency, pulse width, blanking time, and the amplifier gain are controlled by software supplied by Polaroid.

4.1.2 Methodology

The sonar sensing devices are mounted in front of the robot at a height of 24 inches where they don't detect the ground as an object. The devices are configured as shown in Figure 4.1. The sonar detects objects in a 30 degree cone. The sensing device has a range of 12 feet, but the area of interest is restricted to 7'3" radius so as to eliminate noise due to obstacles that are out of the robot path. A fuzzy logic approach is used to avoid the obstacles.
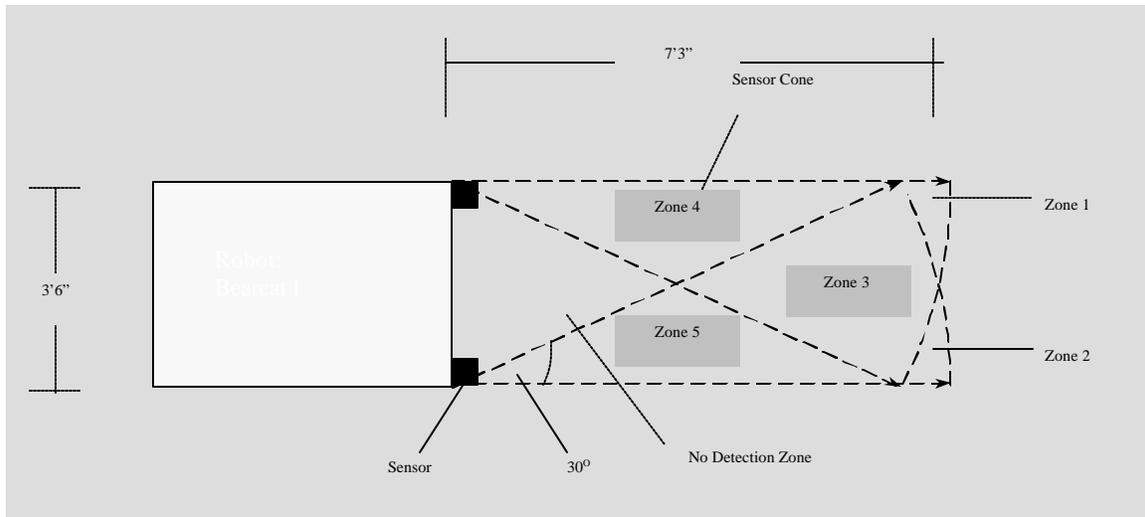
Figure 4.1: Robot with the stationary sonars

As the robot moves, the obstacle can be in zone 1 or zone 2 or both the zones simultaneously. The moment the obstacle is detected in either zone, the robot is steered in the opposite direction till that obstacle is out of way; meanwhile the robot maps its position with respect to the target. The control program always tries to steer the robot towards the target. In the other case when both the sensors sense the obstacles simultaneously this indicates that the obstacle is either a flat object or two separate obstacles parallel to the transverse axis of the robot. In this case the steering decision is taken based on the robot's relative position to the target and its previous motion. Thus the robot avoids obstacles and reaches the target. This method was used on Bearcat I. The advantages and limitations of this method are discussed in the following sections.

4.1.3 Advantages

This cost-effective method has a simple implementation. The algorithm for obstacle avoidance using this method is simple as it has minimal data handling resulting in ease of computations and faster processing.

4.1.4 Limitations

Common to all sonar ranging systems is the problem of sonar reflection. With light waves, our eye can see objects because most objects reflect the incident light energy. Some energy will reach our eye, regardless of the angle of the object to us or to the light source. This scattering occurs because the roughness of an object's surface is large compared to the wavelength of light (0.550 nm). Only with very smooth surfaces (such as a mirror) does the reflectivity become highly directional for light rays.

Ultrasonic energy has wavelengths much larger (0.25 in) in comparison. Hence, ultrasonic waves find almost all large flat surfaces reflective in nature. The amount of energy returned is strongly dependent on the incident angle of sound energy. Figure 4.2 shows a case where a large object is not detected because the energy is reflected away from the receiver. Although the basic range formula is accurate, there are several factors when considering the accuracy of the result. Since the speed of sound relies on the temperature, a 10° temperature difference may cause the range to be in error by 1%. Geometry of the object also affects errors in range detected by the sonar.
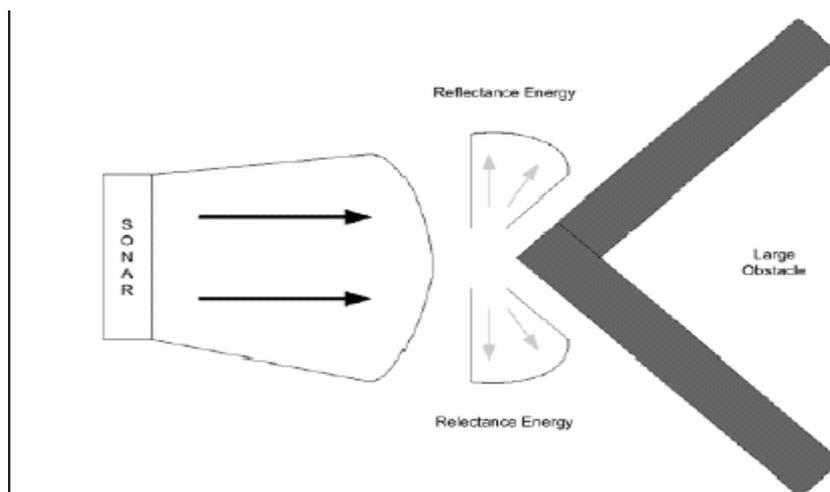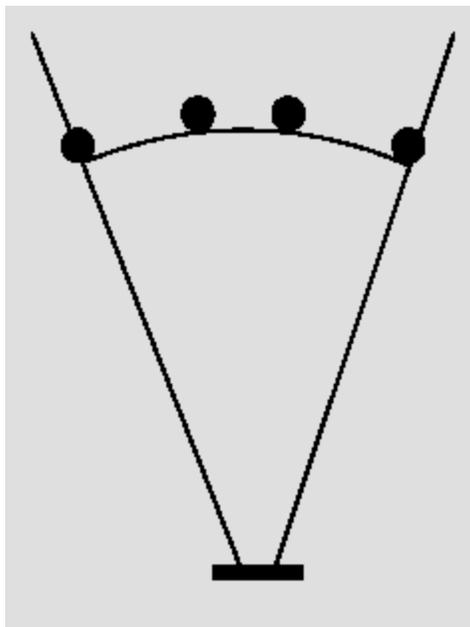
Figure 4.2: Undetected large object due to reflection

