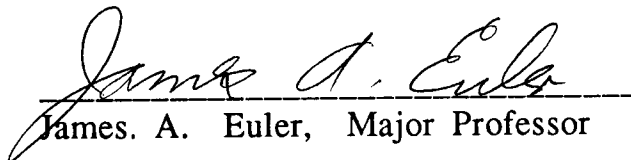
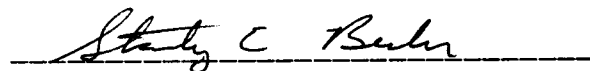


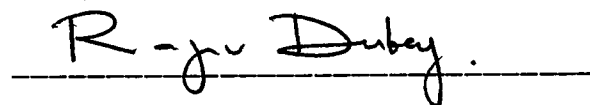
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**APPLICATION OF AN INEXPENSIVE ULTRASONIC
SENSOR AS AN OBJECT DETECTION DEVICE
FOR A ROBOTIC ARM**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

QAMAR ASGHAR

December 1990

*This thesis is dedicated
to my late loving
mother, who has been a
source of great
inspiration through out
my life . . .*

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ABSTRACT

Kinematically redundant robots have been the subject of many investigations in which researchers have tried to avoid obstacles by using the available degree of redundancy. These schemes are usually based on the assumption of a well defined obstacle location and position in the robot's work space. A more complete solution to this problem includes a continuous feedback mechanism for accurate location of moving obstacles or objects in the robot's work envelope.

A robot which can "see", can prove to be more dextrous in the performance of complex tasks while at the same time it requires less stringent control mechanisms than preprogrammed machines. A sensory, trainable system is also adaptable to a much larger variety of tasks, thus achieving a degree of universality that ultimately translates into lower production and maintenance cost.

An obstacle avoidance scheme based on sensory feedback is presented for the kinematic control of a robotic manipulator with a single degree of redundancy, which can be extended to manipulators with multiple degrees of redundancy. An inexpensive ultrasonic sensor is used to locate obstacles in the robot's workspace and provide feedback for modification of the robot's wrist trajectory. The kinematic control scheme which uses the feedback from the sensor for local optimization of trajectory parameter is based upon the gradient projection method developed by Dubey and Euler et al. [5].

This study also explores the possibilities of using the sensor as an inexpensive feedback control loop device to duplicate the results of computer vision.

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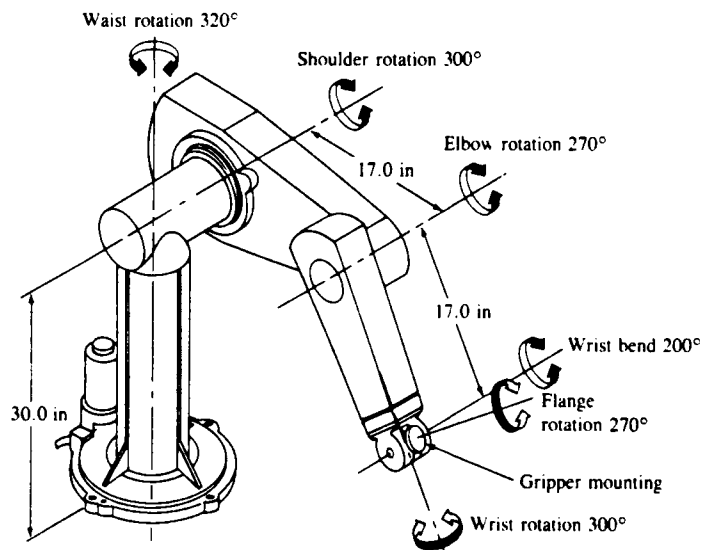
CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Robots with the minimum number of joints required for achieving a particular task are prone to encounter singular configuration during the course of manipulation figure 1.1. In singular configuration extremely high or unrealizable velocities are needed to move the end effector with a finite velocity. Manipulators with minimum number of joints face singularity mainly because of the loss of at least one degree of freedom.

A redundant robot is defined as the manipulator with the joint space dimension greater than the dimension of its workspace figure (1.2). Robots which fall into this category have the liberty to utilize their redundant degree of freedom to avoid singular configuration. Inverse kinematics of redundant robots are computationally exhaustive because of an infinite number of possible solutions (joint velocities). A number of schemes have been proposed for the inverse kinematics and optimization of joint velocities for redundant robots Slotine and



Figure(1.1) Cincinnati Milacron T³ robot arm.
K.S. Fu, R.C. Gonzalez, C.S.G. Lee, "Robotics: Control, Sensing, and Intelligence", McGraw-Hill Book Company, 1987.

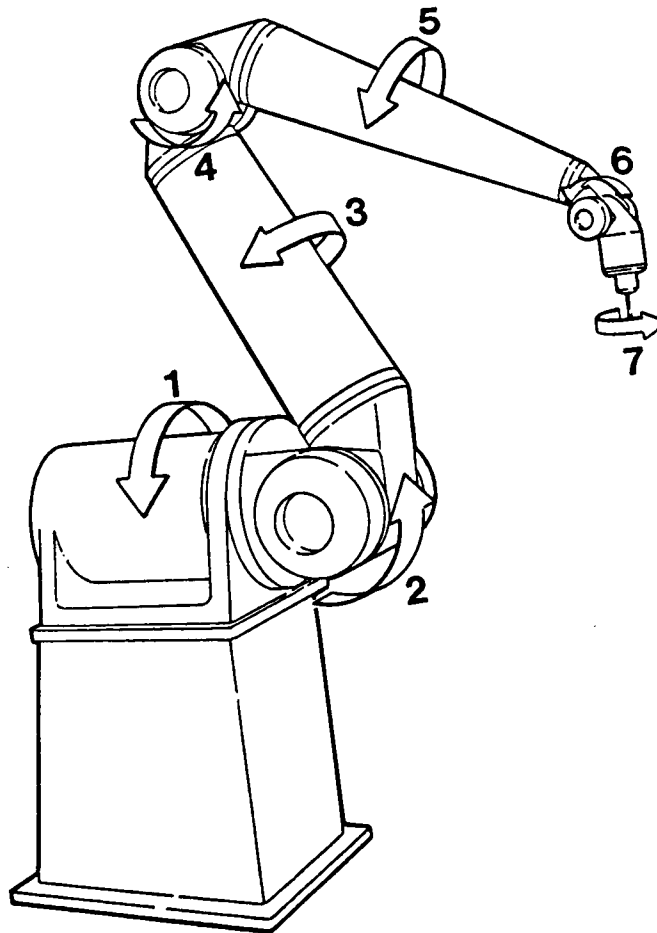


Figure 1.2 Seven degree-of-freedom redundant robot
Courtesy: Robotics Research Corp.

Sheridan[1], Chevallereau and Khalil[2], Chang[3], John Baillieul[4]. A computationally efficient scheme for the optimization of joint velocity was proposed by Dubey et al. [5]. The same scheme was used by Zghal[6] for defining performance criteria for avoiding obstacle and joint limits. Baillieul [7] presented an obstacle avoidance technique based on optimizing the distance criteria. Most of these collision avoidance schemes are based on the assumption that the location of the obstacle is known to the manipulator. Zghal tackled the window problem by first defining the location and size of the window. Similarly Baillieul's scheme [7] assumes location of cylindrical objects is precisely known. Such schemes work well when the robot controlled environment is known and all the tasks and motions to be performed are planned in advance. If robotic systems are increasingly required to operate in complex domains, where the environment and the tasks are unknown or uncertain, then an allowance given for uncertainty will be insufficient to ensure safe, efficient, and accurate operation of the robotic system.

A more complete solution to the collision avoidance problem includes some kind of mechanism which interacts with the environment (the obstacles) and provides the necessary feedback for subsequent motion. A dynamic feedback mechanism in conjunction with a numerically efficient kinematic control scheme ensures flexible (ability of a robot to change the direction of its end effector motion)

and dextrous manipulation. An increased interest in developing sensory feedback mechanism for robotics application is observed in recent years [9], [10], [11] and [12]. The need for such systems stem from a desire for a robot with a higher degree of intelligence and autonomy. Such a robot must be capable of using different sources of sensory information in an active (real time processing of sensory data) and dynamic (responding to changes in the environment) way.

A number of techniques such as vision, touch sensing, force sensing and range sensing [13] are available to interact with the robot environment (figure 1.3) . Each of these techniques unveils a particular set of properties of the sensed environment. Although vision sensing is cheap but extracting three dimensional information from it is often a difficult task and requires rigorous sensing. On the other hand range sensing of imaging is cumbersome but gives definite and explicit three-dimensional shape information. Most of the accurate ranging systems are limited either for research work or for military use and are too expensive for the use of general purposes. Tasks such as collision avoidance or object detection do not have a pressing restriction on the accuracy of the manipulator's operation. Another application which requires precise and accurate detection of object with a reasonable information about the shape of the object is in assembly lines and other shop floor pick and place operations.

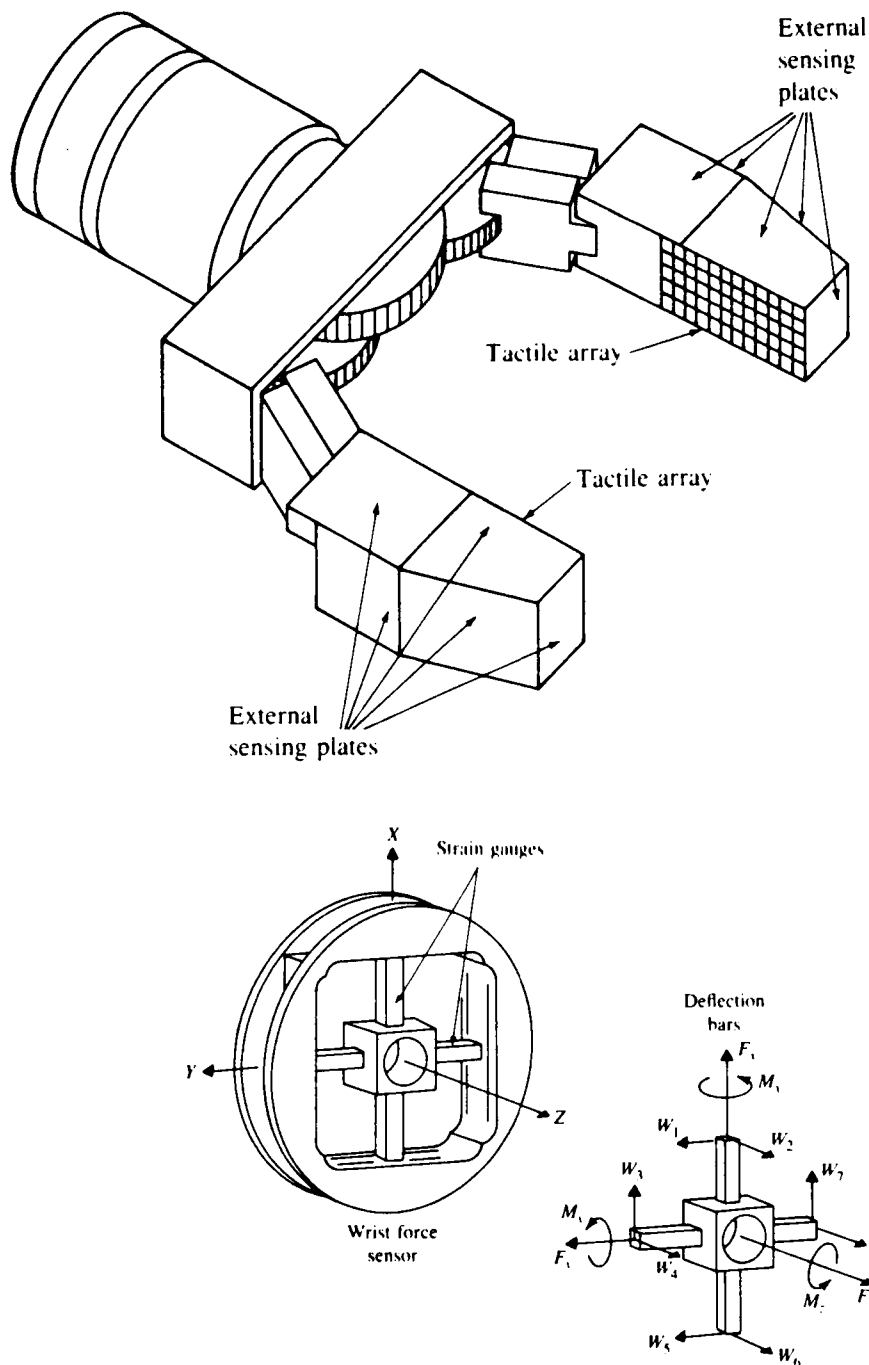


Figure 1.3 Force and tactile sensing devices
 (K.S. FU, R.C. Gonzales, C.S.G. Lee, "Robotics: Control, Sensing, Vision,
 and intelligence", McGraw-Hill Book Company, 1987.)

1.2 THESIS OBJECTIVE

The object of this study is to explore the possibility of using an inexpensive sensing device for generating feedback signals for obstacle avoidance and its use in shop floor environment as a vision tool. This scheme is to be implemented in a dynamic (changing environment) and active (real-time processing) way.

The task of obstacle avoidance requires only the information about the location of the obstacle. A device which measures distance between the nearest object and itself can be used to gather distance data for this purpose. The distance data can be collected over an area and then each distance information can be plotted against the corresponding sensor location to get a three dimensional plot of the scanned area. Different types of objects can be scanned and a comparison between the actual profile and the profile obtained by scanning the surfaces can be used to find the ways and techniques to be used for manipulating the feedback signals for robot manipulation. The scheme is applied to a four-degree-of-freedom IBM7547 with the polaroid ultrasonic ranging system as the sensing device. Objects to be scanned are supposed to have sharp edges, all surfaces are either vertical or horizontal (either parallel of

orthogonal to the direction of propagation of the acoustic wave). The same sensor can be used to scan surfaces in any orientation.

1.3 ORGANIZATION

Organization of the remainder of this thesis is as follows. Chapter 2 presents an overview of the hardware before the ultrasonic transducer was introduced to the system. Chapter 3 focuses on some of the ranging techniques available today, and the reason for choosing the ultrasonic system. Chapter 4 describes the obstacle avoidance scheme for the transformed 7547 manipulator with a single degree of redundancy. Chapter 5 describes the hardware development phase and overall working of the robotic system. Chapter 6 presents some of the experiments and accuracy results. Conclusions and recommendations are given in chapter 7.

CHAPTER 2

HARDWARE OVERVIEW

2.1 INTRODUCTION

The hardware system consists of two main parts, which are the IBM 7547 manufacturing system and a Poloroid ranging unit. We will discuss each of these in detail to understand the existing capabilities of the systems and then will assess what needs to be done for integrating the two components.

2.2 The IBM 7547 MANUFACTURING SYSTEM

The manufacturing system itself can be sub-divided into three main entities, which are the IBM 7547 manipulator, the 7547 controller and an IBM personal computer (figure 2.1).

2.2.1 The IBM 7547 MANIPULATOR

IBM 7547 robot is a four degree of freedom industrial robot, useful in pick and place operations. The manipulator is shown in figure 2.2.

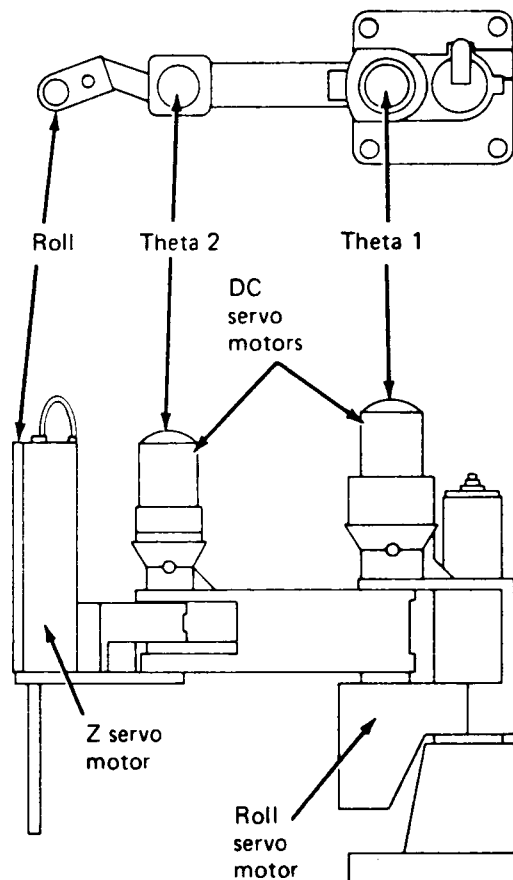


Figure 2.1 The IBM 7547 manufacturing system
Reprinted from the IBM 7547 manufacturing system
hardware library (site preparation).

