Part III

Direction measurable sonar-ring

Chapter 6

Introduction to direction measurable sonar-ring

A sonar-ring is a system placing multiple sets of pulse-echo method ultrasonic sensors on a ring for measuring all around a robot and it is one of the most popular sensor for indoor mobile robots, because it is simple and gives omni-directional distance information directly.

In mobile robot navigation tasks, such as wall following, doorway traversal, obstacle avoidance and sensor based positioning, accurate bearing information of the reflecting points has been requested [Rimon 97]. On the other hand, many research approaches – sensor-based path planning of mobile robots in unknown or complicated environment, assume that robots are able to measure precise angle information. In real robot navigation, not only accurate measurement data but also fast measurement is an essential factor.

However, up to now, there is not a system which can achieve those requirements. Therefore I would like to propose a new sonar-ring system which can achieve fast and accurate measurement.

Before explaining the fast and accurate sonar-ring, in this chapter, I explain current technology as the back ground and show statements of the new sonar-ring in those background.

6.1 Background

Basic of ordinary ultrasonic sensors, sonar-ring which is one of the most popular system for mobile robots, an accurate reflecting point measuring method employing multiple receivers and multiple objects detection are the keys for the proposed system, and explained here.

6.1.1 Conventional pulse-echo ultrasonic sensors

The pulse-echo ultrasonic sensor is well known for its simplicity and low cost within robotics applications. It can detect easily distance to a reflecting object just by measuring time from a pulse is transmitted till the echo is coming back, and the time is called Time-Of-Flight (TOF). The distance to the reflecting object is calculated as follow:

$$L = \frac{1}{2} \cdot \frac{TOF}{c}. \tag{6.1}$$

where, L is measured distance, TOF is measured Time-of-flight and c is sound speed which is about 340 m/s in the air.

However the accurate direction to the reflecting object is not easy to measure with conventional ultrasonic sensors, since the direction of the object is estimated based on the heading direction of the transducer and the directivity of its beam. The directivity is about $30 \sim 60$ degrees and it is not sufficiently sharp to measure the direction of objects.

6.1.2 Sonar-ring

A sonar-ring sensor is one of the most popular sensor system for indoor mobile robots [Walter 87]. Multiple sets of conventional pulse-echo ultrasonic sensors are placed on the ring for measuring all around the robot, and they are driven in sequence to avoid their interference. A conventional sonar-ring is regarded as difficult to measure accurate bearing of reflecting points due to wide directivity of ultrasonic transducers, because it is a system which conventional ultrasonic sensors are just placed on a ring [McKerrow 93b].

There is a method using narrower-beam width transducers for improving the bearing accuracy, but the method has a problem of size because narrower-beam transducers are larger, and dead angle is arisen because number of transducers are limited to mount on a robot [Everett 95]. Furthermore, it is slow to get full 360 degrees directional information due to sequential driving of the transducers for avoiding interference.

Consequently it has been difficult for a mobile robot to move with the sonar-ring in a relatively complicated environment without extra sensor data processes [Budenske 94].

6.1.3 Accurate reflecting point measurement

Many objects in indoor environment can be assumed to be specular reflectors for ultrasonic waves, especially at a leading edge of an echo, since wave lengths of ultrasound used in air are from 4mm to 20mm. Specularity implies that the reflection comes from a point, not from an area, and that the reflecting position is the surface of the wall which is perpendicular to the incident direction of a plane or curved surface, or a convex corner. Hence, when we can measure the accurate bearing angle of the reflecting point, useful informations as the bearing angle of the wall can be gotten.

The accurate bearing angle measuring methods of a reflecting point using the propagation time difference has already been proposed [Nagashima 92] [Peremans 94]. In the method, a pulse is transmitted from a single transmitter and an echo which is coming back from the same object is received by multiple receivers simultaneously (Figure 6.1). The bearing angle is calculated using the difference of the propagation time as follow:

$$\theta \simeq sin^{-1}(\frac{TOF_{diff}/c}{d}). \tag{6.2}$$

Where, θ is measured bearing angle, TOF_{diff} is difference of Time-of-flight, c is sound speed and d is distance between receivers (Figure 6.1).

These methods accomplish bearing angle measurement which is more accurate than the beam width of the transducers.