When the object is at an angle to the receiver, the range computed will be to the closest

point on the object, not the range from the centerline of the beam as shown in Figure 4.3.
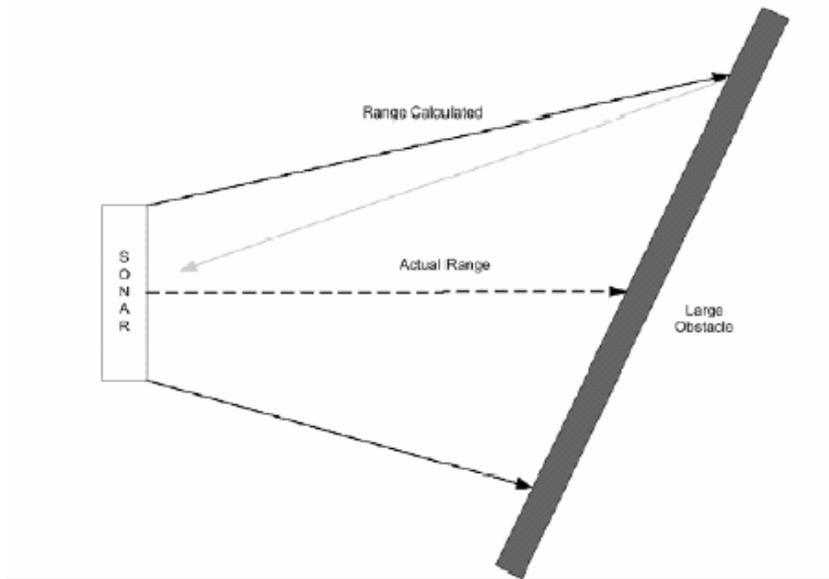
**Figure 4.3: Range errors due to angle between object and sonar**

Figure 4.4: Equal responses for different positions

As seen in Figure 4.4, the sensor would give the same distance value if the object were present anywhere along the curve. Thus the sensor does not give the exact location of the object. In the case of ramps and dips, the sensor will detect the ground as an obstacle. Also as the system does not give the profile of the object, trivial objects such as grass, when detected by the sonar, are also regarded as obstacles, resulting in a redundant obstacle avoidance.

4.2 Rotating Sonar System

4.2.1 The System

The rotating sonar system used on Bearcat II is described here. For accurate path navigation, in addition to the proper functioning of the vision system, the obstacle avoidance system must also function to perfection.
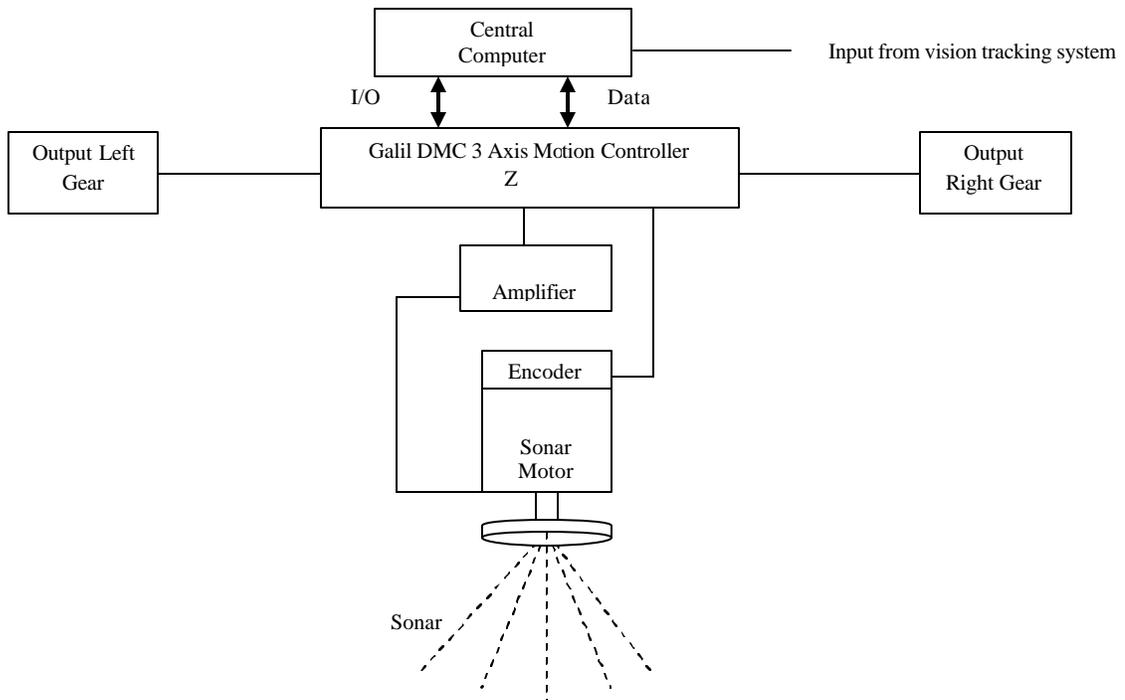
Figure 4.5: Sonar obstacle detection system

This obstacle avoidance system consists of a single rotating transducer. Figure 4.5 shows the setup for obstacle avoidance using a rotating sonar sensor. This setup uses a single Polaroid ultrasonic ranging system and a drive system to rotate the transducer. The drive system for the transducer consists of a Galil DC motor and its control circuitry. With this arrangement the transducer is made to sweep an angle depending on the horizon (range between which we need detection). The loop is closed by an encoder feedback from an encoder. The drive hardware comprises of two interconnected modules, the Galil ICB930 and the 4- axis ICM 1100. The ICM 1100 communicates with the main motion control board the DMC 1030 through an RS232 interface. The required sweep is achieved by programming the Galil. Adjusting the Polaroid system parameters and synchronizing them with the motion of the motor maintain distance values at known angles with respect to the centroid of the robot.