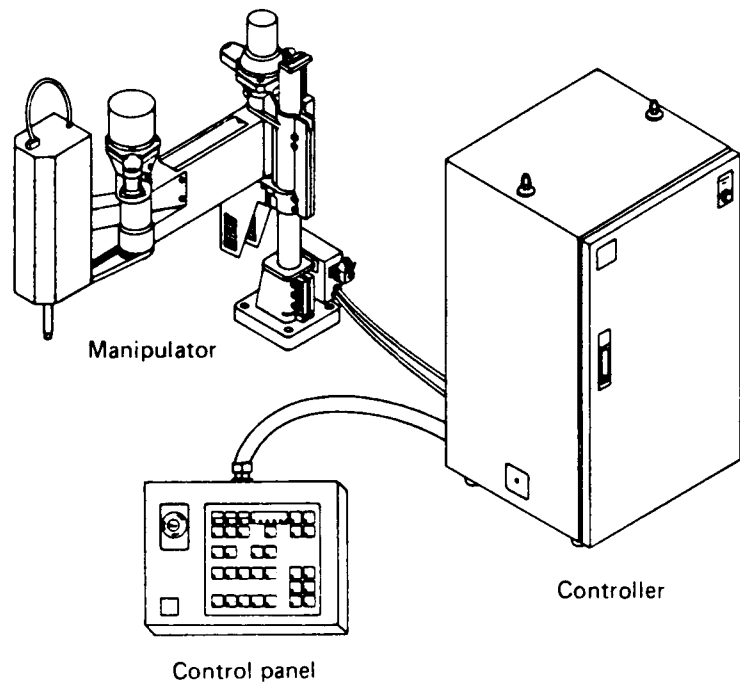


Figure 2.2 The IBM 7547 manipulator
Reprinted from IBM 7547 manufacturing system hardware
library (site preparation)

It has two revolute joints which help the manipulator to move in a plane. The third degree of freedom allows the robot to move its wrist in z-direction. The fourth degree of freedom is used to orient its gripper with respect to the object for accurate and smooth pick and place operations. The manipulator's position, and speed is continuously monitored by encoders, servos and internal sensors. These informations are passed on to the motor controller board (MTCB) for further action. Some of the important parameters for the manipulator are shown in figure 2.3.

2.2.2 THE 7547 CONTROLLER:

The heart of the controller is a motor control board which contains a microprocessor, storage, interface circuits, and communications circuits as well as circuits to control movement, as directed by the microprocessor. The microprocessor processes all the information from the sensors, encoders, servos and external devices as well as the instructions from the application program before making any move. The 7547 controller has four motor drivers, a power supply with a range of supply voltages. Motor drivers can be instructed to move the robot either through a control panel instruction or through an application program down loaded on one of the memory partitions. A big application program can occupy all of the five

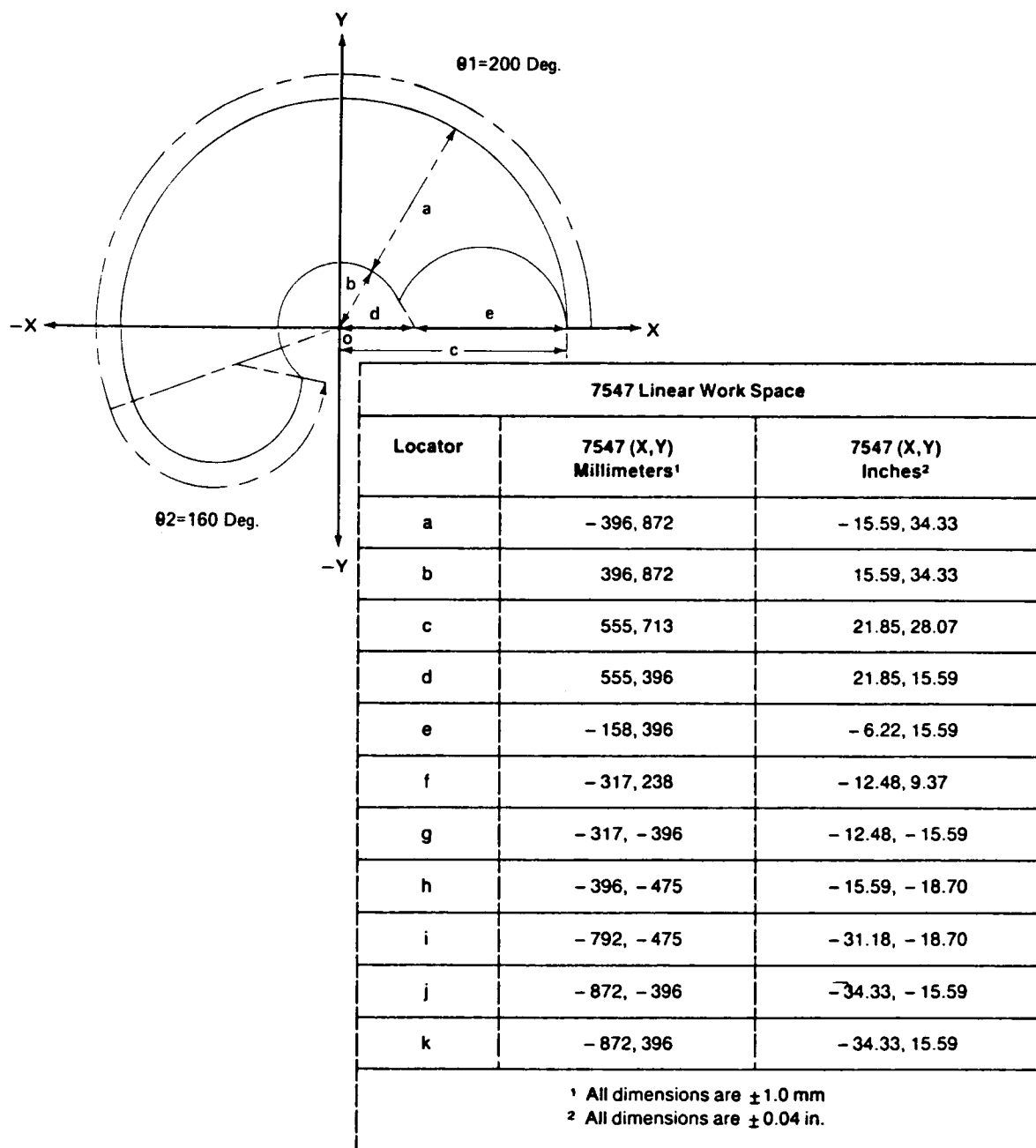


Figure 2.3 Parameters for the IBM 7547 manipulator
 Reprinted from IBM 7547 manufacturing system hardware
 library (site preparation).

memory partitions. The controller has five communication ports (C1, C2, C3, C4 and C5), which it uses to communicate with the robot as well as with external devices.

C1 port is meant for communication between the controller and the personal computer. The controller receives its instructions for subsequent action through this port. The instruction may ask the controller to erase the contents of a particular partition or to overwrite one.

The controller communicates with external devices such as a conveyer belts, solenoid valves, encoders etc, via communication port C2. The port can be used to monitor up to 16 digital input and sixteen output signals. The DI signals are used to monitor some ongoing process and the data through these signals can be manipulated inside the controller's memory for subsequent action. Same is true for the DO port, which is activated or deactivated by internal relays. User has the flexibility of setting the voltage level according to situation and requirement. This is achieved by grounding the bit for 0 logic level and leaving the bit floating for logic level 1. Floating bit does not have any voltage and the user pulls the bit up according to his requirements. The monitoring capabilities of the controller can be extended up to 32 additional bit by using extended DI/DO card. Details of the connector and the wiring diagram for both DI/DO cards

is shown in figures of chapter 5. Ports C4 and C5 are used to control stepper motor and receive signals from built in sensors.

2.2.3 USER INTERFACE TO THE CONTROLLER (THE IBM PERSONAL COMPUTER MODEL AT)

A personal computer is used to write application program for the IBM 7547 industrial robot. Since the controller accepts application instructions only in ASCII format the application which is written in AML has to be compiled in computer's memory before it is down loaded into controller's memory.

2.3 SONAR RANGING SYSTEM

The sonar ranging system consists of two main components, the acoustic transducer and an electronic module.

2.3.1 ELECTROSTATIC ACOUSTIC TRANSDUCER

The principal component is the electrostatic acoustical transducer which acts both as loudspeaker and microphone (figure 2.4). It is composed of a very thin , Kapton-film diaphragm vacuum coated with gold to form the negative electrode. The positive electrode is the

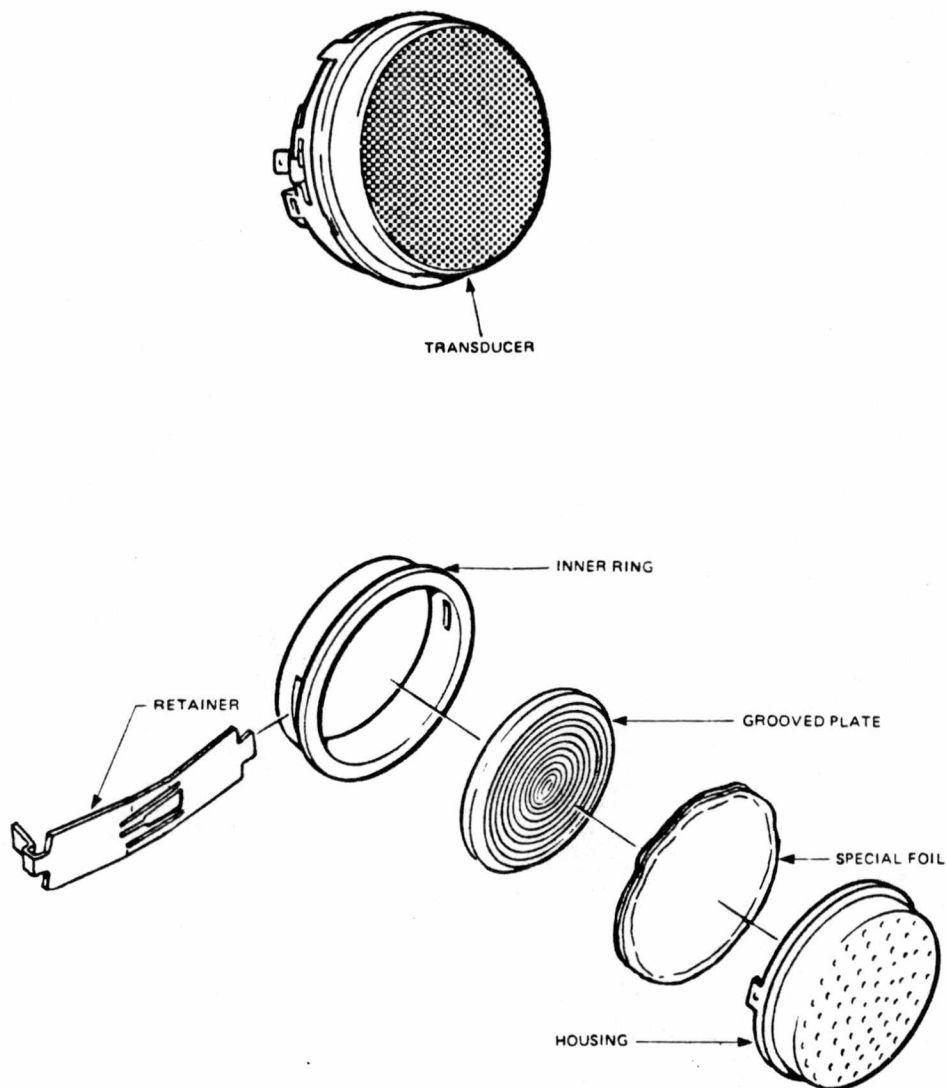


Figure 2.4 The electrostatic acoustic transducer
Courtesy: Polaroid ultrasonic ranging system user's manual and application notes.

coined aluminum back plate which also provides the resonant structure for the diaphragm. Mechanical bias , as well as , electrical contact is provided by a stainless steel leaf spring. The transducer is 4 centimeter in diameter and weighs only 8 grams.

The thin foil is the moving part which transforms electrical energy into sound waves, and, conversely, sound waves into electrical energy. The foil is stretched over the aluminum back plate. Back plate and foil represent an electrical capacitor. When charged, an electrostatic force is exerted on the foil. An AC voltage of given frequency forces the foil to move at the same frequency and to send out sound waves. A DC bias is applied externally. For reliable function the thin film has to be under constant tension. Stainless steel leaf spring helps in maintaining this constant tension. The perforated front cover mechanically protects the foil with a small loss of signal strength. In an application like our's , the sound output has be maximized while the phase and the distribution of the output across the transducer have to be well defined and uniform. This is because they determine the lobe pattern. The large diameter of the transducer, the high frequency used, and an accurate in-phase condition create a narrow beam for transmission as well as reception.

2.3.2 The ELECTRONIC MODULE

The electronic module which drives the electrostatic acoustic transducer, contains the necessary circuitry for generating signals at transmission and reception. The system drives the transducer with a 1 millisecond tone burst at 300 volts peak-to-peak and 150 volts DC bias, producing an output sound pressure level at 50 kHz of approximately 118 dB SPL at 1 meter. The transmitting response is seen to be quite flat to beyond 100kHz. This provides the transducer with very fast damping so that ranging at high gain can be achieved as quickly as possible after transmit. The very wide bandwidth and extremely high output allows the system to operate over a very wide distance range. The system is capable of a minimum range of 10.4 inches. With a receiving sensitivity of -45dB. The diameter of the transducer determines the acoustical lobe pattern or acceptance angle, during the transmit and receive operation.

CHAPTER 3

RANGING TECHNIQUES

3.1 INTRODUCTION

Efficient mechanical design can ensure flexibility (adaptability and varsatility w.r.t appliction), improved maneuverability (ability to change direction of motion without noticeable vibration), enhanced work space but to make a robot intelligent so that it can make decision on its own, based upon what it encounters in the real world requires much more than that. External devices can be used to communicate and interact with the world around them to serve as eyes, ears and fingers. Preprogrammed operation in which a robot is "taught" to perform repetitive tasks via a set of programmed functions can not be useful under a changing environment.

3.2 SCOPE AND APPLICATIONS

It seems inevitable for an intelligent robot to use external sensing mechanisms which would allow the robot to interact with its environment in a flexible manner. This is in contrast to the

preprogrammed operation described earlier. Although the preprogrammed option is by far the most predominant form of operation of present industrial robots, the use of sensing technology to endow machines with a greater degree of intelligence in dealing with their environment is, indeed, an active topic of research and development in the robotics field. A robot which can see can prove to be more dextrous in the performance of complex tasks while at the same time requiring less stringent control mechanisms than preprogrammed machines. A sensory, trainable system is also adaptable to a much larger variety of tasks, thus achieving a degree of universality that ultimately translates into lower production and maintenance cost.

An important application of external sensing is in detecting the presence of objects in a robot's work envelope (Figure 3.1). The task of this type of sensing is not only to detect an object but also to estimate where that object is with respect to a reference point. This type of sensing falls into the category of range sensing. A range sensor measures the distance from a reference point (usually on the sensor itself) to objects in the field of operation of the sensor. All the living creatures use some type of ranging, e.g, humans estimate distance by means of stereo visual processing, while other animals such as bats, utilize the time of flight concept in which distance estimates are based on the time elapsed between the

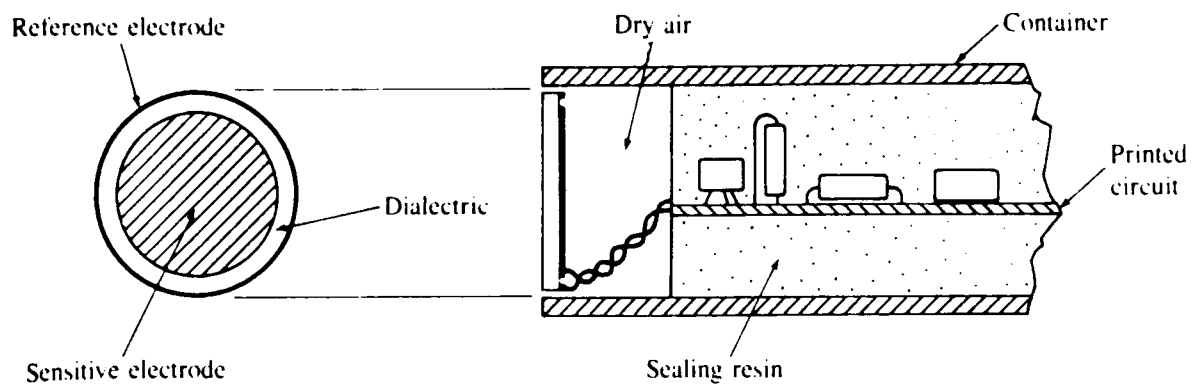


Figure 3.1 Capacitive range (proximity) sensing.
(K.S. FU, R.C. Gonzalez, C.S.G. Lee, "Robotics: Control, Sensing, Vision, and Intelligence", McGraw-Hill Book Company, 1987)

transmission and return of a sonic pulse. Range sensors are used for robot navigation and obstacle avoidance, where interest lies from estimating the distance to the closest objects, to more detailed applications in which the location and general shape characteristics of objects in the work space of a robot are desired.