This method can measure bearing angle accurately without relating with its wave length. Because, this method is different from beam forming methods using wavefront synthesis. The TOFs are measured at first and then accurate bearing angle is measured by processing those TOFs. This is possible because of the specular reflection assumption. Consequently, accurate bearing angle measurement without relating with the wave length is achieved.

However, in case of using a single transmitter and two receivers, the measurable area is only the overlapping area of the directivity of the three transducers, and it is not enough for robotics applications. For that reason, mechanical rotations had to be employed in past research [Nagashima 92] [Peremans 94], and it requires time to scan and is slow to get information from wide area.

6.1.4 Multiple objects detection

A conventional ultrasonic sensor is detecting only a leading edge of the first echo, consequently it measures only the distance to the nearest object. However, if leading edges of the second and following echoes should be detected for getting more information (Figure 6.2). For example, when two poles exist in front of a wall and they are distant enough, we can observe three echoes and we can know distance to them just by detecting TOFs of these three echoes simultaneously.

6.2 New sonar-ring

Based on those background (Figure 6.3), here I propose a new sonar-ring sensor which take advantages as follows:

- Good distance accuracy as same as the conventional ultrasonic sensor
- Accurate bearing angle measurement
- Wide measurable area in a single measurement, consequently fast measurement
- Multiple objects detectable measurement

A new sonar-ring sensor with such characteristics is explained in the following sections.

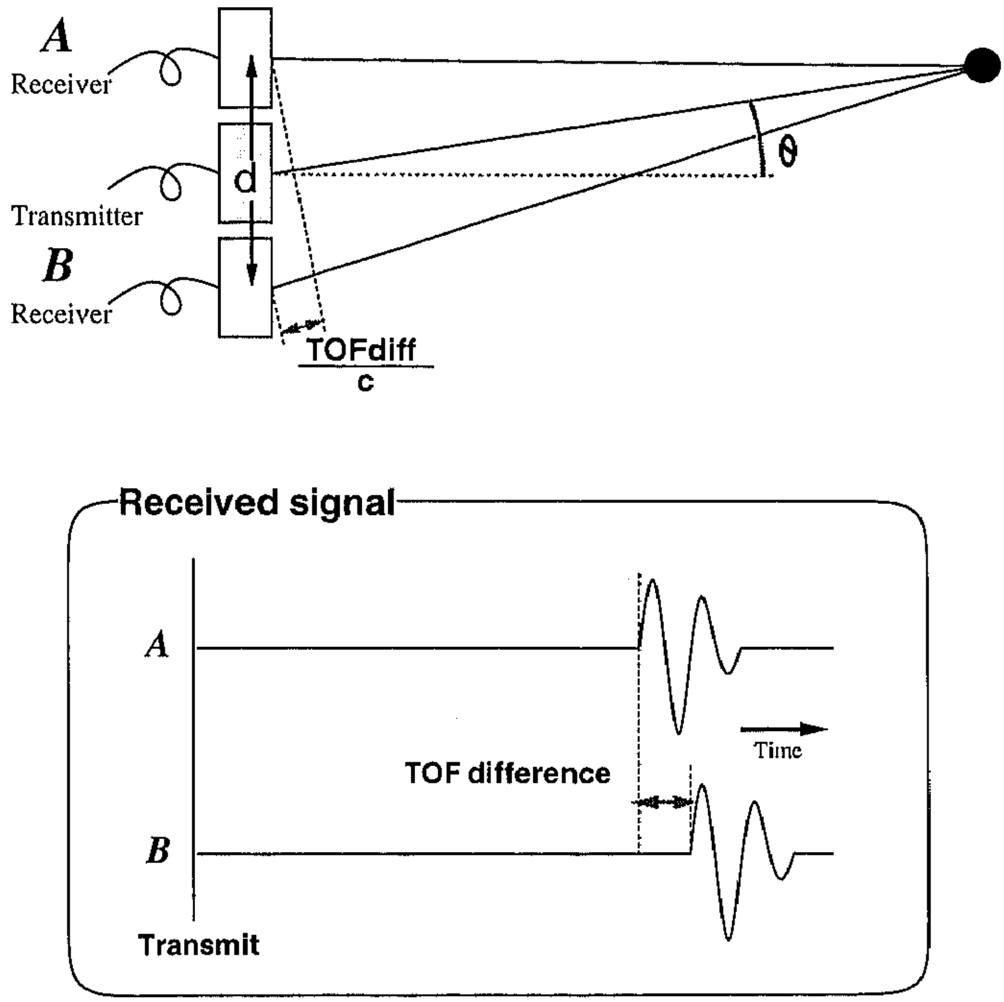

Figure 6.1: Bearing measurable ultrasonic sensor using TOF difference.