4.2.2 Methodology

This section discusses the basic nature of relationships between the robot and the obstacle. Before the system takes any decision, it is important that we know the distance, width, and shape of the obstacle. Depending upon these factors, the robot has to make a decision as to whether it will go straight, turn left or turn right. Also it has to decide upon the amount of turn depending on the nearness of the target to the robot.
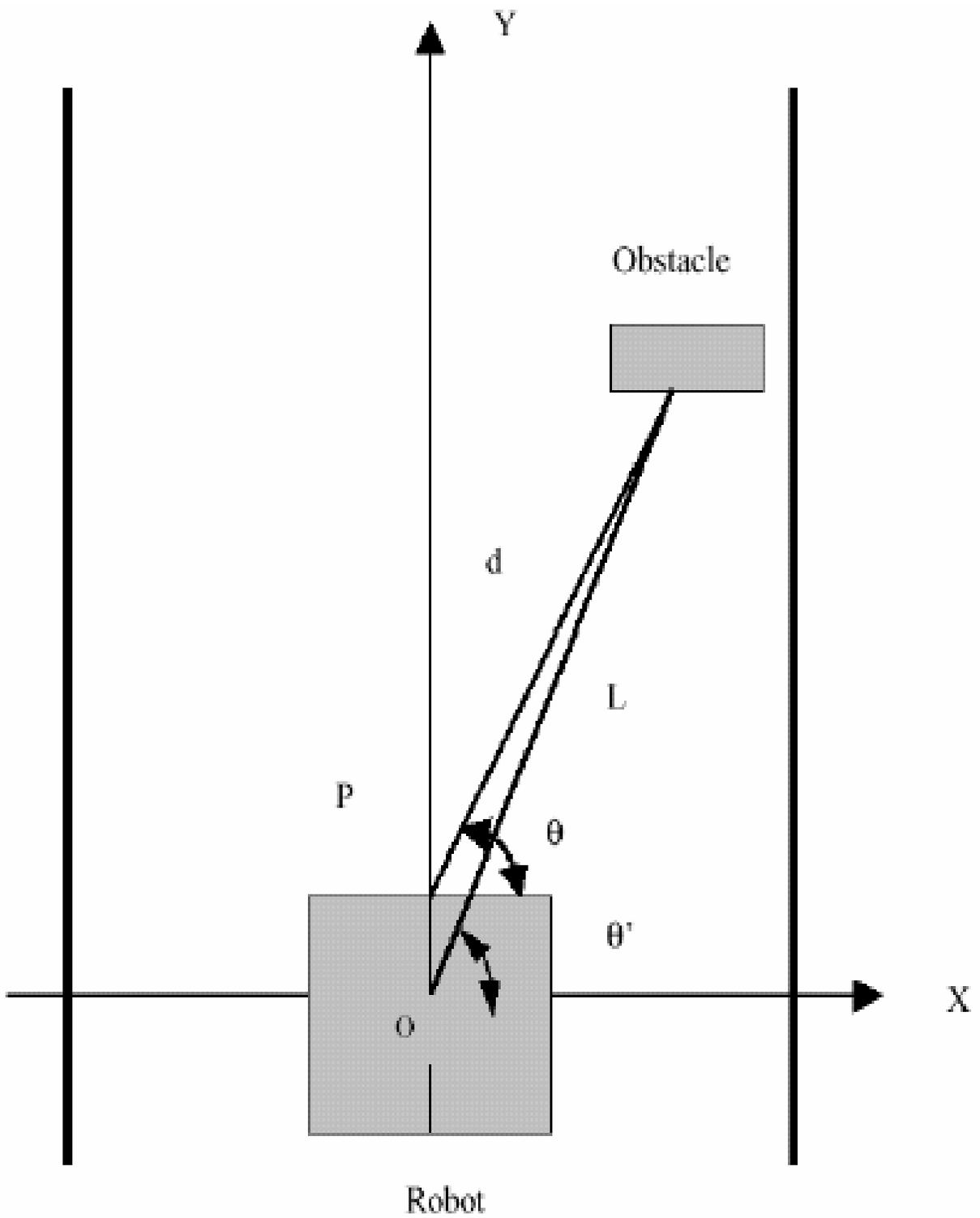
Figure 4.6: Robot with the rotating sonar

The optimal angle of sweep per reading should be obtained in such a way that it does not slow down the overall system performance. From Figure 4.6, we can obtain the value of the distance of the obstacle (L) from the robot center (O). The sonar system returns the distance d and angle θ for the obstacle.

$$d\,Cos\theta = L\,Cos\theta' \qquad\qquad ------\ (4.1)$$

Solving for L we get

$$L = d\,Cos\theta\ /\ Cos\theta' \qquad\qquad ------\ (4.2)$$

And

$$d\,Sin\ \theta + PO = L\,Sin\theta' \qquad\qquad ------\ (4.3)$$

We get

$$L = (d\,Sin\theta + PO)\ /Sin\theta' \qquad\qquad ------\ (4.4)$$

Equating equation 4.3 and equation 4.4

$$d\,Cos\theta\ /\ Cos\theta' = (d\,Sin\theta + PO)\ /\ Sin\theta' \qquad\qquad ------\ (4.5)$$

$$Tan\ \theta' = (d\,Sin\theta + PO)\ /Cos\theta \qquad\qquad ------\ (4.6)$$

$$\theta' = Arctan\ [(d\,Sin\theta + PO)\ /\ d\,Cos\theta] \qquad\qquad ------\ (4.7)$$