3.3 RANGING TECHNIQUES

Ranging techniques can be divided into two broad classes.

- a) Vision based ranging
- b) Time of flight based ranging

3.3.1 VISION BASED RANGING

Two most common ranging techniques which are based on vision are

- a) Structured lighting approach
- b) Method of triangulation

The structured lighting approach makes use of the relationship between projected and distorted light patterns in a known

configuration. The distorted pattern can be observed by a camera which is located at a known distance from the light source.

3.3.2 TIME OF FLIGHT BASED RANGING

If we measure the time that a laser pulse takes to reflect back from a surface to the point of its origin coaxially (i.e, light beam follows the same path) then an easy estimate of the distance between the laser source and the object from where it was reflected can be calculated as

$$\text{distance} = d = cT/2 \quad \dots\dots\dots (3.1)$$

Where c is the velocity of light

T is the time of flight

Since the velocity of light is 186,000 miles per second which is approximately 1 ft/ns , this implies that in order to have a resolution of 1 ft the supporting electronic instrumentation should be capable of 1-ns ($1\text{ns}=10^{-10}$ s) time resolution. Furthermore if a resolution of 1/4 inch is required, the clocking sysem must be of 50 ps ($1\text{ps}=10^{-12}$ second)time resolution.

Jarvis [1983] was able to produce a two dimensional image of a setup where the intensity of light was proportional to distance. The two dimensional scan was obtained by reflecting the laser pulses through a rotating mirror.

The second method involves using a continuous laser beam . The arrangement consists of a laser beam source, a beam splitter and a phase measuring arrangement as shown in figure 3.2. An emitted laser beam passes through a beam splitter before it reaches the object. The beam splitter divides the beam into a reflected part and a part which passes through the splitter. The reflected part strikes a phase measuring device. The part which passes through the splitter strikes the object and is reflected back to the beam splitter and is again reflected to the phase measuring device which records the phase shift. It is apparent that the beam which strikes the object travels a distance

$$D' = L + 2D \dots\dots\dots(3.2)$$

where

L = distance between the beam splitter and the phase measuring device.

D = distance between the object and the beam splitter.

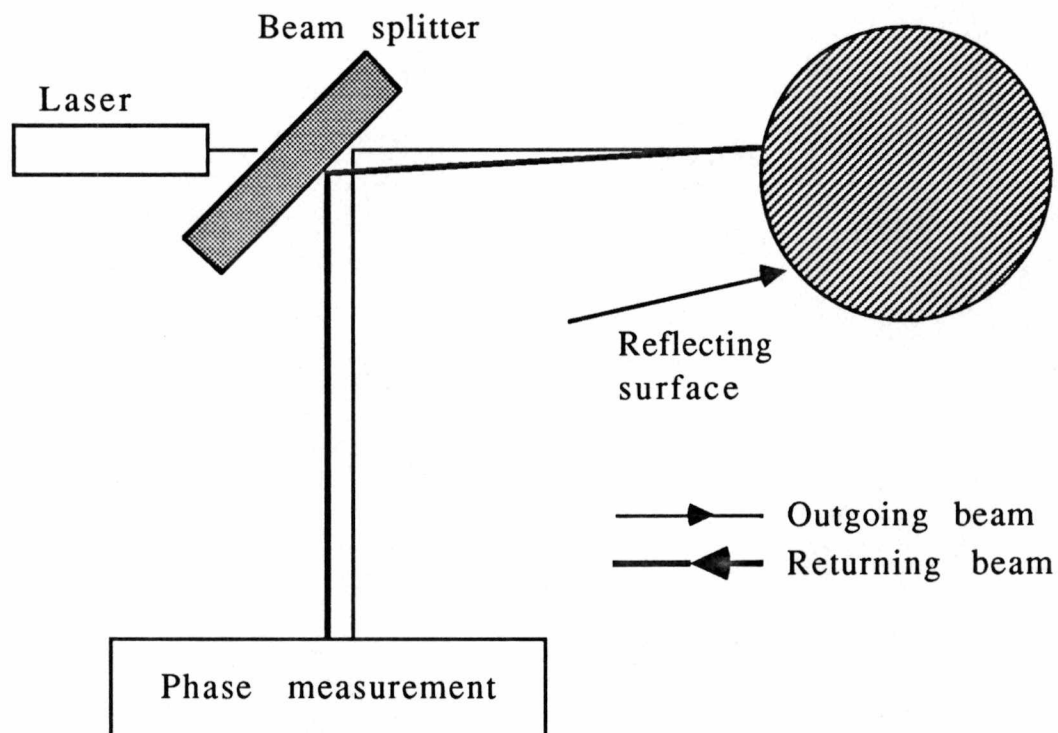


Figure 3.2 Ranging based on phase shift

D' = Total distance covered by the beam which is reflected by the object.

If the object is at zero distance from the beam splitter than

$$D' = L \dots\dots\dots(3.3)$$

and both light beams would reach the phase measuring device at the same time with no phase shift. Now if we increase the distance between the object and beam splitter than the light which passes through the splitter travels a longer distance before it reaches the phase measuring device, which causes a phase shift. Let the wavelength of the laser beam be λ and the phase shift measured at the measuring point be θ then the total distance covered by the beam reflected from the object can be calculated as

$$D' = L + \theta \lambda / 360 \dots\dots\dots(3.4)$$

It can be noticed here that if the phase shift turns out to be any integer multiple of 360° then there would be no phase shift and we would not be able to differentiate between the two beams based on

shift measurement alone. Therefore a necessary condition for obtaining a unique solution is

$$\theta < 360^\circ \quad \text{or} \quad 2D < \lambda \quad \dots\dots\dots(3.5)$$

Combining equation (3.1) and (3.3) we get

$$D = \theta \lambda / 720 \quad \dots\dots\dots(3.6)$$

Equation gives the distance in terms of phase shift if the wavelength is known.

This method of ranging is not practical for robotics application because the wavelength of laser light is very small, e.g, 632 nm for a helium-neon laser. This impracticality can be overcome by modulating the laser beam by a beam of much longer wave length and amplitude. A laser beam is shown to be modulated by a beam of a longer wave length in figure 3.3. For example the same laser beam can be modulated by a beam of frequency $f=10$ MHz which has a wavelength of 30 meters. This brings us in to a workable frequency range. The basic technique remains the same with the only difference being that now a modulated laser signal is sent out to the target and the returning beam is stripped of the

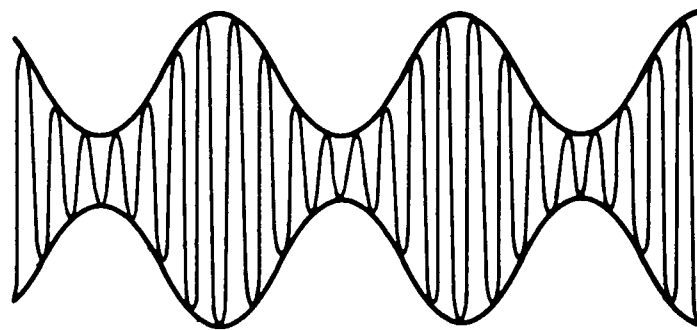


Figure 3.3 Use of modulated laser beam in range sensing
(R. S. Fu, R. C. Gonzalez, C. S. G. Lee, " Robotics: Control, Sensing, Vision
and Intelligence", McGraw-Hill Book Company, 1987)

modulating signal, and then compared against the reference to determine the phase shift.

Another type of ranging based on the time of flight concept is ultrasonic ranging. The basic principle involves recording the time it takes between transmission and reception of a particular signal. The only difference between pulse laser ranging and ultrasonic ranging is that ultrasonic ranging relies on a sonic pulse whereas laser ranging involves a laser beam.

An ultrasonic chirp is transmitted over a short period of time. The speed of sound is known for a given medium at a given temperature. A simple calculation involving the time of flight (the time interval between the outgoing pulse and the return echo) and the velocity of sound yields an estimate of the distance to the reflecting surface. The same ultrasonic ranging principle can also be applied for proximity sensing. In fact ultrasonic proximity ranging has an advantage over others that its function is independent of the material being sensed.

A typical ultrasonic transducer is shown in figure 3.4. The important element is an ultrasonic transducer which produces a chirp of known frequency. This element is usually a piezoelectric ceramic type. A resin layer is kept in front of the transducer to protect it against humidity, dust, and other environmental factors. It also acts

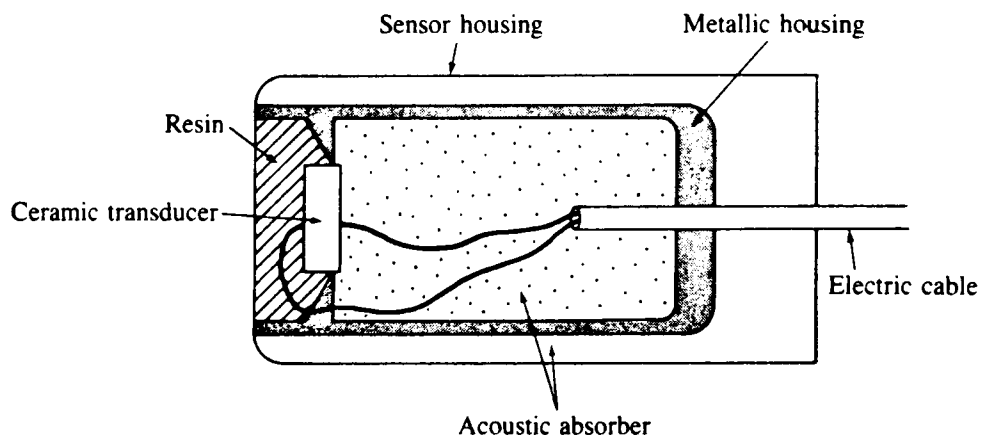


Figure 3.4 An Ultrasonic proximity sensor
(R. S. Fu, R. C. Gonzalez, C. S. G. Lee, "Robotics: Control, Sensing, Vision and Intelligence", McGraw-Hill Book Company, 1987.)

as an acoustical impedance matcher. A general requirement for this kind of transducer is that it should be able to damp acoustical energy produced during transmission as fast as possible for close range detection. This requirement is met by providing acoustic absorbers, and by isolating the transducer from its housing. The housing is designed so that it produces a narrow acoustic beam for efficient energy transfer and signal directionality.

3.4 SIGNAL PROCESSING AND DISTANCE CALCULATION

The operation of object detection and determining the time between transmission of the sonic pulse and detection of the returning echo can be best understood by analyzing the timing diagram shown in figure 3.5. The sequence of events govern the wave form and the accuracy of which is highly dependent on the support electronic hardware.

The first wave form is generated whenever the transducer is in transmission mode. This wave may be started by a gating signal which controls the transmission. By looking at this wave form the user knows at what instant of time chirp was transmitted. Since the transducer can not receive and transmit simultaneously, therefore whenever this signal is high, only noise can cause a received signal to show up.

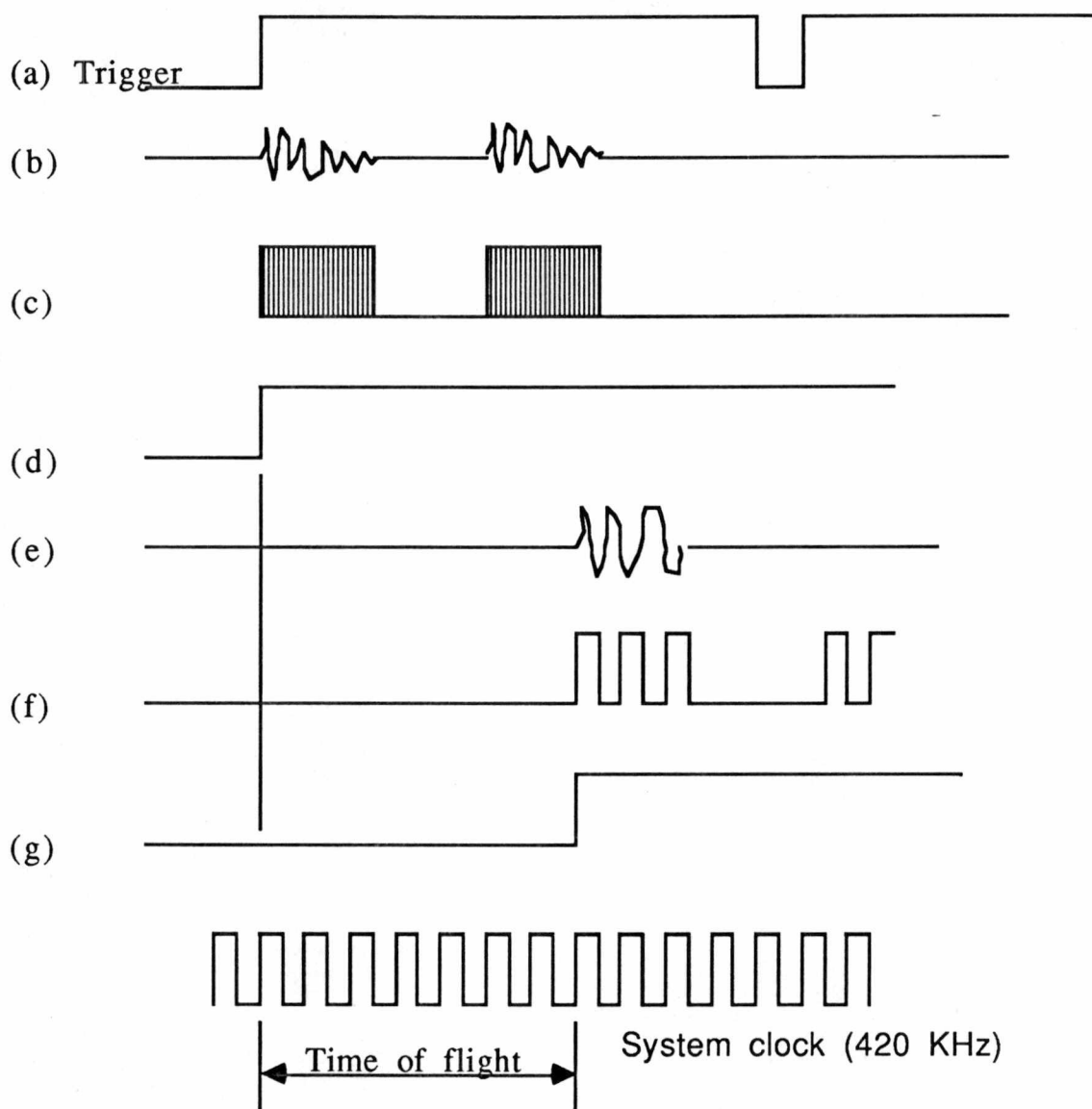


Figure 3.5 Timing diagram for measuring time of flight

Wave form (B) is generated whenever the transducer is either transmitting or receiving an echo. Again by comparison of the two wave forms one can easily conclude which signal corresponds to user knows at what instant of time chirp was transmitted. Since the transducer can not receive and transmit simultaneously, therefore whenever this signal is high, only noise can cause a received signal to show up.

Wave form (B) is generated whenever the transducer is either transmitting or receiving an echo. Again by a comparison of the two wave forms one can easily conclude which signal corresponds to a transmission and which corresponds to an echo.