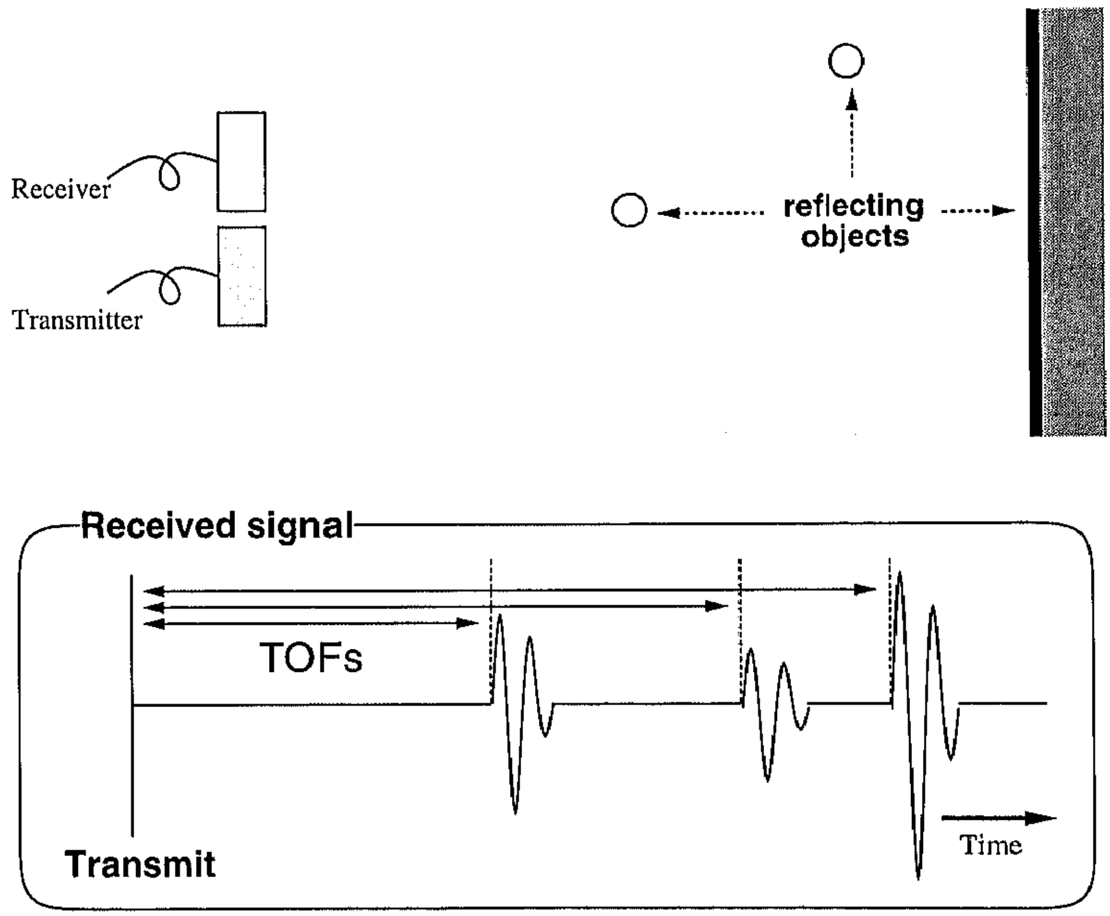

Figure 6.2: Multiple objects detection by multiple echoes detection.