We can thus get the value of L that is the distance of the obstacle from the center of the robot. Another important thing to know is the width of the obstacle. Assuming that θ_F' is the angle of the first sonar contact with the obstacle, θ_L' is the angle of the last sonar contact with the obstacle, θ_F-1' is the angle just before the first contact with the obstacle, θ_L+1' is the angle just after the last contact with the obstacle, we can get the value for the width of the obstacle by the difference in the width of the two angles. D_F and D_L are the distances for first contact and last contact, respectively.
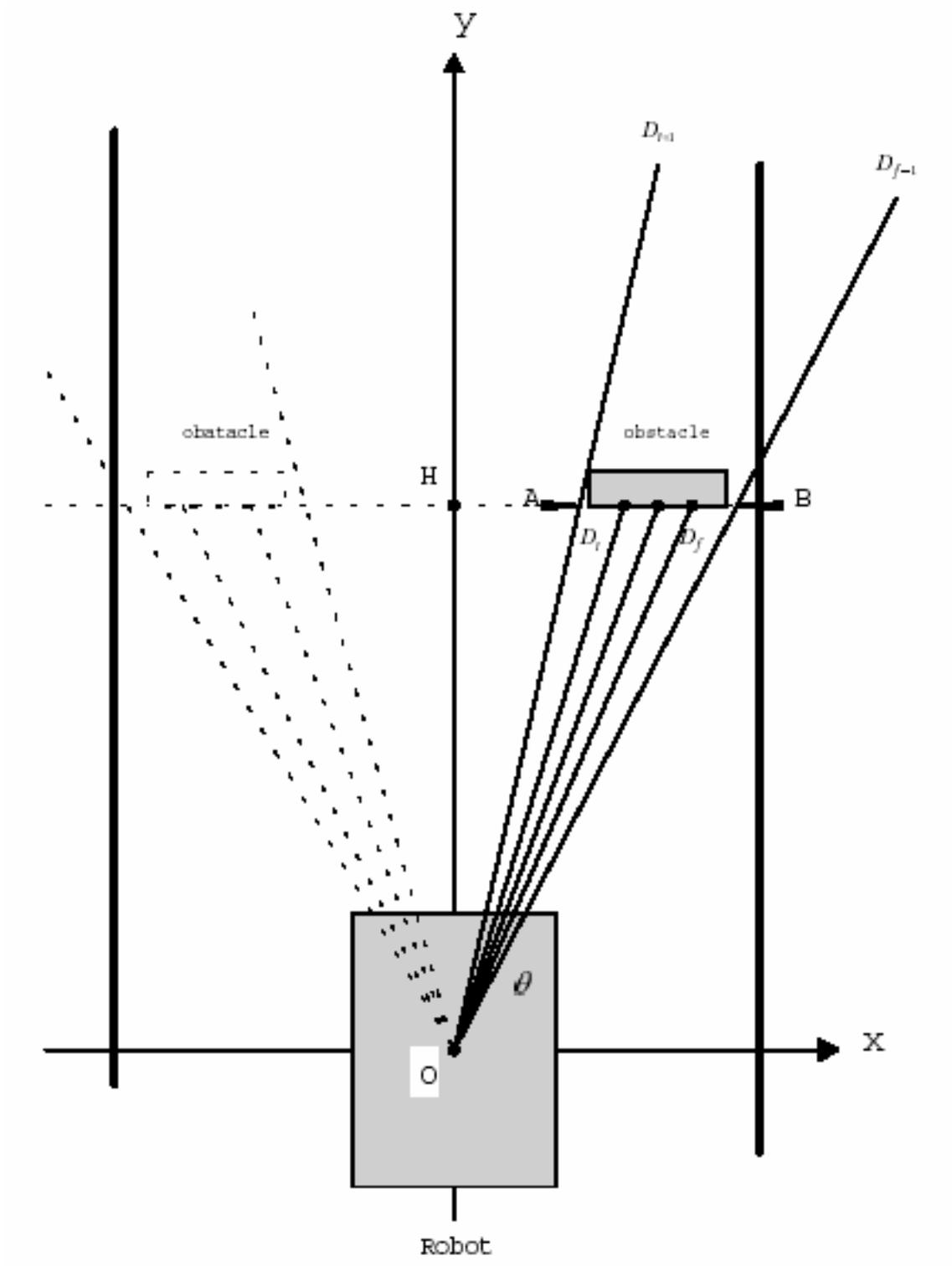
Figure 4.7: Width of the obstacle

$$\text{OB Sin}\theta_F - 1 = D_F\text{Sin}\theta_F \qquad \text{-----} \quad (4.8)$$

$$\text{OB} = \frac{D_F\text{Sin}\theta_F}{\text{Sin}\theta_F - 1} \qquad \text{-----} \quad (4.9)$$

And

$$\text{OA} = \frac{D_L\ \text{Sin}\theta_L}{\text{Sin}\theta_L + 1} \qquad \text{-----} \quad (4.10)$$

Thus we have the width of the obstacle as:

$$\text{AB} = \text{OB Cos}(\theta_F - 1) - \text{OACos}(\theta_L + 1) \qquad \text{-----} \quad (4.11)$$

However, it should be kept in mind that the accuracy of this width is dependent on the

angle of sweep and the intermittent stops between the angles the sonar motor stops.

The sonar uses the "Time of Flight" approach to detect these angles. Once the values of

θF and θL, we can estimate the direction of the obstacle with respect to the robot. Three

possibilities arise:

- **$q_L < 90°$ and $q_F < 90°$; is an indication that the obstacle is to the right.**

- **$q_L > 90°$ and $q_F > 90°$; implies that the obstacle is to the left.**

- **$q_L < 90°$ and $q_F > 90°$; implies that the obstacle is straight ahead.**

Depending on the cases above, the robot makes an effort to avoid the obstacle, while

simultaneously making sure that it stays inside the track. The advantages and limitations

of this system are discussed in the following section.

4.2.3 Advantages

Compared to the stationary sonar, the data received from this method can be used to estimate the size and direction of the object. It has an added advantage of using a single transducer. Since the system returns readings at different angles it is possible to get an idea of the angular position of the obstacle with respect to the robot.