A wave form such as (C) is generated by the user to introduce detection capability. This wave form is dependent on transducer characteristics and clock resolution. The time interval Δt_1 is the hardware response time. In other words, this is the least time after the transmission that support hardware needs to switch into receiving mode. This means that the system can not respond to any echo before the time interval Δt_1 . Thus Δt_1 puts a restraint on the minimum distance which can be accurately measured. It should be noted that time intervals are equivalent to specifying distances because the propagation velocity of an acoustic wave is known in a given transmission media. Let $(\Delta t_1 + \Delta t_2)$ is the time interval which corresponds to the maximum measureable distance. The time of

flight for any object located at a measureable distance must be with in these time constraints. Wave form (D) can be generated by properly gating wave forms A, B, and C. This wave form D assumes a digital high whenever it encounters a low in (A), a low in (B) and a high in (C). It goes to a low logic level whenever it comes across a falling edge in (A). The purpose of this wave form is to locate the instant when an echo was detected.

Wave form (E) is set high on the positive edge of a pulse in D and is reset to low when D is low and a pulse in (A) occurs. Thus (E) would tell whether an object is present or not.

Now we can manipulate wave form (A) and (D) to calculate the time of flight. If this time is T then the distance would be given by

$$\text{distance} = d = cT/2$$

Where c is the local velocity of sound.

T is the time of flight.

CHAPTER 4

THE GRADIENT PROJECTION SCHEME

4.1 INTRODUCTION

A kinematically redundant robot is defined as a manipulator which has more degree of freedoms than is necessary to reach a desired target point by the end effector. A spatial or a scarer robot without redundancy has a unique joint velocities, configurations for every point in its work space. In general dexterity (dexterity is defined as the manipulators ability to reach a point in more than one joint angle configuration) and maneuvering capabilities for robots are greatly reduced due to this uniqueness of joint angle configuration. A redundant robot uses its redundant degree of freedom to its advantage in two ways:

1. For improved dexterity in maneuvering work space with obstacles.
2. It can avoid singular configuration which are impossible to avoid in non- redundant robots.

Several kinematic control schemes have been developed to tackle the obstacle avoidance problem. One the scheme based on the technique developed by Dubey and Euler et al.[15] and later extended by Zghal [6].

4.2 THE GRADIENT PROJECTION METHOD

Joint and end-effector velocities of a typical robot with n-degrees of freedom is related by the following equation:

$$\dot{\mathbf{X}} = \mathbf{J} \dot{\boldsymbol{\theta}} \dots\dots\dots(4.1)$$

where J is an mxn jacobian matrix, and $\dot{\mathbf{X}}$ and $\dot{\boldsymbol{\theta}}$ m-dimensional vectors representing the end-effector and joint velocities vectors respectively. If the dimensions of work space is equal to the number of degrees of freedom then the jacobian is a square matrix. If the number of joints or the number of degrees of freedoms are greater than the dimension of the work space then the jacobian would be rectangular matrix. Now, if the square matrix is of full rank (i.e, all the columns or rows are linearly independent) then its invertible and cold be used to calculate the unique joint velocities for the desired end effector velocity.

$$\dot{\theta} = J^{-1} \dot{X} \dots\dots\dots (4.2)$$

A rank deficient jacobian matrix points to one the the two possibilities

1. The manipulator is in a singular configuration.
2. the manipulator has at least one degree of redundancy.

For a redundant robot the joint velocities needed to move the end-effector at a certain velocity can be calculated from the following equation:

$$\dot{\theta} = J^+ \dot{X} + (I - JJ^+) \dot{\phi} \dots\dots\dots (4.3)$$

Where I is an (n x n) identity matrix , $\dot{\phi}$ is an n-dimensional joint velocity vector . J^+ is known as the pseudo-inverse or the Moore-Penrose generalized inverse of the jacobian matrix and is given by:

$$J^+ = J^T (J J^T)^{-1} \dots\dots\dots (4.4)$$

$J^+ \dot{X}$ is the projection of $\dot{X}$ on to the row space of J, thus represents the least norm solution. In equation (4.2) $(I - JJ^+)$ is the projection

matrix projecting $\dot{\phi}$ on to the null space of J , hence represents the homogeneous solution. The homogeneous solution does not contribute in changing the end-effector velocity and is termed as self motion. Improved manipulator performance can be ensured for a desired trajectory by selecting an appropriate homogeneous part of the solution. If $H(\theta)$ is the performance criterion then using the gradient projection method, redundancy can be resolved by substituting $\dot{\phi}$ with $k \nabla H(\theta)$.

$$\dot{\theta} = J^+ \dot{X} + k (I - J^+ J) \nabla H(\theta) \quad \dots\dots\dots (4.5)$$

The coefficient k in equation (4.5) is a real scalar constant, and $\nabla H(\theta)$ the gradient vector of $H(\theta)$ which is given by :

$$\nabla H = \left[\frac{\partial H}{\partial \theta_1} \quad \frac{\partial H}{\partial \theta_2} \quad \dots \quad \frac{\partial H}{\partial \theta_i} \quad \frac{\partial H}{\partial \theta_n} \right] \quad \dots\dots\dots (4.6)$$

The scalar constant k is taken to be positive if $H(\theta)$ is to be maximized and negative if $H(\theta)$ is to be minimized. A larger value of k will optimize $H(\theta)$ at a faster rate. However, the maximum allowable value of k is limited by bounds on the joint velocities.

k will optimize $H(\theta)$ at a faster rate. However, the maximum allowable value of k is limited by bounds on the joint velocities.

4.3 AN EFFICIENT OPTIMIZATION SCHEME FOR A PLANER ROBOT WITH ONE DEGREE OF REDUNDANCY

This scheme was developed by Dubey and Euler et. al. [5] and was implemented on a seven degree of freedom redundant robot. This scheme is an efficient implementation of the gradient projection method for the control of manipulators with one degree of redundancy. It eliminates the need of computing the generalized inverse of the Jacobian.

Consider the vector spaces of the Jacobian for an n-degree of freedom robot. Joint velocity vector belongs to the row space of the Jacobian i.e.

($\dot{\theta} \in R^n$) which is an n-dimensional space. Similarly the end-effector velocity vector belongs to the column space ($\dot{X} \in R^m$) which is an m-dimensional space. We know the two sub-spaces of a particular robot are related by Jacobian matrix by the simple matrix equation

$$\dot{X} = J \dot{\theta} \quad \dots\dots\dots(4.7)$$

Jacobian will have a dimension of 2×3 . Now if assume the rank of the Jacobian is 2 i.e, it has two linearly independent columns or rows; we partition the matrix by grouping the linearly independent columns together as follows

$$\mathbf{J} = [\alpha \mathbf{J}^*] \dots\dots\dots (4.8)$$

where α is the linearly dependent column and $\mathbf{J}^*$ consists of linearly independent column of the Jacobian matrix. Now we rearrange the end-effector velocity column vector and rewrite the equation (4.7)

$$\dot{\mathbf{X}} = [\alpha \mathbf{J}^*] \dot{\boldsymbol{\theta}} \dots\dots\dots (4.9)$$

Since equation. (4.9) is a differential equation the solution would consist of two parts namely, a particular solution $\dot{\boldsymbol{\theta}}_p$ and a homogeneous solution $\dot{\boldsymbol{\theta}}_h$. The joint velocity vector is then given by:

$$\dot{\boldsymbol{\theta}} = \dot{\boldsymbol{\theta}}_p + \mathbf{K} \dot{\boldsymbol{\theta}}_h \dots\dots\dots (4.10)$$

where $\boldsymbol{\theta}_h \in \mathbb{R}^n$ and $\boldsymbol{\theta}_p \in \mathbb{R}^m$ both are of dimension 4×1 . The particular solution can be determined by choosing the first element

in this column vector as zero, and the remaining elements can be obtained for equation (4.9). $\dot{\theta}_p$ can be shown to be equal to

$$\dot{\theta}_p = \begin{bmatrix} 0 \\ J^{*-1}X \end{bmatrix} \dots\dots\dots(4.11)$$

The homogeneous solution can be obtained by substituting the first element equal to one, and the remaining elements of the homogeneous solution can be obtained by solving the following equation:

$$[\alpha \ J^*] \dot{\theta}_h = 0 \dots\dots\dots(4.12)$$

The above equation gives the following value for $\dot{\theta}_h$

$$\dot{\theta}_h = \begin{bmatrix} 1 \\ -J^{*-1}\alpha \end{bmatrix} \dots\dots\dots(4.13)$$

Substituting the values of $\dot{\theta}_p$ and $\dot{\theta}_h$ to get the general solution for the joint velocity vector.

$$\dot{\theta} = \begin{bmatrix} K \\ J^{*-1}(X-K\alpha) \end{bmatrix} \dots\dots\dots(4.14)$$

4.4 LEAST NORM SOLUTION

As we know that the homogeneous solution does not contribute to the end-effector velocity. Now if the particular solution is the least norm solution then the projection of the particular solution on to the null space of the Jacobian should give a value of zero. Now if the particular solution is not the least norm solution then it is not orthogonal to the null space and would have some component along the null space. By subtracting its component along the null space we ensure to have the least norm solution.

Recall from linear algebra that the dot product of two vectors A and B given by $A^T \cdot B$ gives a component of vector A along B . Using this property we get the component of $\dot{\theta}_p$ along $\dot{\theta}_h$. Let us define a unit vector in the direction of $\dot{\theta}_h$ which is given by

$$\bar{u} = (\dot{\theta}_h / (\dot{\theta}_h^T \cdot \dot{\theta}_h)^{1/2}) \dots \dots \dots (4.15)$$

Now by dot product we get the component of $\dot{\theta}_p$ along $\dot{\theta}_h$ and then subtracting this component from $\dot{\theta}_p$ gives us

$$\theta_{\min} = \left[\dot{\theta}_p - (\dot{\theta}_p^T \cdot \dot{\theta}_h) / (\dot{\theta}_h^T \cdot \dot{\theta}_h) \right] \dots \dots \dots (4.16)$$

Notice that the minimum norm solution in equation (4.16) and the first term of equation (4.3) are by definition of pseudo inverse are identical. Comparing equations (4.16) and (4.10) we get

$$K = - (\dot{\theta}_p^T \cdot \dot{\theta}_h) / (\dot{\theta}_h^T \cdot \dot{\theta}_h) \dots\dots\dots (4.17)$$

substituting the values of q and K in equation (4.10), we get

$$\begin{bmatrix} -\theta_p^T \cdot \theta_h / \theta_h^T \cdot \theta_h \\ J^{*-1} (X - \theta_p^T \cdot \theta_h / \theta_h^T \cdot \theta_h) \alpha \end{bmatrix} \dots\dots\dots (4.18)$$

In order to get the second term of the equation (4.3) which represents the the projection of the gradient vector onto the null space of J, can also be determined by projecting the performance criterion using the concept of dot product. We have already defined a unit vector in the direction of homogeneous solution.

$$(I - J^+ J) \nabla H(\theta) = \left(\nabla H^T(\theta) \dot{\theta}_h / \dot{\theta}_h^T \cdot \dot{\theta}_h \right) \dots\dots\dots (4.19)$$

It can be shown that $(I - J^+ J)$ is indeed a projection matrix that projects any vector onto the null space of J.

4.5 DETERMINATION OF THE SCALER CONSTANT K

The value of the scaler coefficient K in equation (4.5) may be selected on the hardware limits and bounds on the joint velocities. A scheme was proposed by Euler et al. [] for evaluating the scaler constant. The scheme is applied here to determine the constant. As discussed earlier the the joint velocity consists of two parts namely, a homogeneous part and a particular part and the general solution is the sum of two:

$$\dot{\theta}_p = \dot{\theta}_{\min} + \dot{\theta}_h$$

Where $\dot{\theta}_{\min}$ is the least norm solution. If $\dot{\theta}_{\max,i}$ and $-\dot{\theta}_{\max,i}$ are the upper and lower bounds on the i^{th} joint velocity and the upper and lower limits on K be $K_{\max,i}$ and $K_{\min,i}$ which are determined as follows:

$$K_{\max,i} = \max \left((\dot{\theta}_{\max,i} - \dot{\theta}_{\min,i}) / \dot{\theta}_{h,i} , (-\dot{\theta}_{\max,i} - \dot{\theta}_{\min,i}) / \dot{\theta}_{h,i} \right) \dots\dots\dots(4.20)$$

$$K_{\min,i} = \min \left((\dot{\theta}_{\max,i} - \dot{\theta}_{\min,i}) / \dot{\theta}_{h,i}, (-\dot{\theta}_{\max,i} - \dot{\theta}_{\min,i}) / \dot{\theta}_{h,i} \right) \dots \dots \dots (4.21)$$

The upper and lower bounds on the the scaler constant K for the joint velocities of a redundant robot with n joints can be determined from the follow equations :

$$K_{\max} = (K_{\max,1}, K_{\max,2}, K_{\max,3}, \dots, K_{\max,n}) \dots \dots \dots (4.22)$$

$$K_{\min} = (K_{\min,1}, K_{\min,2}, K_{\min,3}, \dots, K_{\min,n}) \dots \dots \dots (4.23)$$

Now if $K_{\max}$ is chosen for K, then the criterion $H(\theta)$ will be maximized, otherwise; if $K_{\min}$ is chosen for K, then $H(\theta)$ will be minimized . In this case $K_{\max}$ is greater than $K_{\min}$. If $K_{\max}$ is less than $K_{\min}$, then a value of K does not exist such that the joint velocities are within their bounds. In this case, even the least norm solution results in high joint velocities.

4.6 APPLICATION OF THE GRADIENT PROJECTION OPTIMIZATION SCHEME TO THE IBM 7547 ROBOT

The IBM 7547 is an industrial robot with 4-degrees of freedom. It can be used as a redundant manipulator with only one degree of redundancy at the cost of roll axis. An additional link of known length is added at end effector which gives it the added degree of freedom in plane. Notice the IBM 7547 is redundant only in plane.

The kinematic equation relating the end-effector velocity to the joint velocity vector is :

$$\dot{\mathbf{X}} = \mathbf{J} \dot{\boldsymbol{\theta}}$$

where $\dot{\boldsymbol{\theta}}$ is 3x1 joint velocity vector, $\dot{\mathbf{X}}$ is a 2-dimensional end-effector velocity vector and $\mathbf{J}$ is a 2x3 Jacobian matrix associated the linear motion of the end-effector. Because of the planer nature of the manipulator we don't have any angular motion, and no orientation capability. The jacobian matrix is given by

$$\mathbf{J} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \end{bmatrix}$$

where

$$J_{11} = l_1 C_1$$

$$J_{12} = l_2 C_1 C_2 - l_2 S_2 S_1 = l_2 C_{12}$$

$$J_{13} = l_3 C_3(C_1 C_2 - S_1 S_2) - l_3 S_3(S_1 C_2 - C_1 S_2)$$

$$= l_3 C_1 C_{12} - l_3 S_3 S_{12} = l_3 C_{123}$$

$$J_{21} = l_1 S_1$$

$$J_{22} = l_2 S_2 C_1 + l_2 S_1 C_2 = l_2 S_{12}$$

$$J_{23} = l_3 S_3(C_1 C_2 - S_1 C_2) + l_3 C_3(S_1 C_2 + C_1 S_2)$$

$$= l_3 S_3 C_{12} + l_3 C_3 S_{12} = l_3 S_{123}$$

and

$$S_i = \sin \theta_i$$

$$C_i = \cos \theta_i$$

$$S_{ij} = \sin (\theta_i + \theta_j)$$

$$C_{ij} = \cos (\theta_i + \theta_j)$$

using equation (4.5) we get the joint velocity vector for optimizing the $H(\theta)$ equation (4.24)

$$\dot{\theta} = J^+ \dot{X}_e + K (I - J^+ J) \nabla H(\theta) \quad \dots\dots\dots (4.24)$$

Now if a matrix is formed with two independent columns of J and the remaining column is rearrange as follows

$$\dot{X}_e = \begin{bmatrix} J_0^{2 \times 1} & J_1^{2 \times 2} \end{bmatrix} \dot{\theta} \quad \dots\dots\dots (4.25)$$

Again as the columns of J are rearranged; the entries of joint velocity column vector $\dot{\theta}$ should be arranged accordingly. As already discussed the least norm solution of $\dot{\theta}_{\min}$ can be determined by using equation (4.15)

$$J^+ \dot{X}_e = \dot{\theta}_{\min} = \dot{\theta}_p - \left[\sum_{i=1}^2 \left(\left(\dot{\theta}_p^T \cdot \dot{\theta}_h \right) / \left(\dot{\theta}_h^T \cdot \dot{\theta}_h \right) \right) \dot{\theta}_h \right] \quad \dots\dots\dots (4.26)$$

Where $\dot{\theta}_p$ is the particular solution given by:

$$\dot{\theta}_p = \begin{bmatrix} 0^{2 \times 1} \\ J_1^{-1} \dot{X}_e \end{bmatrix} \quad \dots\dots\dots (4.27)$$

It is noticeable that we chose the J_1 matrix to have only linearly independent column, now since the matrix is square therefore invertible and by Cramer's rule :

$$J_1^{-1} = \frac{1}{\Delta} \begin{bmatrix} J_1^{22} & -J_1^{12} \\ -J_1^{21} & J_1^{11} \end{bmatrix} \dots\dots\dots(4.28)$$

Where Δ is the determinant of the 2x2 Jacobian matrix J .