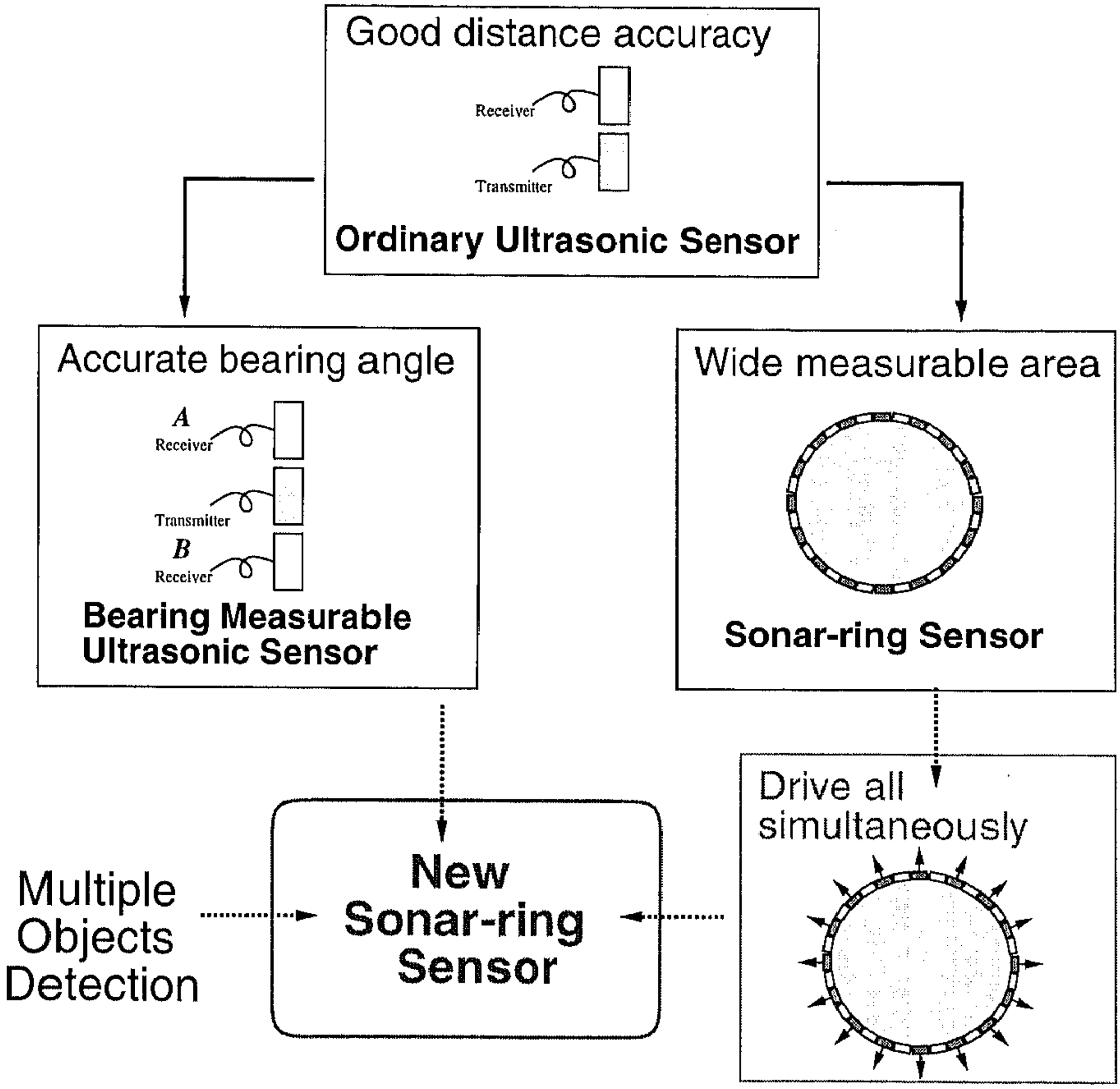

Figure 6.3: Basic ideas for a new sonar-ring sensor.

6.3 Overview of part III

In this part, I will propose and investigate a fast and accurate direction measurable sonar-ring sensor system based on the background. In the next chapter, I will propose basic idea and explain difference of a proposed system from previous methods. In chapter 8, I will explain system design of the proposed direction measurable sonar-ring, and experimental results using the system will be shown in chapter 9. At the end of this part, in chapter 10, I will discuss the proposed method and conclude this part.

Chapter 7

Fast and accurate direction measurable sonar-ring

A new sonar-ring sensor which can measure accurate bearing angles to reflecting points rapidly is proposed here.