4.2.4 Limitations

Apart from the limitations of the sonar system discussed in Section 4.1.4, this has an added limitation of the drive motor synchronization and it is relatively costly due to additional equipment. The motor has to make a slow rotating motion so that the transducer has enough time to send and receive the acoustic pulses. As the time of flight varies with the distance of the object, only objects within a certain range can be detected successfully. Also, the vibrations of the drive motor lead to noise in the data received. This method is complex and the programming has to control the drive mechanism. Another disadvantage is the error in width detection as shown in the following Figure 4.8 We can see that the last angle of contact is not at the edge of the obstacle and thus gives an error in calculations for the width of the obstacle.
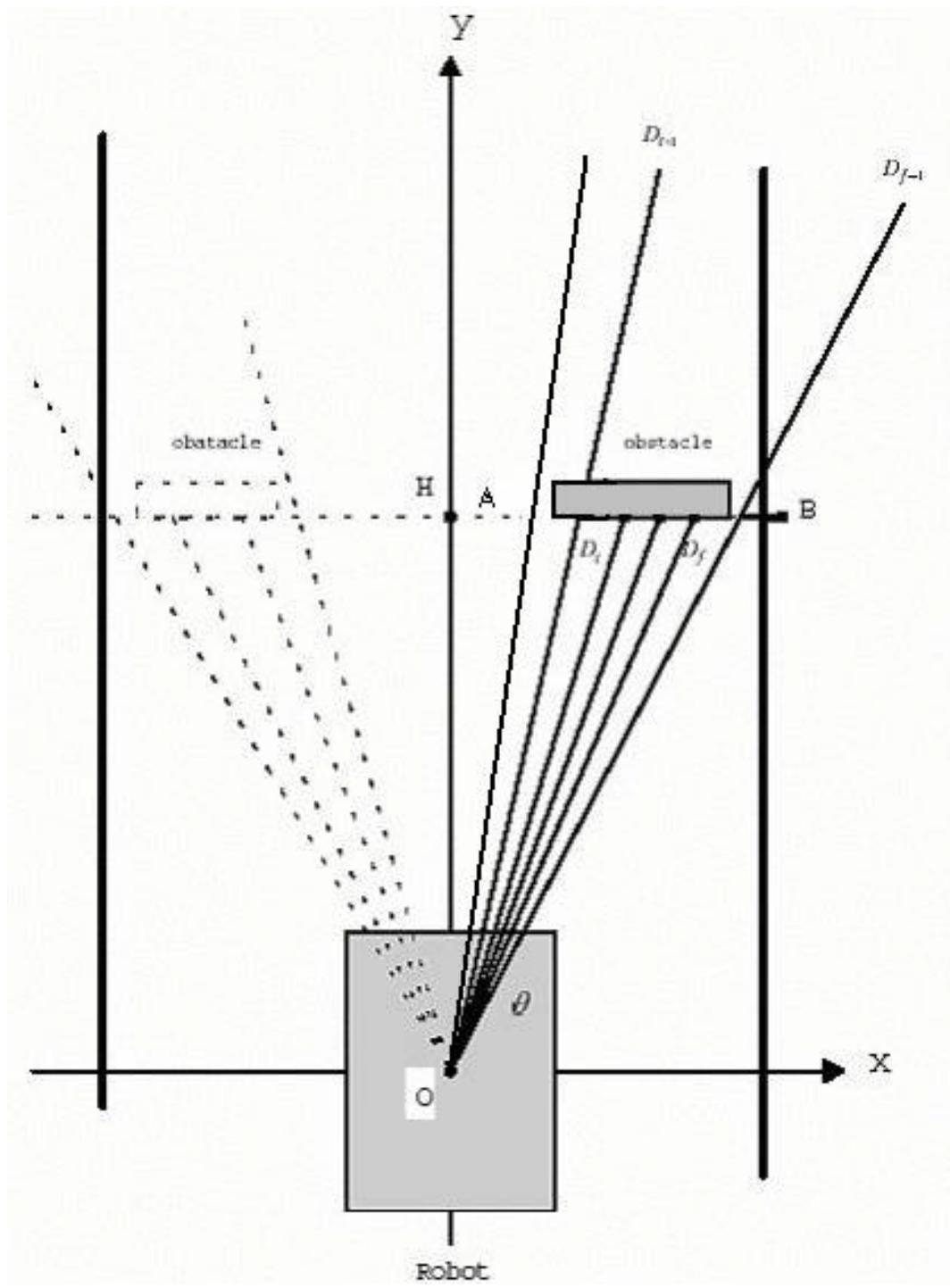
Figure 4.8: Error in width detection with rotating sonar

4.3 Laser Range Scanner System

4.3.1 The Laser Scanner Theory & System

Programming third-generation robot systems is very difficult because of the need to program sensor feedback data. A visualization of the sensor view of a scene, especially the view of the laser scanner, helps programmers to develop the software and verify action plan of a robot. A laser range scanner operates on a similar principle to conventional radar. Electromagnetic energy is beamed into the space to be observed and reflections are detected as return signals from the scene. The scene is scanned with a tightly focused beam of amplitude-modulated , infrared laser light (835 nm). As the laser beam passes over the surface of objects in the scene, some light is scattered back to a detector that measures both the brightness and the phase of the return signal. The brightness measurements are assembled into a conventional 2-D intensity image.

The laser scanner has the advantage that it gives us a detailed description of the field of view. The laser scanner works by measuring the time of flight[15] of laser light pulses. It is a non-contact measurement device that scans its surroundings two dimensionally. The pulsed laser beam is deflected by an internal rotating mirror so that a fan shaped scan is made of the surrounding area and the shape of the object is determined by the sequence of impulses received. We can get a maximum scan angle of 180° with a resolution of 0.25°, 0.5°, or 1°. Now with this resolution and scan angle we get a clear profile of the path in front of our robot. We get data such as at every angle scanned the distance of the point of reflection of laser beam from any object in the field of view with its coordinates can be determined. Giving these values in the algorithm used for tracking the robot can

avoid obstacles easily. The main strength of the laser scanner is the data accuracy and resolution that is returned from the scanned field. The laser scanner on the robot communicates with the host computer using a serial interface. Any of the common interfaces, which are RS 422 or 232 can be used. The transfer rate varies from 9.6 K baud to 500 K baud, which can be set as desired. The data is transferred in binary format where a byte of data consists of 1 start bit, 8 data bits, a parity bit with even parity or without parity and 1 stop bit. The real time measurement data scanned by the device is given out in binary format via the RS-232/422 serial interface, which is available for further evaluation. We are using a RS-422 serial interface card with our scanner, which supports higher baud rates for faster communication[16][17].

The measurement data from the laser scanner is used for object measurement and determining position. The measurement data corresponds to the surrounding contour scanned by the device and are given out in binary format via the RS 422 interface. This data can be seen in a GUI environment gives us the coordinates of every point in the field of view. We can see all the objects in the field of view, which reflect the laser beam so we can get the position and size of every object. In the binary format as the individual values are given in sequence, particular angular positions can be allocated on the basis of the value's positions in the data string.