CHAPTER 5

HARDWARE DESIGN METHODOLOGY

5.1 INTRODUCTION

The task of collision avoidance has already been addressed in detail in previous chapter. One of the assumption made in the scheme is that the robot is well aware about the locations of obstacles in its work space. Zghal [5] attempted the window problem, the solution was limited to off line programming because the location of the window is defined to the robot before it starts to move. As the robot moves in its work space, the existing position of the window with respect to the end-effector is continuously updated on the basis of the previously defined location of the window. Another reason to address the same problem is that it does not tackle the problem if the obstacle moves with respect to the manipulator's inertial frame of reference. In order to handle such situation in real time there has to be a continuous feedback mechanism which would keep the robot updated about the position of obstacles. An ultrasonic sensor can be used to locate the obstacle with fairly good accuracy. In the

following sections we would discuss the electronic hardware which is needed to interface the sensor with the robot controller.

Recall from the previous chapter that an ultrasonic sensor sends an ultrasonic acoustic pulse when triggered and receives the returning echo. The same transducer functions both as a loud speaker and as a microphone. The whole strategy is focused on recording the time of these events for estimating the distance between the transducer and obstacles. The electronic module which comes with the transducer maintains the voltage and amperage necessary for proper transmission and reception. It is also equipped with the circuitry for analog to digital conversions . The electronic module is designed to generate a digital pulse (XLOG) whenever the transducer begins to transmit an acoustic chirp. After the transmission it changes its mode and gets ready to receive the returned echo. Energy of the returned echo is used to generate an analog signal, which subsequently passes through an analog to digital converter to generate a flag. The flag attains a digital high whenever an echo is received. We would denote this signal as (FLG) in discussions to follow.

5.2 HARDWARE DESIGN OBJECTIVES

The objectives of the hardware design and a brief description of each is given below.

1. To trigger the sensor either at regular intervals or intermittently according to the requirement of application. e.g, for the purpose of obstacle avoidance a good approach would be to trigger the sensor at regular intervals. It must be noted here that whenever the transducer is triggered, the robot has to come to a complete halt for accurate and precise measurement. Therefore the triggering has to be synchronized with the stop instruction of the robot. Another example of a triggering situation would be when the transducer is used to verify the presence of an object at a particular point within the robot's work space. In this situation a regular search is not only meaning less but would also require far more time to reach the target point.

2. The circuit should be able to process the signals (XLG and FLG) from the electronic module and transform them into some information which can be used to determine the time of flight. This task can simply be achieved by triggering a clock at the transmission and stopping the clock when echo (FLG) is received. The clock count would then represent the time of flight of the acoustic pulse.

3. The third and one of the important task is to transmit these informations to the manipulator's controller. Since the logic level at the DI/DO port C2 is different from the usual TTL logic level therefore we need to design an interface between the controller and the hardware designed in step (1) and (2) so that the communication between the two does not cause any malfunction in either of the two.

4. Since the transducer and the supporting circuitry is designed for ranging within certain working range, therefore there should be a mechanism for generating an error signal, whenever the object or the obstacle is outside the working range of the sonar system. This signal can be very easily generated by monitoring the maximum time that corresponds to the maximum workable distance.

5. Finally the circuit should be simple to build and should be designed for maximum adaptability to varied workable ranges and resolutions. Also it should be easy to trace and repair in case of any malfunction.

The whole task was divided into sub-task and a functional diagram is drawn on the basis of the well defined objectives and priorities defined in the last section. The diagram shows the sequence of

operations which are supposed to be taken for achieving these objectives.

5.3 FUNCTIONAL DIAGRAM

We know that the events reported by the electronic module are the only information available to us. Electrical noise is a problem in any circuit, but in a digital circuit noise spikes are extraneous pulses and destroy the meaning of existing 1's and 0's. Now since the sonar system is designed to operate in an environment of high electrical noise therefore we have to be very careful about the validity of the two signals (FLG and XLG) given by the electronic module. There can be a number of reasons which may cause these signals to change their states during a single ranging scan and lead the manipulator to wrong conclusions. One of our basic task for accurate ranging is to make sure that these signals do not change their logic level during a scan. And if somehow they change their state, the hardware should be able to track the good signal. As shown in the functional diagram (figure 5.1) these signals are kept in some kind of memory unit for avoiding any transition during a reading. The memory unit must retain this information at least until results are obtained. The mechanism of the memory unit should be such that once it has been reset, it waits for a change and as soon as it notices a transition in

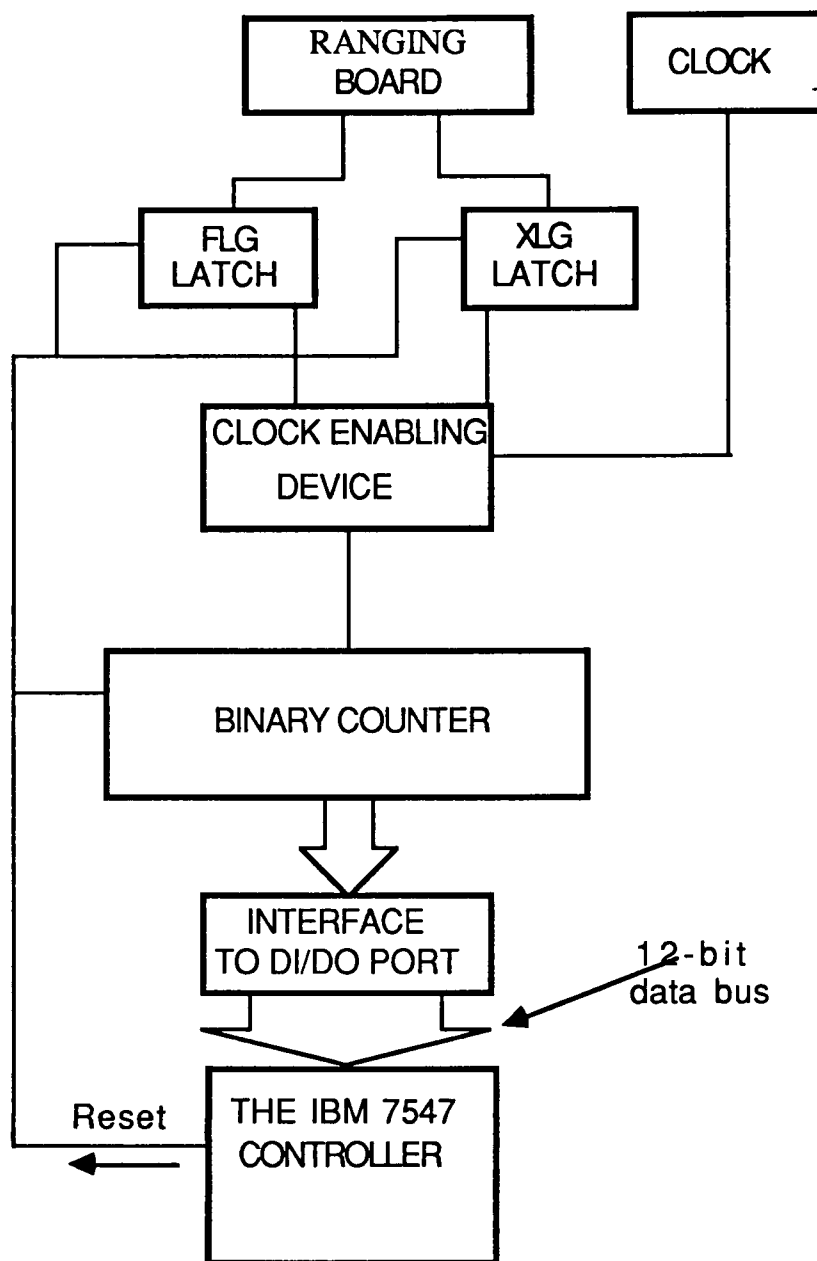


Figure 5.1 Functional diagram

signal (say XLG) then it remains in its modified or changed state until it receives an instruction to reset itself for another reading. The functional diagram shows two memory unit one for storing XLG and the other for FLG.

After making sure that during a range there would not be any transition in the original signal, we need to move to the next step . In order to determine the time of flight we need to start the clock at the first transition in XLG and stop it at the first transition in FLG. For this purpose a clock enabling block has been drawn which enables the clock only after it receives a clock enabling signal which is XLG. As soon as it receives FLG it disables the clock. For determining the time of flight we need to know for how long the clock was enabled. We would discuss the digital clocking techniques in a later section. For now we assume a functional block which keeps record of the time during which the clock was enabled. This block is reset to zero value whenever the two latches are reset. We call such a block as a counter. Now as a measure of precaution, the time of flight given by the counter is compared with a preset value, which defines the limit on the distance that can be measured. We call such a device as an error block. The error block generates an error signal whenever the counter value is equal to the preset value. This error signal is used to let the controller know that there is no obstacle within the working of the ultrasonic transducer. The working range of the

transducer is kept greater than the manipulator's work space. A master reset is generated by the controller whenever it is ready to trigger the sonar.

5.4 LOGIC DIAGRAM AND ALGORITHMIC STATE MACHINE CHART

Because of the asynchronous nature of our input signal we will not build an algorithmic state machine (ASM) chart. It is possible to build asynchronous state machines, which depend not on a clock but on changes in inputs themselves to cause state transitions. Troubles abound with this form of design, due primarily to these factors:

- a) All inputs must be "clean" with no glitches, since any instability or noise on the input signals may induce spurious state transitions.
- b) The theory of asynchronous circuits is very complex and diverse, involving numerous special cases and usually invoking unacceptably restrictive design conditions.
- c) The debugging of asynchronous systems is quite difficult.

In this section we would discuss the logic development (figure 5.2) based on our objectives and the functional diagram developed in the last two section. A logic diagram is a symbolic representation of

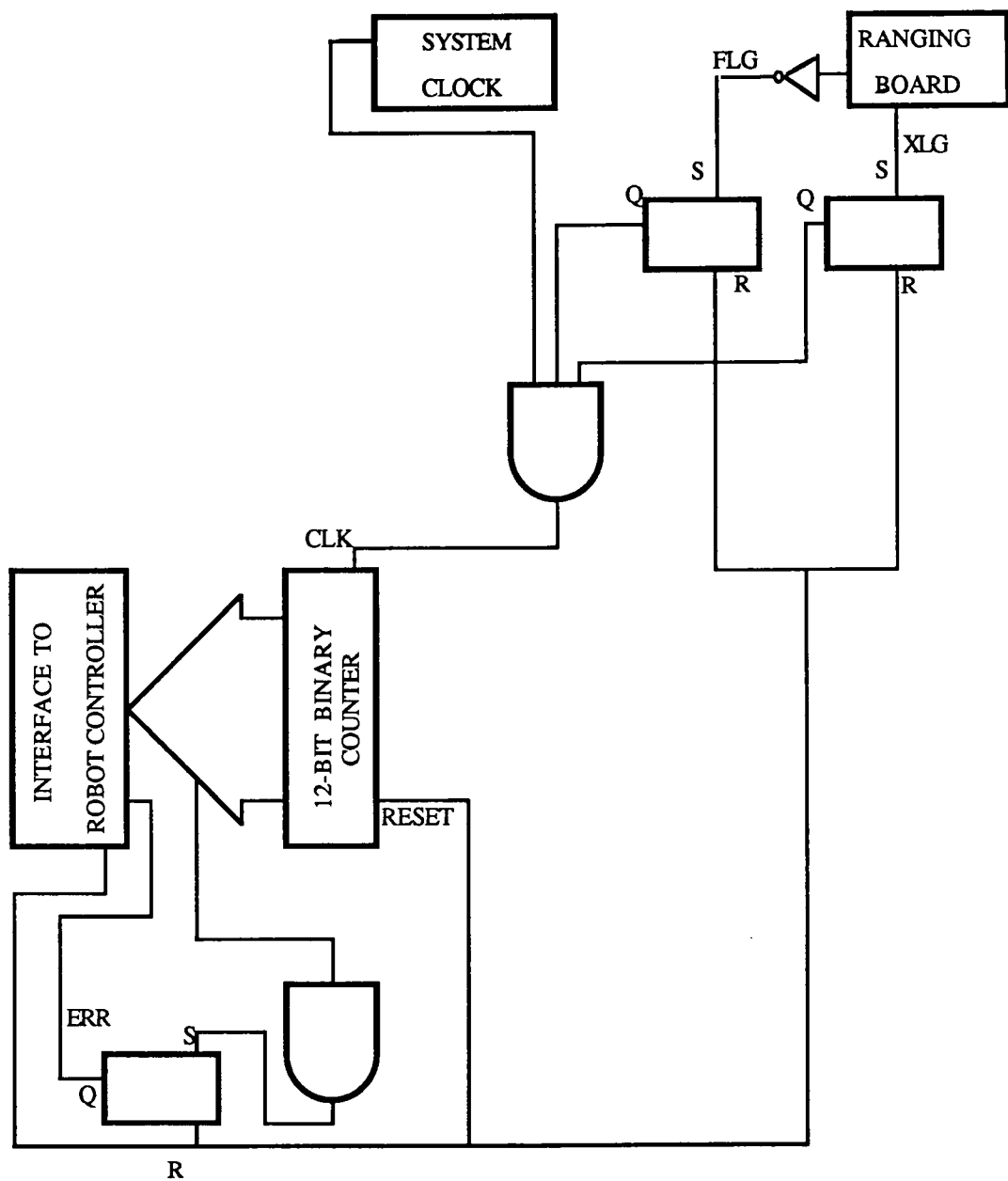


Figure 5.2 Logic diagram

digital circuits use as building blocks, connected together in developing a larger circuit to achieve a well defined task. As shown in the functional diagram, we first need to store the signals from the electronic module, avoiding any changes and at the same time making it available for further use. The memory element must have the following properties:

1. Accept input data signal.
2. Store data until needed.
3. Present data whenever necessary.

A truth table would be helpful in explaining the function of the building block. We already have the description of the memory unit and in our particular case it performs the following functions:

1. Waits for a digital high to occur at S.
2. Makes this high signal available to drive other circuit.
3. No matter what happens to the signal from the electronic module it keeps the last value (which is high) until it receives a reset instruction.

Let S be the point where the memory unit receives a signal from the electronic module, R be the point where it receives a reset signal and Q be the point where the stored value is available for use. The truth table is shown on the next page :

<u>R</u>	<u>S</u>	<u>Q</u>
0	0	0
0	1	1
0	-	1
1	-	0

“ - “ in the last two rows of the truth table shows a don't care situation, in other words for any value of S the relationship holds. Any logic device whose truth table is compatible with the truth table given above can serve as a potential memory unit. If we compare our truth table with the truth table of some of the very common flip-flops we would generally notice a similarity among them. Incidentally the basic building block of memory in typical computers of today is also a flip flop. There are a number of flip flops available with specifications suitable to a variety of applications. One can find several types of flip-flops which may perform the same action equally well. There are other considerations which may affect the choice of a particular flip-flop. For example if a particular application requires a very high speed

switching than the designer has to make sure that the flip flops he is using have a very short response time. If the output of a flip flop is driving another logic device which requires a large amount of current then the power rating may become a deciding factor between the number of flip flops available. In an application such as the one we are discussing, flip flops are referred to as "Latches". We are using two flip flops for storing the two signals from the electronic module namely XLG and FLG.

A clock enabling device is the second functional block in our functional functional diagram. The functional description of this block gives us the following truth table:

<u>XLG</u>	<u>FLG</u>	<u>CLK</u>	<u>Q</u>
0	0	-	0
1	0	1	1
1	0	0	0
1	1	-	0

Since there is no single logic device which can perform the above operations therefore we have to use a combinational logic which satisfies our functional need. Again the strategy is to keep the building block as simple as possible. Now if complement of FLG

denoted by MFLOG is used instead of FLG then the truth table is as shown on the next page.