As it has explained at the previous chapter, a sonar-ring is one of the most popular sensors for indoor mobile robots, because it is simple and gives omni-directional distance information directly. However, it is difficult to measure accurate directions of reflecting points by a conventional sonar-ring sensor. Further more, conventional sonar-ring sensors are slow to get full 360 degrees informationdue to sequential driving of transducers for avoiding interference. Here, I propose a new sonar-ring sensor system for a mobile robot which can measure the accurate bearing angles of reflecting objects in a single measurement (Figure 7.1). The proposed system employs the measurement by using differences of Time-Of-Flight (TOF) and by simultaneous transmit/receive of all directions, and consequently achieve accurate and fast measurement.

7.1 Basic ideas

I propose a new sonar-ring which can measure accurate direction and distance to reflecting points rapidly. A conventional ultrasonic sensor, a sonar-ring, an accurate reflecting point measurement method and multiple objects detection are back ground of this proposed method.

The basic idea can be expressed in four steps:

- Transmit an ultrasonic pulse simultaneously: Rapid measurement is achieved with the omni-directional transmission in a single transmit cycle.
- Receive the echoes with plural wide beam receivers on the circumference: Place the receivers to overlap their directivity, and measure differences of the propagation time of echoes. Each TOF is measured by detecting the leading edge of the echo.

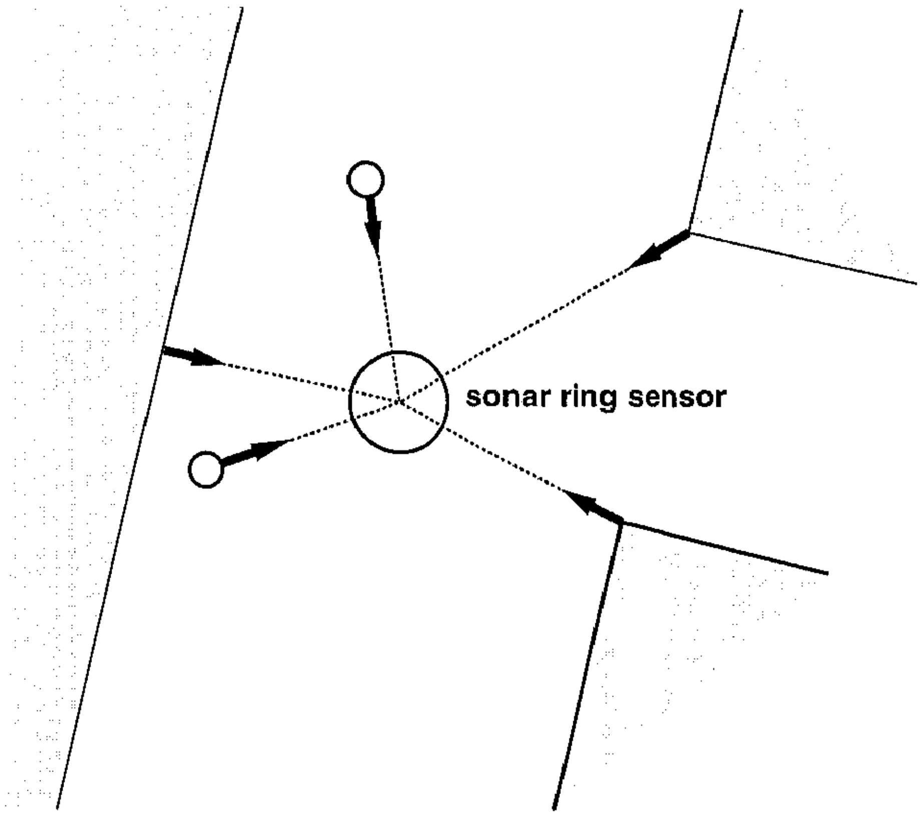

Figure 7.1: The proposed sonar-ring sensor measure accurate multiple reflecting points around the robot with a single measurement.

- Detect TOFs for multiple echo blocks at each transmit in each receiver: Since, multiple objects can be included in the beam of each receiver (Figure 7.2), all echoes should be detected by each receiver to achieve the measurement of these objects.
- Calculate the direction of reflecting points: Accurate bearing angle are calculated from the differences of TOFs.

Combining these steps as a system, it becomes possible to achieve accurate and rapid measurements of the bearing angles to the reflecting points in all directions.

7.2 Difference from previous methods

This fast and accurate direction measurable sonar-ring can achieve what was impossible by a conventional sonar-ring.