4.3.2 Methodology

With the laser scanner, sensing becomes an active process; the robot decides at each step of its path what sensory information[18][19] is required for generating its next step. The robot

has to decide upon the amount of turn depending on the nearness of the target to it. The optimal angle of sweep per reading should be obtained in such a way that it does not slow down the overall system performance. The scanner is mounted such that the sweep is 8 inches above the ground level. The laser scanner gives us a field of view showing the complete 180° sweep made by the laser beam. The laser beam starts from the right and goes to the left. So at every angle, depending on the resolution set, we can get the distance and position of the objects along the robot's path. With these values we know exactly at what angle is an obstacle present and what its size is. This simplifies the problem in earlier algorithms with the sonar systems where we could not get the exact position and size of the obstacle. The data returned for every degree scanned allows us to generate a profile of the size, shape, distance and orientation of the obstacle in the scanned area. Thus for a scanner resolution of 0.5°, we get 361 values for the field of scan. The fuzzy logic can then decide the path the robot must follow, the angle it must turn to avoid the obstacle. In addition the scanners contour measurement data can be evaluated to determine the relative positions and sizes of objects. LMS 200 with 10mm resolution offer programmable monitored zones with corresponding switching outputs in stand-alone operation, i.e. without external evaluation. The functions and options required can be configured within the scanner itself. The laser scanner returns accurate and reliable data for obstacle detection.
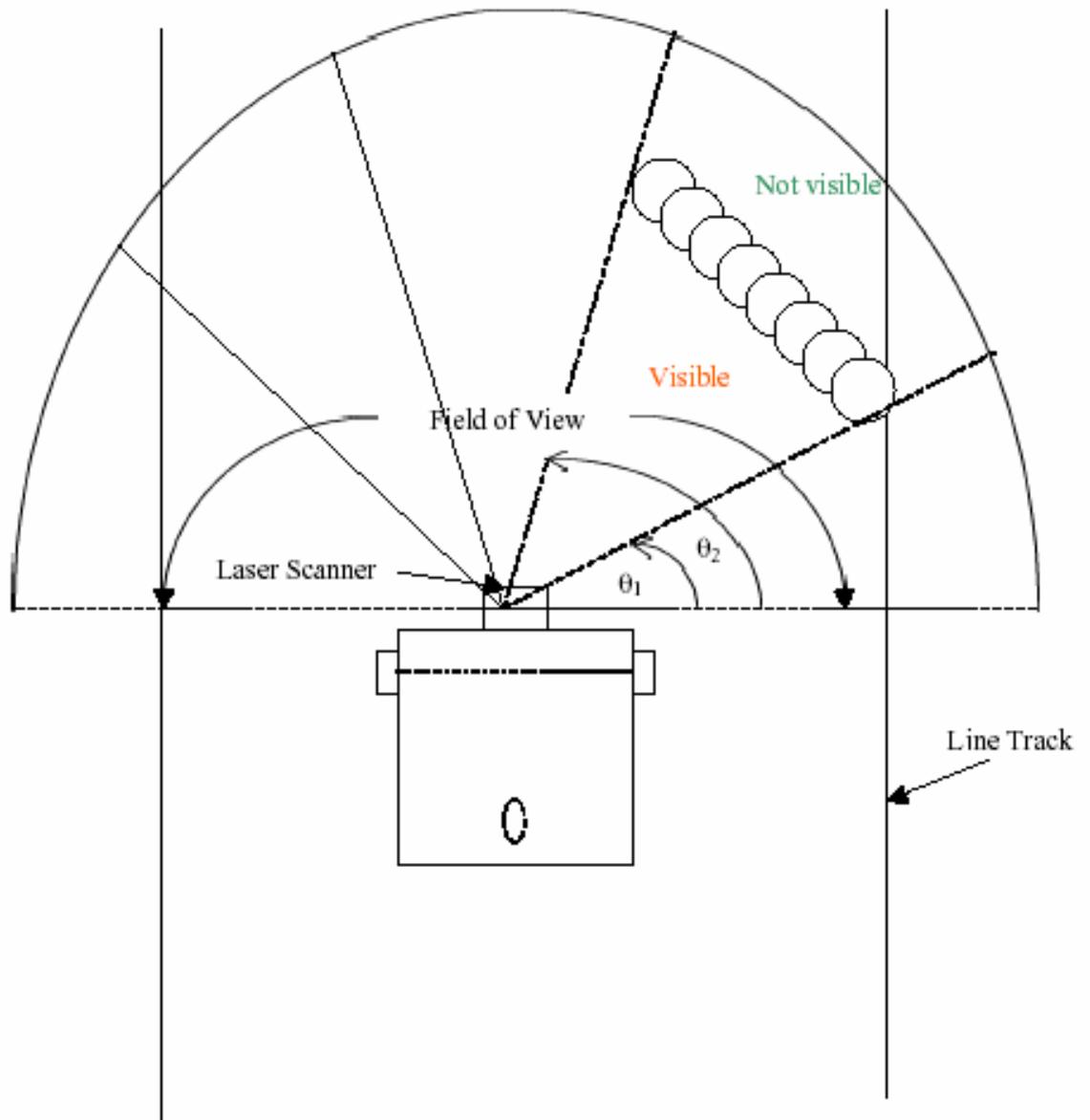
Figure 4.9: Scanner range detection