<u>XLG</u>	<u>MFLOG</u>	<u>CLK</u>	<u>Q</u>
0	1	-	0
1	1	1	1
1	1	0	0
1	0	-	0

A close look at row 2,3 and 4 reveals that if XLG and MFLOG signals are high then the clock signal is the output signal. In other words the clock is enabled. The output clock is out of phase with the original clock by a time corresponding to the response delay time of the combinational logic. The truth table presents a typical logic AND gate with three inputs. Thus a three input AND gate can do the job provided we use XLG, clock and the complement of FLG signal as input. FLG's complement can be obtained by using an inverter or a logical NOT gate.

We need a counter which can keep a record of the clock pulses to give some kind measure to estimate the time of flight. The counter should keep the count until the data has been used to calculate the time. A variety of CMOS binary counters are available with different designs to fulfil the requirements of a wide range of applications. The

number of output data bits determine the maximum number that a counter can count. It is a usual practice to choose counters to count data less than its full capacity. Thus the third building block in our circuit uses a binary counter with 12 bits.

The next functional block requires finding the logic which would keep the counter from exceeding its maximum value. A second option could be to let the counter read more than its full capacity and use a carry bit to indicate that the counter has rolled over at least one time hence doubling the capacity of the counter data. In any case a block which records the occurrence of all high (or the maximum value) on the 12-bit binary counter is needed. A very simple approach would be to AND all the data bits of the binary counter. The occurrence of the maximum value passing through the AND gate would raise a flag by setting its output to logical high or binary 1. This flag can be used either as a carry bit or to generate an error in the circuit. The error generated can be used to stop and reset the flip flops and counter. The two options defined above can be implemented as follows:

1. To use the flag as an error signal, we need to use a logical NOR with FLG and ERROR signals as its input. Making use of DeMorgan identities it can also be shown that an AND gate with complements of FLG and ERROR signals as its input also gives the required logic level.

2. For using it as a carry bit it can be directly fed to the controller and let the controller monitor this bit for a binary 1. Now if the controller finds this bit high it would add the maximum value of the counter (which in our case is 4095) to the existing count.

So far we have discussed the logic design needed to clock the time of flight. The time of flight measured at the counter must be transmitted to the controller for calculating the distance which in turn is used in further manipulation. As discussed in chapter 2 the input/output port enables the controller to transmit and receive digital data from external devices such as sensors, encoders etc. Now since the logic levels, response time and the working mode of the two electronic modules are different, we need to design an interface between the two module for data transfer. Figure 5.3 illustrates the working of the digital input port. Each of the input points has a solid-state, non-isolated type circuit which can read input bits from devices such as relay contacts, open-collector output etc. Fig 5.4 is self explanatory in regard to its working. When the relay contact is open the input bit is pulled up to 24 volts and the controller takes it as a binary 0. On the other hand when the relay contact is closed the input bit is grounded with resistance between 0 to 400 ohms. The

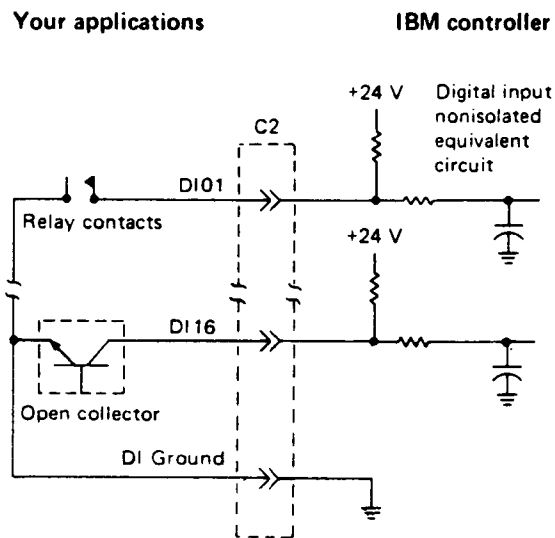
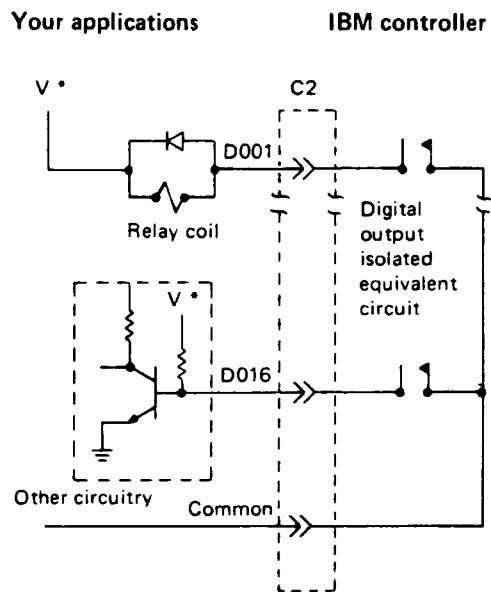


Figure 5.3 Wiring diagram and working principle for digital inputs.
 Courtesy: IBM 7547 manufacturing system hardware library (site preparation).



* +24 Vdc maximum supplied by you.

Figure 5.4 Wiring diagram and working principle for digital outputs
 Reprinted from IBM 7547 manufacturing system hardware
 library(site preparation).

only point which requires a little thought is that these inputs are being pulled up internally to 24 volts. A direct connection between the controller input points with the appropriate counter-bit would either result in unreliable data or in smoking the counter chip.

A solid state relay would work only when it works between 1 to 5 volts range, in fact all TTL circuits are limited to the same working voltage level. We would use a LINEAR open collector device which can withstand such a high levels of voltage. A darlington pair is an open collector device with workable voltage range up to 50 volts.

Digital output works on the same principle as the digital input. Figure 5.2 shows how it can be used to send an electrical pulse to drive external circuit and devices. One has to be careful in using digital output instructions. The instructions work in opposite sense. e.g, When relays are set to close contact (which represents a binary 1.) the output point is dragged down to a zero voltage level and vice versa.

5.5 PARTS SELECTION

a) FLIP-FLOPS

As was mentioned earlier that a variety of flip-flops are available which can be adapted for use as a basic building block. The particular

application of this chip in our case can be described as an asynchronous data storage. Before we select one of the several kinds of flip-flop available, let us look into some of the options available to us:

1. D flip-flop
2. RS flip-flop
3. JK flip-flop

The truth tables and a brief description of each of these flip-flops is given in appendix B. The D type of flip-flops alone is out of the question, because of the nature of the XLG signal. Theoretically an RS flip-flop can be used with an advantage of a higher speed, but it is highly sensitive to noise (glitches) on the S input when in the reset state, and on R input when in the set state. The JK type of flip-flop is basically a controlled storage. The most general use of the JK flip-flop, and the one that gives it such power and flexibility, is as a storage element under explicit control. Whenever we must set or clear or toggle a signal to form a specific value for later use, we usually think of a JK flip-flop. The 74LS76 is a dual low power, low speed JK flip-flop, one of the most common used. The flexibility and accuracy that it provides makes it ideal for use in our application.

b) AND GATES FOR CLOCK ENABLING BLOCK AND ERROR CIRCUIT

The 74LS11 is a standard triple low power 3-input AND gate based on TTL logic. It's truth table and pin out are given in appendix. In our application this block would be used as a clock enabling device.

The 74LS20 is a dual low power 4-input NAND gate. Four 4-input NAND gates with inverted outputs were used for ANDing the 12 output bits from the counter.

c) SYSTEM CLOCK

The system clock runs at a frequency of 420 KHz. The clock frequency is a ceramic resonator controlled for optimum accuracy. Temperature, humidity variations and electrical noise does not seem to affect the clock performance.

d) DRIVER FOR THE ELECTRONIC MODULE:

The 9667 is a high power darlington array with over voltage protection. This chip was used as a trigger to the electronic module. A pulse of 5 volts lasting at least 10 ms is needed to trigger the electronic module. A high power PNP transistor receives this signal

and outputs a high power burst which is necessary for the transducer to transmit the acoustic pulse.

e) DARLINGTON PAIRS FOR INTERFACING THE SONAR WITH THE CONTROLLER

The requirement of an integrated circuit which is open collector, can set desired logic levels and could withstand as high as 24 Volts makes the 9667 a good choice for its use as an interface between the two modules.

Apart from the parts already discussed, two hex invertor 74LS04 chips, a DP25 cable connector and a 25 conductor stranded wire, fully shielded cable was needed to complete the system.

5.6 OVERALL WORKING AND SEQUENCE OF OPERATIONS

At the start up of the system flip-flops and counter attain random states and the first signal from controller should always be a reset signal to reset all the flip-flops and the counter.

Ranging begins with a controller initiated trigger by sending a five volt pulse to the ranging board via a high output triggering circuit. The circuitry on the electronic module gets into transmitting mode,

and the ultrasonic transducer transmits at least fifty six cycles of acoustic pulses with a frequency of 49-50 KHz before it gets into receiving mode. As soon as the trigger is received and a chirp is transmitted, the following sequence of operations takes place on the sonar board:

1. An electrical wave form of the same frequency is received at pin 1 of 74LS04, which is inverted and is fed to preset line (pin 7) on the JK flip-flop 74LS76.
2. At the first rising edge of the XLG the 74LS76 gets set (pin 11) and the output is passed to the 74LS11 at pin 2. At this point the clock signal starts reaching the counter (CD4040) at pin 10.

The ranging board gets into receiving mode 1 ms after the chirp transmission and waits for an echo. As soon as an echo is received, the following transitions take place on the sonar board:

- 1) FLG signal makes a transition from a binary 0 to 1. This signal is received at pin 3 of 74LS04 where it is inverted and is then passed to 74LS76 at pin 2.
- 2) 74LS76 which is a dual JK flip-flop with clear and preset gets set and the output at pin 15 changes to a binary 1.

3) Output from the 74LS76 is inverted and is fed to the 74LS11 at pin 13. 74LS11 is a three input AND gate and with one of its input at 0 binary the gate is disabled and the clock signal stops reaching the counter. In other words the clock or counter is stopped whenever FLG goes high.

4) Data is collected at the counter's output bits and is fed to the controller at its communication port C2.

5) The controller first looks for the error or the carry bit.

a) If it finds the error bit high then it discards the counter data and initiates a reset signal otherwise it advances to step (b).

b) If it finds the carry bit it advances to step (6) with a counter value of 4095.

6) The controller reads the counter value as a binary number and converts it into decimal by using a user written routine. It calls another routine which calculates distance between the object and the sensor.

7) This value is passed on to the application program which uses it as a feedback for its next move.

8) Steps 1 through 8 are repeated beginning with the controller resetting all the building blocks and gets ready to trigger the sensor for the subsequent readings.

CHAPTER 6

APPLICATIONS AND ACCURACY

6.1 INTRODUCTION

The objective of this chapter is to address the subject of applicability, usefulness and accuracy of the ultrasonic ranging. The two most important ranging applications involve object detection and profile evaluation by scanning a surface. Accurate object detection by measuring the distance to the nearest object provides the basis for some interesting applications, such as obstacle avoidance and flexible pick and place operations.

6.2 CONTOUR SCANNING

In an unknown working environment object detection alone does not guarantee smooth manipulation. In such situations contour scanning becomes necessary because of two reasons.

1. A Contour or profile scan gives a complete information about the approximate dimension of the surface in one direction. A mismatch

erroneous operations (objects with dimension bigger than the maximum opening of the gripper can not be picked up) .

2. A two dimensional contour scan provides all the details for intelligently orienting the gripper. Two dimensional images or contour profile can be constructed by scanning the surface under investigation in multiple scans along the length and the width with the help of only one sensor figure 6.1a. Another possible way is to sweep the surface with an array of sensors . Fig 6.1b explains why a two dimensional scan is necessary for manipulation in an unknown environment.

The actual profile and the profile mapped by the information from the sensor are shown in Fig 6.2. Nonconformity of the scanned profile to the actual profile can be attributed to a number of reasons. First, since the acoustic impedance of the air is quite low (sound waves can freely travel in air) and typical acoustic impedances of solid objects are much larger, all solid surfaces appear as acoustic reflectors. Also since the acoustic wavelengths are generally quite long, most surfaces appear to be acoustic mirrors. Consequently, surfaces that are not orthogonal to the directions of acoustic propagation reflect the incident pulses away from the source, and in such configuration the surface contour mapped by the sensor is highly unreliable. Furthermore, from a typical ultrasonic sensor, the problem of acoustic beam expansion of the transmitted signal allows

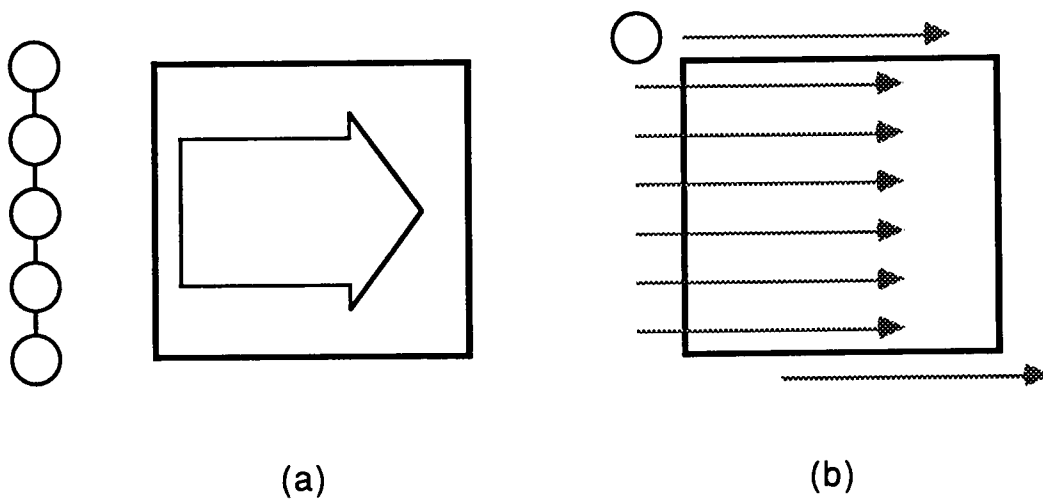


Figure 6.1 Profile scan of a surface by
a) an array of transducer, and
b) a single transducer

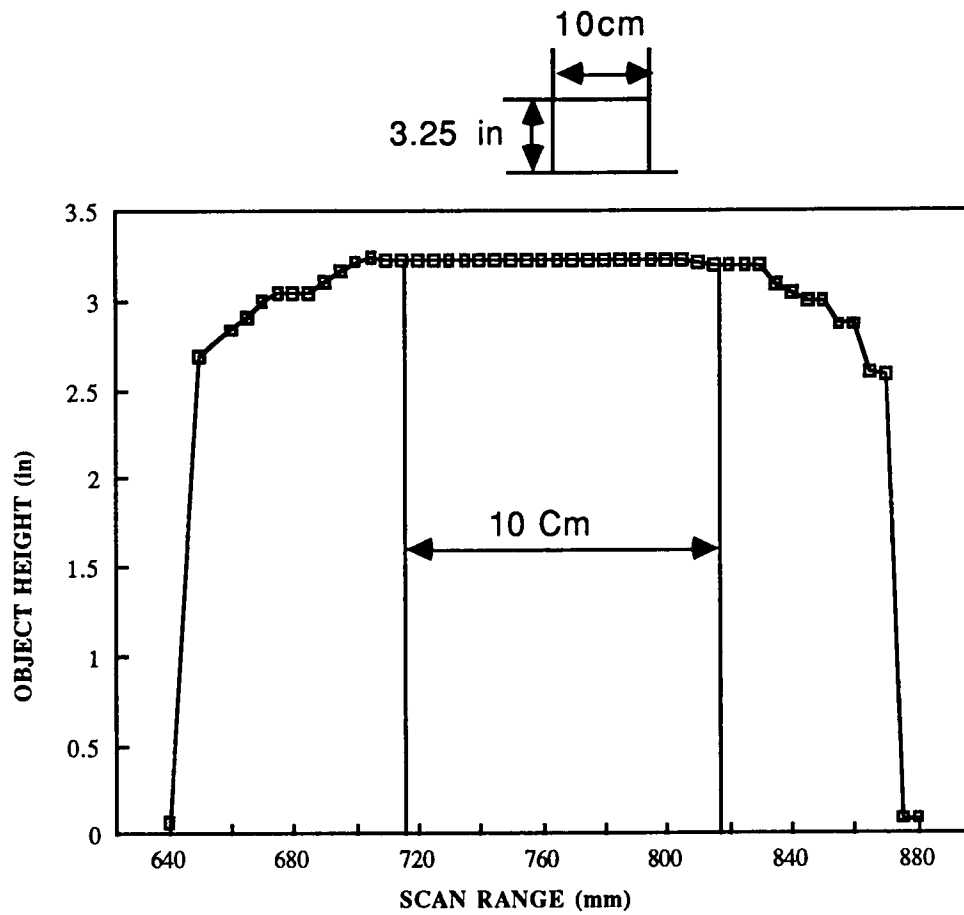


Figure 6.2 Contour or profile scan of a metallic block

acoustic beam expansion of the transmitted signal allows return echoes to be obtained from any angle inside the cone of propagation. Also the magnitude of the range depends on the velocity of the sound in ambient air, which is affected by air currents and temperature. Under these conditions sometimes even smooth flat surfaces can appear to be quite rough to a scanning ultrasonic sensor.