With respect to the difference from a conventional sonar-ring sensor, the conventional sonar-ring is nothing but placing plural sets of imprecise ultrasonic sensors on the robot's

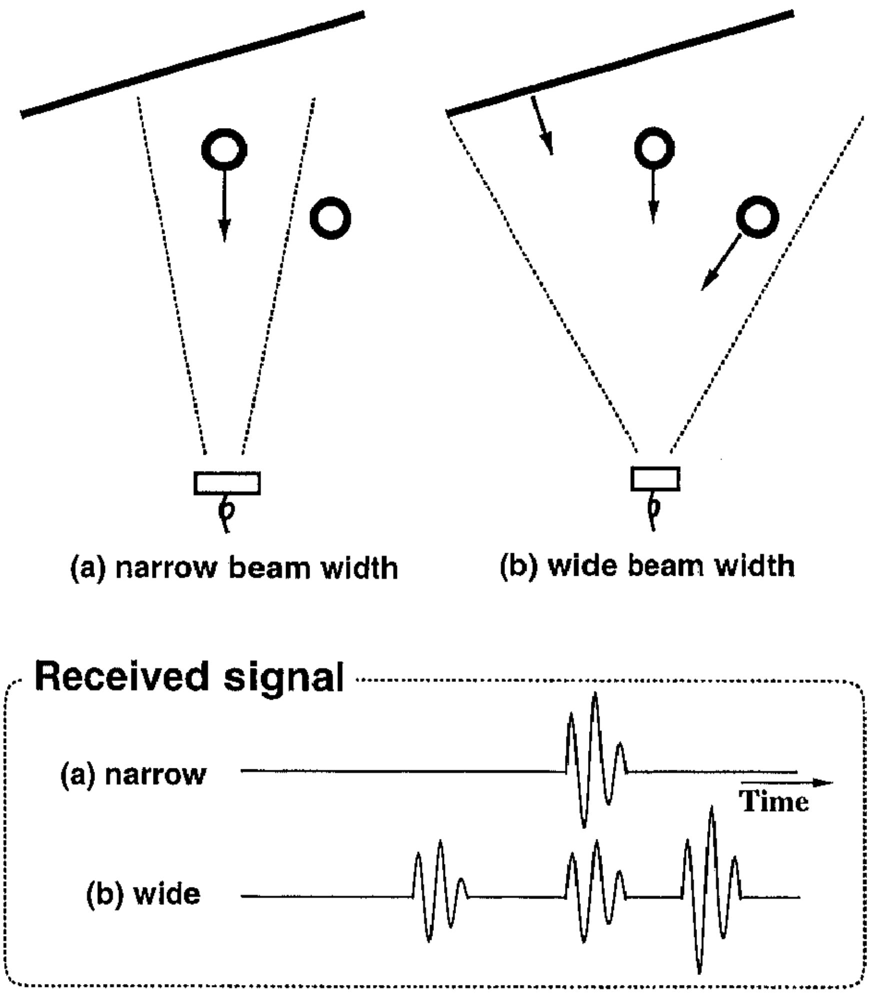

Figure 7.2: In case of using the wider beam width transducer, possibility of that multiple objects are in the beam increases.

circumference, however the proposed sonar-ring sensor uses all transducers at the same time and processes the received signals based on the assumption that the ultrasound reflection comes from a point. Therefore, it is possible to measure all directions in a single transmit/receive cycle, and consequently achieve fast measurement.

Robots become possible to do following what was impossible with ordinary sonar-ring:

- Measurement of all around the robot in a single transmit/receive cycle.
- Detection of multiple reflecting points in a single measurement.
- Accurate directional measurement of reflecting points on a wall, a pole or a corner.

Moreover, the proposed sonar-ring sensor is different from a system which is just driving all receivers of conventional sonar-ring [Korba 94] [Masek 99]. The difference is that directivity of receivers are positively overlapped to achieve accurate directional measurement. When the directivity of transducers are overlapped, it is possible to receive echoes from a single object by multiple receivers, and it becomes possible to calculate more accurate direction than beam width using difference of TOFs measured by multiple receivers.