Figure 4.10 shows the placement of the obstacles and the robot[19].
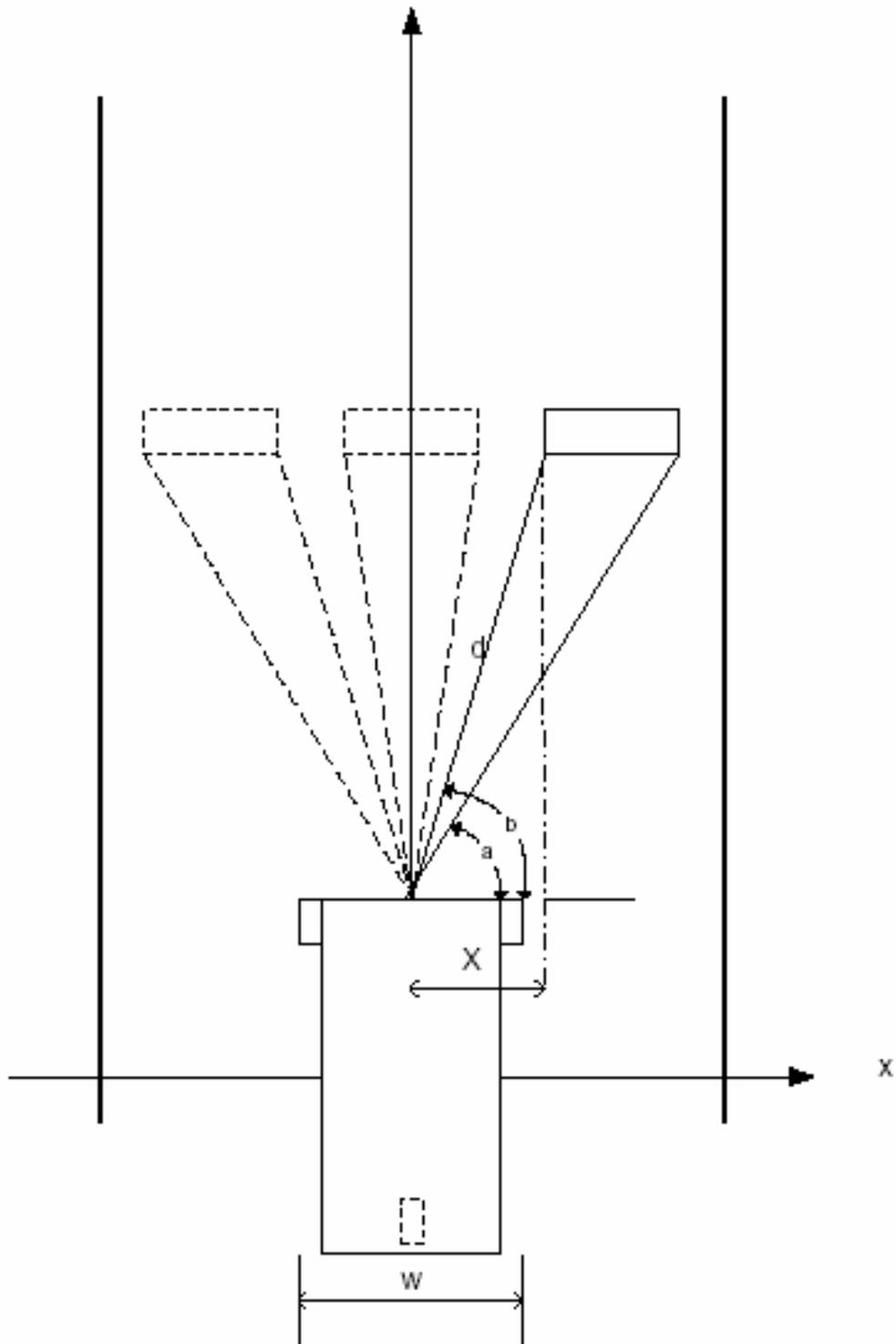
Figure 4.10: Position of obstacles with respect to the robot

The obstacle can be to the right, the left or in front of the robot. With the laser scanner we get a 180 degree field view with resolutions of 0.25, 0.5 or 1 degree. Knowing the distance of the object at these angles we can find the profile of the obstacle. The obstacle can be located such that the robot can maintain the same path without touching the the obstacle or it can be in the path of the robot. The robot checks if it can maintain same path and avoid obstacle without offsetting the centroid of the robot from the center of the track.

From figure 4.10 we can see that If $X = d*Cos$ (b) and $X > ½$ w it can continue on a straight path without offsetting robot centroid. In such a case the robot will maintain the same heading. However if $X = d*Cos$ (b) and $X < ½$ w the robot cannot maintain the same heading. In this case the vehicle has to plan a new path to be able to navigate around the obstacle. The obstacle avoidance routine takes over from the line following as soon as the obstacle is detected. The Figure 4.11 represents the path taken by the robot once an obstacle is detected. If the obstacle is to the right the robot will navigate around the left of the obstacle. If the obstacle is displaced to the left the robot will navigate toward the right of the obstacle. When the robot detects an obstacle in front it will navigate around the obstacle from the right or left depending on the distance of the robot from the line it is following at that moment. This decision is made such that it will not go out of the line track while trying to avoid the obstacle. The steps taken by the robot to avoid the obstacle are described below.
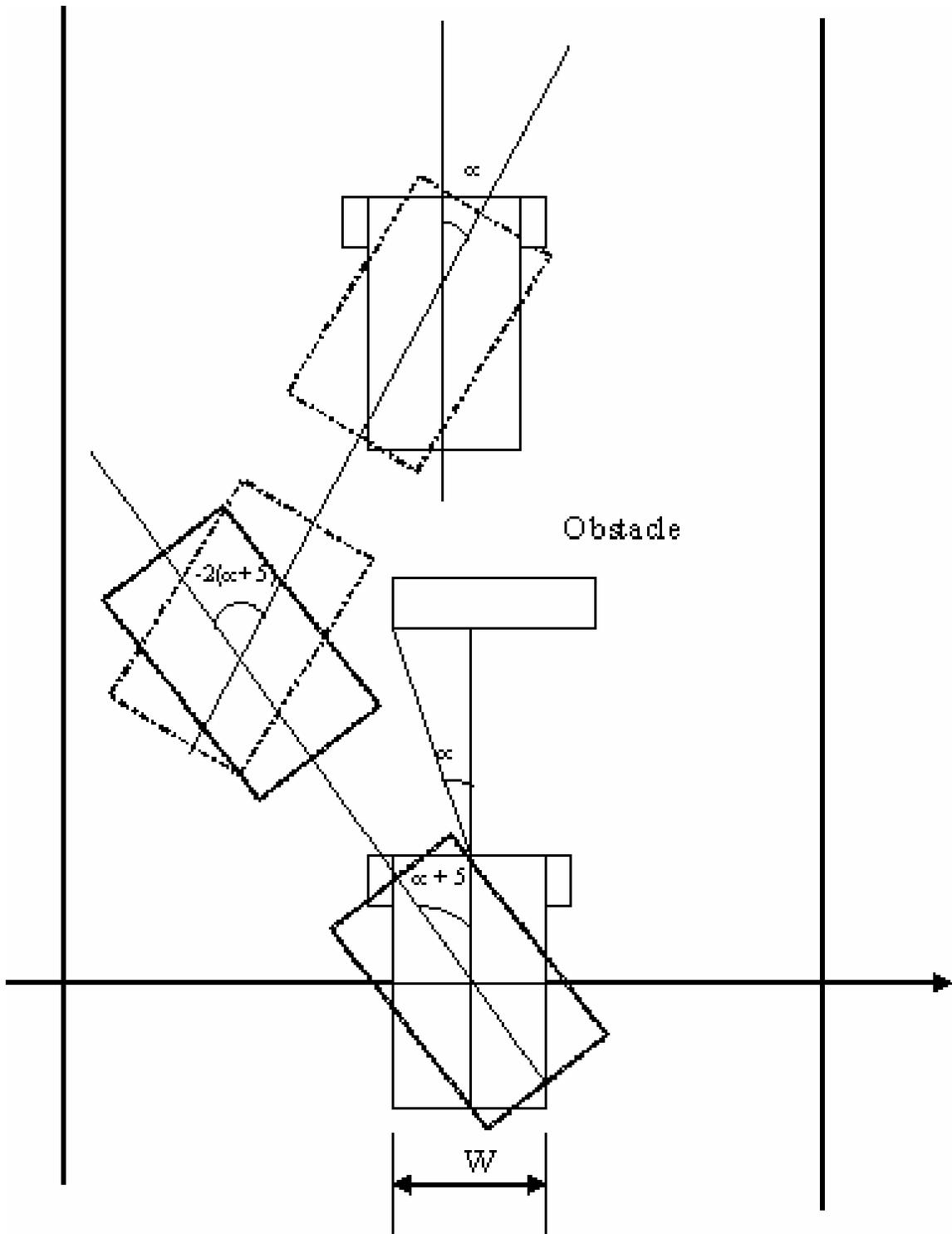
Figure 4.11: Path taken by the robot to avoid obstacles