6.3 EARLY DETECTION OF OBJECTS

It is noticeable that the sensor picks up signals from objects well before it is right at top of the surface. The process of an early detection can be explained using figure 6.3. It shows the configuration when the surface is not orthogonal to the direction of acoustic wave propagation but one of its edges lies within the acoustic cone. It is interesting to see that the table supporting the rectangular block is orthogonal to the acoustic chirp still the transducer does not record its presence. Because of corners, edges and the rough nature of surfaces in general some of the objects within the acoustic cone reflect back the echo to the sensor before it detects any of the orthogonal surface with its acoustic cone. It is obvious now that the sensor doesn't have any preference for orthogonal objects. It detects the nearest object within the acoustic lobe figure 6.4.

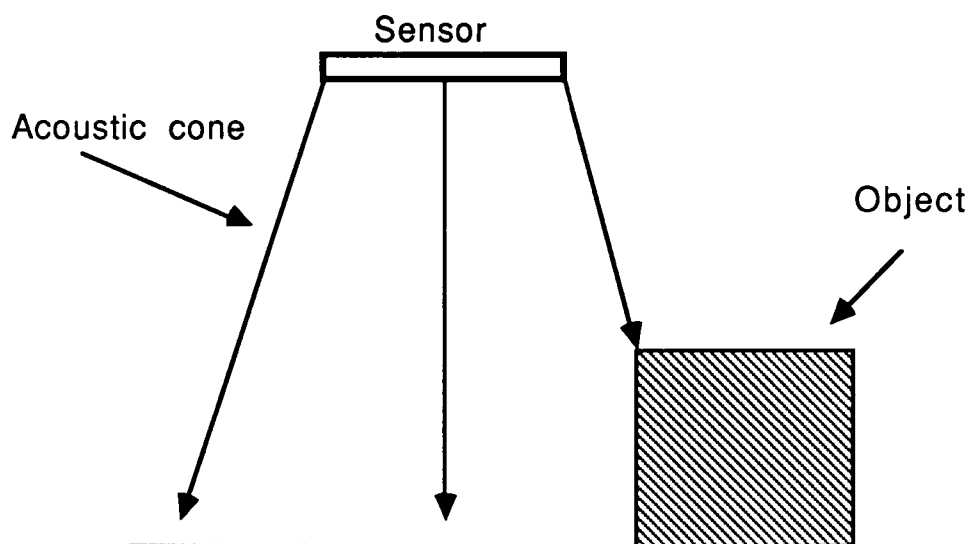


Figure 6.3 Early object detection and propagation cone angle

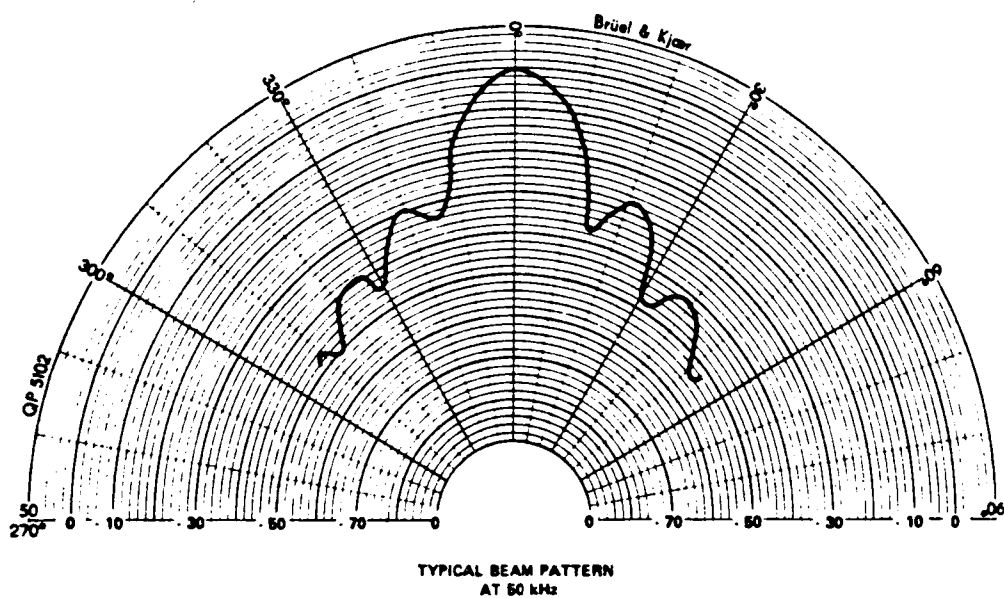


Figure 6.4 Typical beam pattern of the transmitted pulse
Courtesy: Poloroid Corporation

Early detection is a complex phenomena and to predict actual location on the basis of early detected signals requires a thorough knowledge of the scanning configuration and the type of surfaces being scanned. The factors that contribute to the phenomenon are:

1. Distance between the sensor and the object.
2. Orientation of the surface with respect to the sensor.
3. The acoustic cone angle.

The greater the distance between the sensor and the object, the more likely it is to come in to range of vision and be detected earlier. This is because of the fact that the acoustic cone which emanates from the sensor covers a bigger area as it moves away from its apex (the sensor) . Consider two metallic blocks object 1 and object 2 in Fig(6.5). Even though object2 is nearer to the sensor but because of the nature of propagation of acoustic waves object1 would be detected first.

6.4 EFFECTS OF ORIENTATION ON OBJECT DETECTION

The detection of objects is greatly affected by their orientation with respect to the sensor. A surface at an angle to the direction of propagation of the acoustic beam as shown in figure 6.6 may not be

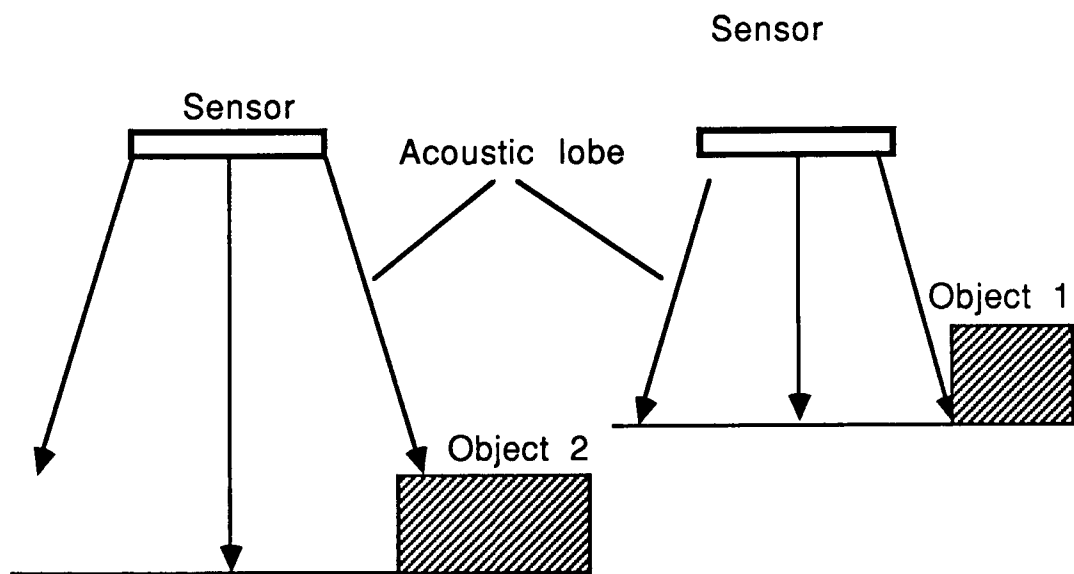


Figure 6.5 Relationship between early detection and the distance between the sensor and the object.

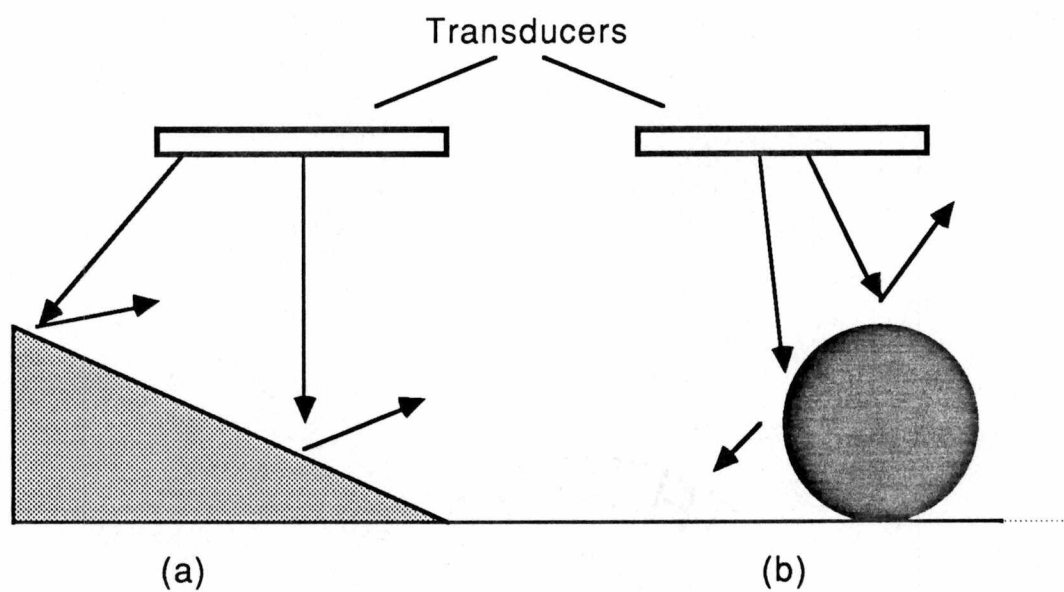


Figure 6.6 Relationship between the intensity of the returned echo and the orientation of objects.

detected as accurately as a surface orthogonal to the direction of transmission . The reason behind this is the fact that the solid bodies act like acoustic mirror, and the intensity of the returned echo is not uniform in all direction. The intensity of the returned echo will be greatly reduced from a surface with orientation as shown in figure (6.6). A rough surface is highly unpredictable to detect. Because of the random nature of the angle of incidence and reflection the measurements have some inherent noise.

6.5 DISCONTINUITY DETECTION LIMITATION

The problem of distinguishing objects which are not too far apart from each other points to the fact that the accuracy of the sensor is a highly relative term. Fig(6.7) and (6.8) show scanned profile of two steel blocks, each with a hole in the center. The first plot shows the profile scanned by the sensor when the blocks were 3 cm apart. Evidently the sensor was not able to see any hole or discontinuity, which is predictable. An explanation can be given on the basis of Figure 6.9 which depicts the scanning process limitation in closely placed objects. The figure suggest that the sensor can hardly notice any discontinuity among objects with the same height, which are separated by a distance comparable to the diameter of the cone. Notice that the diameter of the transmitted cone does not remain

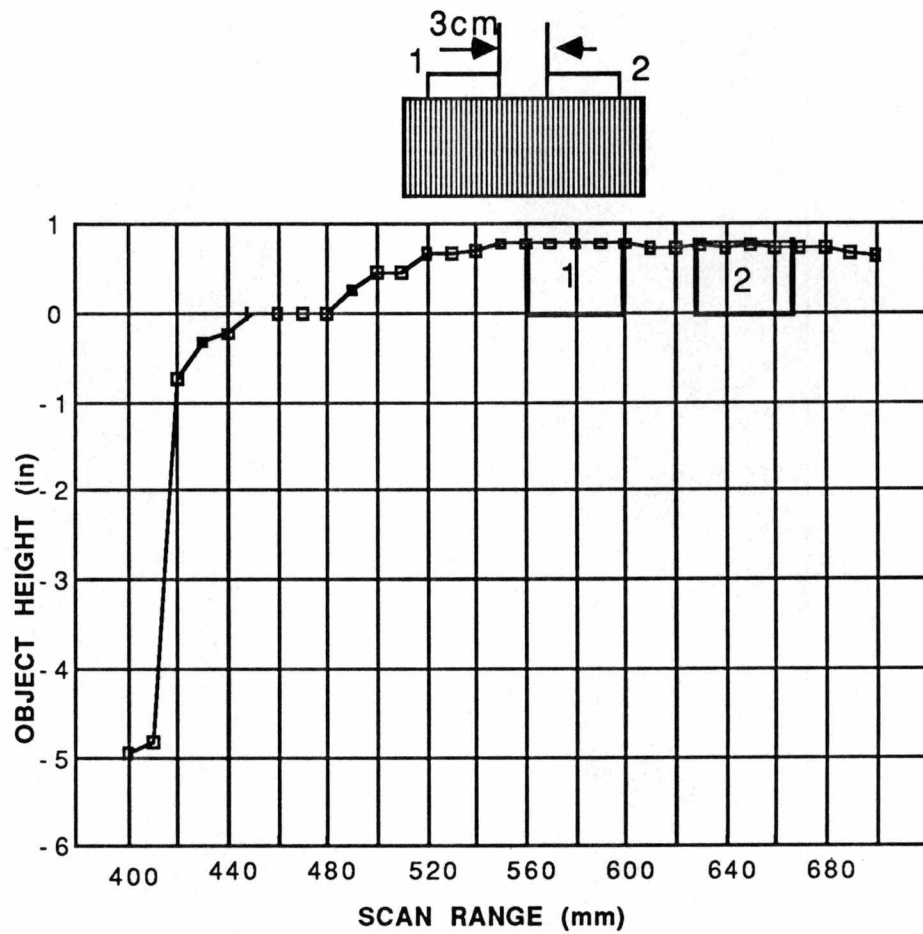


Figure 6.7 Contour scan of two adjacent (3 cm apart) objects.