1. The angle $\propto$ can be calculated as the last contact angle of obstacle – 90 degrees.

2. The robot turns an angle of ($\propto$ + 5) degrees.

3. If D is the distance of the obstacle from the front center of the robot and L the robot length the robot moves a distance of (D+L/2) / cos($\propto$+5).

4. The robot then turns by an angle of -2($\propto$+5) degrees.

5. The robot moves a distance of L+2 feet..

6. The robot then turns by an angle $\propto$ degrees.

7. The control is transferred back to the line following routine.

4.3.3 Advantages

The laser scanner gives very high resolution and accuracy in terms of the distance measured. The environmental conditions such as the temperature do not affect the accuracy of the scanner. Real time transfer of measured data is possible and high scanning frequencies up to 75 Hz can be achieved. The laser scanner has a range of 8 meters against 3.66 meters for the sonar systems. It has multiple configuration options, which can be effectively used for elimination of stray and excess data. The object is detected irrespective of its size and its orientation.

4.3.4 Limitations

The method has higher cost compared to the sonar system and interfacing of the system with the controller is complex. The algorithm for data filtering is complex and the large amount of data can cause the processing to be slower and require higher processing power and memory.

Chapter 5

Conclusions

5.1 The Comparison Matrix

The laser scanner and sonar systems are widely used for obstacle detection and avoidance. With the stationary sonar the region in which the obstacle lies can be determined. We need a rule based approach to avoid obstacles. The system has noise and it is difficult to reduce the error. The rotating sonar system gives a more accurate position for the obstacle and has the advantage of using only one sensor. However there is a tradeoff between the number of motor stops and the speed of the robot. Common to both the stationary and rotating sonar systems is the problem of reflection and scattering of sound waves. The laser scanner gives the exact position of the obstacles since we know the range profile over a 2D 180 degree span. The distance accuracy measured by the sonar systems is lower than that obtained by the laser scanner. The angular accuracy is the highest with the laser scanner since we can have a resolution 0.25 degrees with the rotating sonar system this angular accuracy is dependent on the speed of the vehicle, the speed of rotation of the sonar motor and the number of motor stops. Angular accuracy does not apply to the stationary sonar since the systems gives the zone in which the obstacle lies and not the actual angles with respect to the robot. With the stationary sonar it is not possible to reliably say if there are multiple obstacles or if there is one single obstacle. Due to the overlapping of the sonar fields we cannot say if the system has detected two different obstacles or it has detected a larger obstacle. Similarly with the

rotating sonar system though it is possible to detect multiple obstacles there is a high possibility of error or noise in the readings. With the laser scanner it is easy to detect multiple obstacles and generate their two dimensional profile. The orientation of the obstacle can be detected with the scanner. With the sonar systems an obstacle which is at an angle to the robot will increase the error in the readings. Thus it is not possible to detect the orientation of the obstacle with this system. Both the stationary and rotating sonar systems have high data noise compared to the laser scanner. Environmental factors such as humidity and temperature affect he output of the sonar systems. Table 5.1 shows the comparison of the three systems.

Table 5.1: Comparison of the three obstacle avoidance systems

System/ Criterion	Position of obstacle	Distance accuracy	Angular accuracy	Obstacle size	Multiple obstacle detection	Obstacle orientation	Data noise	Environmental effects
Stationary Sonar	Region can be determined	Low	N/A	N/A	No	No	High	High
Rotating Sonar	Approx Position can be determined	Low	Very low	N/A	No	No	High	High
Laser Scanner	Exact position can be determined	High	High	Can be determined	Yes	Yes	Low	Low

The sonar systems are more economical than the laser scanner and are easier to implement since the amount of data received is less. However, there is a loss of accuracy with the increase in complexity of the systems. With the sonar systems it is difficult to develop path planning systems and the algorithms are reactive, the laser scanner gives data which can be used for mapping and planning the navigation of the robot. The three systems have been successfully implemented and tested on the Bearcat.

Chapter 6

Direction for future research

The stationary sonar system on the Bearcat I had two sonar sensors. Using an array of sonar sensors could help my giving more information to help detect the location of the obstacles[9][10]. The sonar motor for the rotating sonar system is difficult to tune and a new motor using a gearbox to reduce the motor clatter is being implemented on the Bearcat III. This will help get more accurate data from the system. The three systems have been implemented independent of each other on the Bearcat III, using the sonar for coarse detection and then the laser scanner for fine detection will increase the system performance. The three sensors can be used simultaneously and data from them can be fused. J.C. Baker[20][21] suggests a method for the fusion of heterogeneous sensors for guidance and navigation of an autonomous guided vehicle. Further; stereo vision systems and radar systems can be explored for implementation on the Beatcat III or the new Bearcat Cub.

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