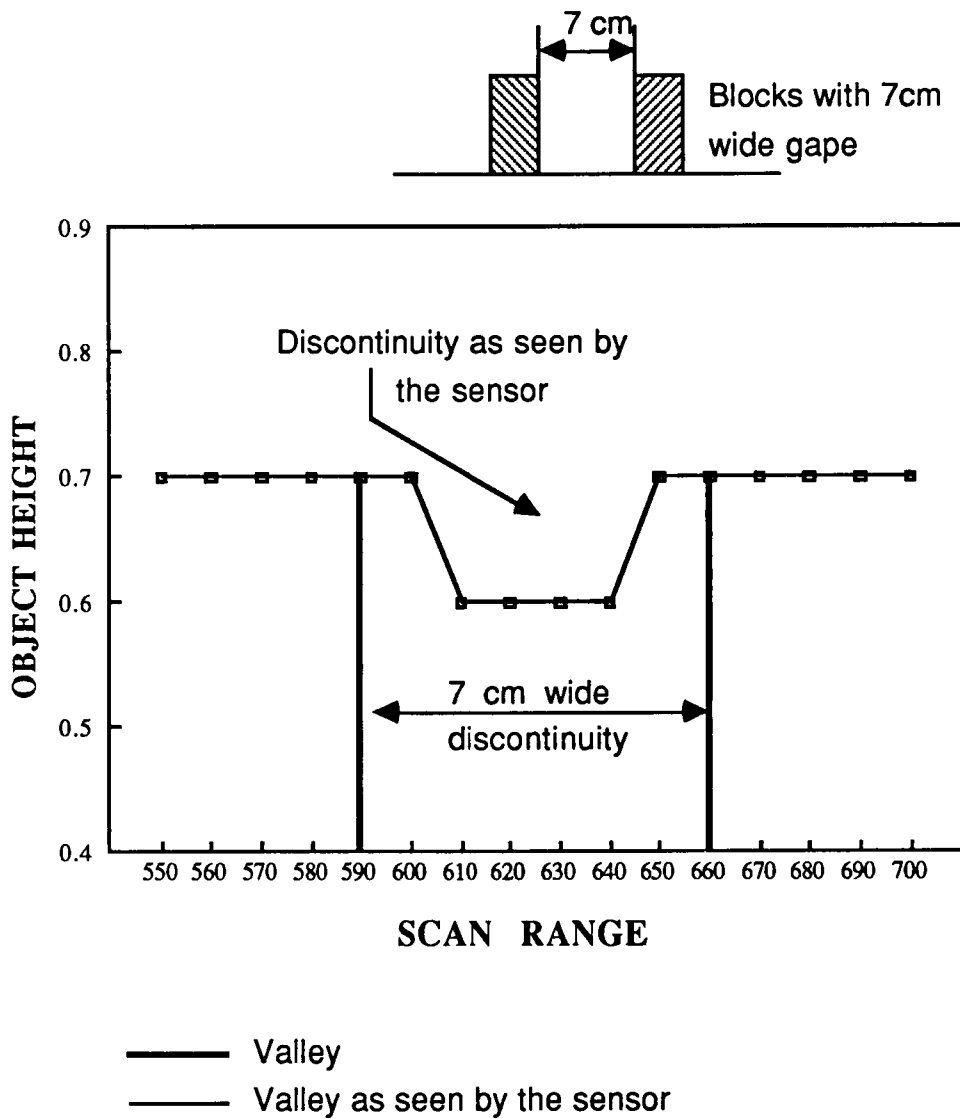
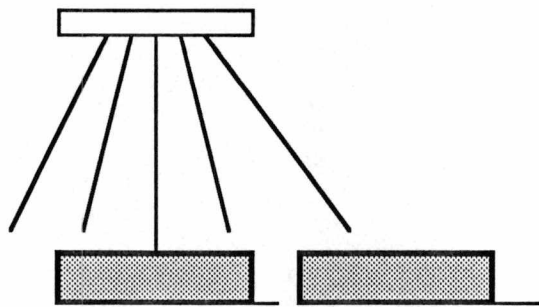
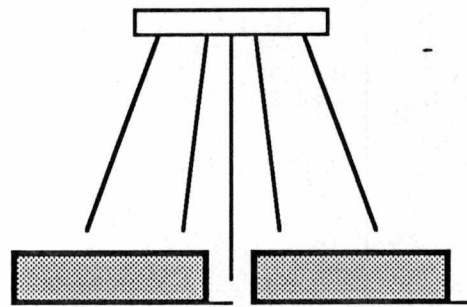


Figure 6.8 Contour scan of two adjacent (7 cm apart) objects.



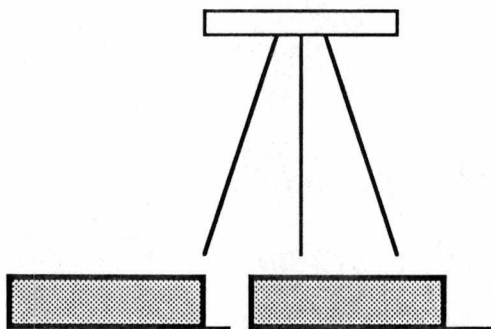
Left object being detected

(a)



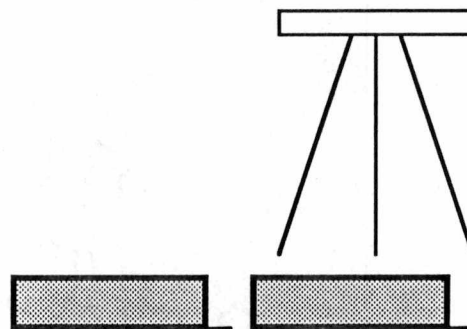
Either of the two objects is being detected. Valley is not being picked up.

(b)



Object on the right is being detected.

(c)



Again the same object is detected .

(d)

Figure 6.9 Limitation on discontinuity detection

constant. Which implies that the discontinuity detection is also dependent on the actual distance between the sensor and the surface. Algorithms have been developed to deal the problem of edge detection, but their application to ultrasonic ranging has met with little success.

As a vision tool the ultrasonic ranging sensor has very limited potential, but its detection capability and accuracy especially for orthogonal flat surfaces in conjunction with its relative low cost makes it a good choice for a variety of applications. Ultrasonic ranging finds a good application in the field of robotics as a tool for avoiding obstacles. Collision avoidance does not require a precise information about the profile of the robot's surroundings. The only information needed is a good estimate of the distance between the nearest object and the robot itself. The sensor can be successfully used as a feedback device for obstacle detection, providing a basis for changing the path trajectories.

The ultrasonic sensor along with the electronic module and the custom made ranging board has been installed on the IBM 7547 robot. Because of the limited capabilities of (A manufacturing language) AML, the obstacle avoidance scheme was not implemented on the robot. But its use in shop floor environment particularly for pick and place operations in an unknown environment were investigated. In the following section we will describe the

experimental setup and results of the experiments conducted.

6.6 APPLICATION EXPERIMENTS

In assembly lines, usually, on-off switches are used to activate robots for loading and unloading purposes. But on-off switches does not take account of object's height. For out of specification objects the possibility of the robot crashing into work items always exists. An experiment was set up to handle the variability of objects heights in such an environment.

An aluminum rectangular block of unknown height is placed in the robot's work space. The exact location of the center of the object is specified to the robot. For keeping the experiment simple the object is oriented along the direction of the gripper so that the gripper does not have to align itself with the block for grabbing it. The width of the block was kept within the maximum opening limits of the gripper to avoid any possible collision between the object and the gripper. An application was written in AML and the experiment was conducted for blocks of varying heights. The application provides the instructions to the robot to reach the point of interest in it's work space and verify the presence of any object. The presence of any object can always be confirmed by comparing two measured distances :

1) Distance between the sensor and the table on which the object rests.

2) The distance between the sensor and the object.

A positive difference between the two measurements gives the information about the height of the object, and a negative difference indicates either a discontinuity or a valley at that point. The experiment was conducted several times to check the variability and the repeatability of the measurements. All the tests show a high degree of reliability for the detection and the measurements made by the sensor. The sensor's feed back is used to first move the robot and approach the object to finally grab it.

After the first successful experiment a more general approach was taken in testing the sensor's performance. There are a number of situations when the exact location of the object is unknown. As the first step an experiment was set up for detecting and locating an object in the robot's work envelope at an unknown location. Again the problem was simplified by orienting the object parallel to the gripper's finger. This alignment of the gripper with the objects eliminates the need for orienting the gripper and lets us focus on detecting the object. In order to make sure that the manipulator doesn't try to hold the block at its edges but holds the object firmly

we need to center the gripper along the length of the block before grabbing it. If we look at the problem, it looks more close to an edge detection exercise. We have seen, from last sections, figure(6.2) that scanning rectangular objects does not give any information about the edges of the block. But the characteristics of the scans in figure 6.2, figure 6.6 and figure 6.7 give enough information about the expected pattern. The experiment was focused on two aspects

1. To detect an object at an unknown place along a known direction. Knowing the direction of the object essentially reduces the variability in a plane to one dimension instead of two.
2. To use the characteristics of previous scan plots for similar objects under similar conditions and develop an algorithm for approximate edges detection.
3. To check the consistency and repeatability of the sensor under investigation.

An application program was written to accomplish the above objectives. Several test runs were made with different objects at different locations. The results show a reliability factor of more than 90% in determining the center of the object along it's length. A 100% repeatability is observed at a particular location for both detection and centering. Object was detected with 100% repeatability and accuracy. 10% of the time the gripper was observed to be off by a

centimeter from the center of the object. This is the fact that the step size used for scanning was kept to a maximum to speed up the scan process. If somehow the edge lies at the beginning of a scan step then the measured length increases by a scan step (which happens to be one centimeter in our case).

6.7 SUMMARY OF EXPERIMENTS

The results of the two experiments described in the last section can be summarized as follows:

1. At a known place within the robot's work space objects with varying heights can be detected with 100% reliability and repeatability.
2. The distance measured by the sensor to the objects are accurate to one tenth of an inch and the maximum error is in the range of 0-0.06.
3. Objects at unknown location along a straight line are trackable with 100% reliability and repeatability.
4. Approximate edge detection based on the information gathered from ultrasonic range scans shows a repeatability of more than 90%. Centers of the objects were located with a great accuracy, and 10% of

the scans were off by a maximum of one scan step.

6.8 LIMITATION ON THE SCANNING SPEED

Because of the uncertainty and noise present due to the power supply and the high speed, high torque stepper motors it seems unavoidable to make measurement more than once and then average them out to get the final distance. Averaging the distances gives a higher degree of reliability and accuracy to the measurements made by the ultrasonic sensor. It is noticeable that every scan requires closing and opening of the mechanical relays inside the 7547 controller. We know from the last chapter that at each reading one needs to trigger and reset the circuit, which requires two closings and two openings of the relays. The response time of the digital input/output port is up to 65 ms (65×10^{-3} s). In order to make sure that the DI/DO port is in its stable state a delay is needed before the controller moves to the next instruction. The minimum time that is handled by AML is 0.1 seconds. This limitation on minimum delay greatly reduces the scan speed. Let us see in a little detail how much reduction in speed is caused by the relays alone. Each scan consumes 0.4 seconds, if the robot makes 10 scan steps then the total time consumed by the relays alone is 4.0 seconds. If each scan step is of one centimeter then the net speed of the scan is 2.5 centimeter per

second, which is awfully low by any standard. The designed hardware has a response time of 26 ns ($1\text{ns}=1\times 10^{-9}\text{ s}$) and is capable of responding to a much faster processing unit. An improvement in the processing speed can improve the speed of the scan from present slow intermittent scans to almost continuous scans.

6.9 ACCURACY AND SCOPE

Before getting into details of accuracy of the measured distance, we first define what is meant by the accuracy and under what conditions the definition is valid. Accuracy is an abstract term and its definition and requirement vary from application to application. As discussed earlier the sensor lacks accuracy in a work area where the objects are separated by a distance comparable to the diameter of the base of the acoustic cone. The basic function of the sensor is to measure the distance between an object and itself when a normal from the surface being scanned passes through the center of the transducer. In such a configuration the sensor is highly accurate. But for the sonar under study measurements are valid only in the range between 11 inches and 35 feet. The minimum response time of the electronic module limits the nearest objects to be at least 11 inches away from the sensor. The other factor which puts a constraint on maximum detectable range is the threshold intensity of the returned

echo from distant objects.

It's application in industry or a shop floor does not show much promise except in situations where the objects are widely scattered and pick and place operations have a big tolerance range. The performance of the sensor can be greatly improved just by reducing the solid angle which is subtended by the pulse at the sensor. A good example of sensors based on time of flight concept with a very narrow cone angles are laser range finders. The cost is a major inhibitor and limits it's frequent use in industry and other areas of general interest.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

All of the main objectives outlined in chapter 1 are successfully achieved. An ultrasonic ranging system was integrated with the IBM 7547 robot. The distance data collected through the ranging system were used to develop contour images. Information from these profile images were used to write applications for pick and place operations. The robot was able not only to locate objects but was able to use the distance informations to find the edges and center the gripper for picking up the objects. The robot was controlled on line during entire process and the informations were used for dynamic manipulation. Because of the limitation and constraint imposed by "A Manufacturing Language" (AML) obstacle avoidance scheme was not implemented on the robot. But the results of the object detection experiments suggest that the scheme should work fine.

It is observed that the scanning speed is too slow for a real world operation. In order to increase the scanning speed it is suggested that the task of triggering the sensor and data manipulation be done on personel computer and the controller's processor be left only for the issuing the move commands.

More accurate contour and three dimensional images can be obtained by narrowing the angle of the cone of propagation. An acoustic horn is generally used to narrow the beam. Development of ultrasonic lenses can bring accuracy close to laser ranging. By focusing or narrowing down the angle of propagation the problem of valley detection or discontinuity detection in closely placed objects can be tackled fairly easily.

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APPENDIX

APPENDIX

TROUBLE SHOOTING

The custom ranging board is designed to interface the ultrasonic sensor with the IBM 7547 controller, but the design is kept so general that the same board can be adapted to any other controller which has a parallel communication port. The only part that needs to be changed from controller to controller is the communication cable which transfers data from the ranging board to the controller or any other processing unit.

In the following sections we will discuss the possible malfunctions and problems which may be encountered during the course of its use.

a) ERROR 001: Measured distance remains zero.

Possible causes:

Suggested remedies

1) Power supply

The custom ranging board is very sensitive to the voltage and amperage getting into the circuit board. The supply voltage should be a noise free stable 5 V. The power supply should be able to pump in enough current during transmission. The maximum current requirement during transmission reaches 2-amperes.

2) Transducer connection to the electronic module

A loose connection will cause only noise instead of the clock signal to appear at the 4040 binary counter. The user must make sure that the transducer is connected properly, a trigger without transducer being connected may damage the electronic module. A proper connection results in an audible chirp which can be heard from a close distance.

3) Improper or loose power and ground on any of the chip on the custom ranging board.

Check all V_{CC} and ground connections on individual chips.

4) Clock not running

Check the clock signal at pin 1 of 74LS11 and make sure clock voltage levels and the frequency is according to the specification. (clock operates between 0-5 volts with a frequency of 420KHz.)

5) False XLG and FLG signals

Check pins 2 and 13 on 74LS11 for XLG and FLG signals. At the reset XLG should be low(0-2 volts) and FLG should be high (3.6-5.0 volts). At the end of any scan XLG is high and FLG is low. If these conditions are verified than disconnect the electronic module from the custom sonar ranging board and probe on pin 12 of 74LS11. If a clock signal identical to the one at pin 1 is observed than this part of the circuit is working fine. A signal other than the 420KHz clock means that the chip is not

working properly. Change the chip and again run the tests.

6) Burnt out 4040 binary counter

Probe on pin 10 of the binary counter at the time of trigger. A short burst of clock signal should appear on oscilloscope. If the clock signal does appear and the count remains zero than there is a strong possibility of a burned out 4040 binary counter. But before changing the chip make sure the reset signal remains low during a scan. Change the 4040 chip and follow the procedure (6) again.

b) ERROR 002 Incorrect distance measurement

1) Darlington 9667 chips may not be connected properly

Check pins 16, and pin 8 on the 9667 (ones which are used for interfacing) for floating and low signals. A more detailed probing involves triggering and resetting through Teach Mode of the AML editor. The sensor can

be triggered and individual bits can be read on the PC screen. Trigger the sonar system several times and observe individual bits. (Individual bits can be observed in teach mode by pressing F5 key. Outside the teach mode one needs to use the communication program comaid.) If there is a visible pattern in all readings than there is a possibility of either a faulty connection or a malfunctioning 9667 chip. e.g bit 8-13 remain low no matter how far is object from the sensor. This kind of pattern shows that one of the 9667 chip is not grounded properly.

2) Glitches on XLG and FLG lines

The problem due to glitches on any gating signal is hard to fix. A step by step probe is necessary to isolate the problem. First check the type of glitches and where they begin to propagate. The glitches may originate from the electronic module. Check pin 3,4,14 and 13 on the 9667. If there is no occurrence of glitches on these pins than we are sure to have functional electronic module. The next

step is to follow the line from the 9667 chip until it reaches the 4040 binary counter. Between the chips check the XLG and FLG signals for glitches. After isolating the origin of glitches carefully look for wires which are running close to the origin of glitches. A wire passing a high voltage pulse, or a clock signal running close to point isolated indicates potential causes of the glitches. Try to separate such lines as much as you can. Again look for glitches if the problem is still there than look for a possible explanation for the glitches to occur and try to eliminate them. A short cut method to remove high frequency noise of glitches is to add a bypass capacitor of very low capacitance between the origin of the glitches and the ground. This method should be used with caution because adding a capacitor always slows down the circuitry and may distort some desirable signals.

3) Sensor not orthogonal to the object

Make sure that the sensor has a good stable seat inside the tube and the surface of the

transducer is normal to the axis of the tube. A slight deviation from this configuration results in picking up echos from objects not under investigation.

c) ERROR 003 Inoperational clock

1) Burnt out light emitting diode (LED)

A burnt out LED will not initiate the transition to start the clock signal. It is necessary to have an operational LED which is compatible with the circuit requirements. When replacing the LED be sure to connect cathode and anode of the diode properly.

2) MPQ 2222 malfunctions

As the first step, test each of the four discrete transistor for their h_{FE} values, and compare these values with the values given by the manufacturer. If these values do not deviate much from the listed values than do the usual battery of tests to check if there is a malfunctioning transistor. If a transistor is

found to be faulty then replace it with a new one.

VITA

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