A difference from wave synthesis method as like holography [Nagai 89] is that the proposed method is not employing beam forming concept. The proposed method calculate the direction to reflecting points by processing only TOFs which are measured at each receiver circuit, and it does not use directivity of transducer to get direction information. Only distance information measured by TOF is used and the distance information does not include wave shape information, and consequently the resolution of the proposed method is unrelated to the wavelength of the ultrasound. This is important because frequency which can propagate in the air is lower and wavelength is relatively long. Assumption of specularity made this method possible. Assumption of specularity is that objects in indoor environment can be assumed as specular surface comparing wavelength of ultrasound which are typically between 5m and 15mm (frequency from 25kHz to 70kHz). The proposed method can achieve accurate direction measurement only by measuring distance from TOF based on assumption of specularity.

7.3 Summary

In this chapter, basic ideas for a fast and accurate direction measurable sonar-ring and difference of the proposed method from conventional methods are described.

Chapter 8

Direction measurable sonar-ring system design

On the mobile robot base, I designed and constructed a proto-type of the new sonar-ring sensor based on the proposed basic ideas. This was constructed for evaluating and knowing potential of the proposed ideas, and clarifying the problems of the proposed system in the real world through real experiments. In this chapter, at first, I will explain about a total system architecture. And then, each parts of hardware and software processing are described.

8.1 System architecture

The hardware and software of the fast and accurate direction measurable sonar-ring system was built. Main flow of this system is the same as a conventional ultrasonic sensor: transmit an ultrasonic pulse, receive the echoes and process the received signal.

All processing flow of this system is shown in Figure 8.1.

One cycle of the measurement is as follow:

1. Output a transmission signal from CPU to transmitter circuit.
2. Transmit a ultrasonic pulse by 30 transmitters simultaneously.
3. Receive the echo by 30 receivers in parallel. Following processes are done during receiving the echo.
   (a) Amplify the received signal independently at each receiver.
   (b) Compare the amplified signal with a threshold level at each receiver circuit.
   (c) Write the binarized data into the 30ch 1bit wave memory.
4. Detect leading edges of echo signal from the memory data.
5. Make groups of the leading edges corresponding to objects.

6. Calculate the positions of reflecting points.

In this one cycle, it is possible to detect multiple reflecting points all around the robot in this system.

8.2 Hardware

In this section, I explain each part of the hardware in the system - a robot used to implement the sonar-ring, transducers, a method of omni-directional transmission, a special omni-directional horn and a 30ch 1bit wave memory system.

8.2.1 Robot

A Standard Yamabico Robot [Yamabico] was used as a base. The robot is self-contained, autonomous and employs its own power source unit, actuators for locomotion and computer systems for control of every part of the robot. The robot has two driving wheels to realize powered wheel steering, and two casters to support the body. The size is $30cm \times 30cm$ and the sonar-ring was set on the robot at 60cm in height (Figure 8.2). The robot employs an original bus system and distributed architecture in the computer system. The CPUs in the controllers for Yamabico systems are T-805 [Transputer 89].

8.2.2 Piezo-electric transducer

Piezo-electric type transducer MA40S4 [Murata 93] was employed because of its simplicity and narrow band frequency for avoiding difference of transmit/receive frequency among transducers. Piezo-electric is a material translating electrical energy and mechanical energy. One big difference in the use of the piezo-electric type transducer from the electrostatic type transducer, as like Polaroid 7000 [Polaroid 93], is that it does not require bias voltage. Therefore, it does not need any power supply to transducer itself when it is receiving. The transducer is narrow band because of its material characteristic. It is strong with noise because of its narrow band. This is important factor in robotics application.

Piezo-electric type transducer, whose center frequency in specifications is 40kHz are used. The structure of the sensor is shown in Figure 8.3 [Murata 94]. Figure 8.5 is a received echo from a pole at distance 1m. The frequency is about 40kHz and it has duration about 500 microseconds.

The diameter of MA40S4 is 1 cm and its directivity in specifications is 80 degrees. Considering the size and directivity of transducers, I have decided to place 30 transmitters and 30 receivers alternately on the ring. Therefore, a transmitter or a receiver is placed each 12 degrees, and each point around the ring can be covered by 6 receivers.

There are transmitter type and receiver type in MA40S4, and those center frequency are slightly different to get maximum power when they are combined [Tanikoshi 94]. However, those frequency difference cause beat in the received echo signal, and this beat is avoided

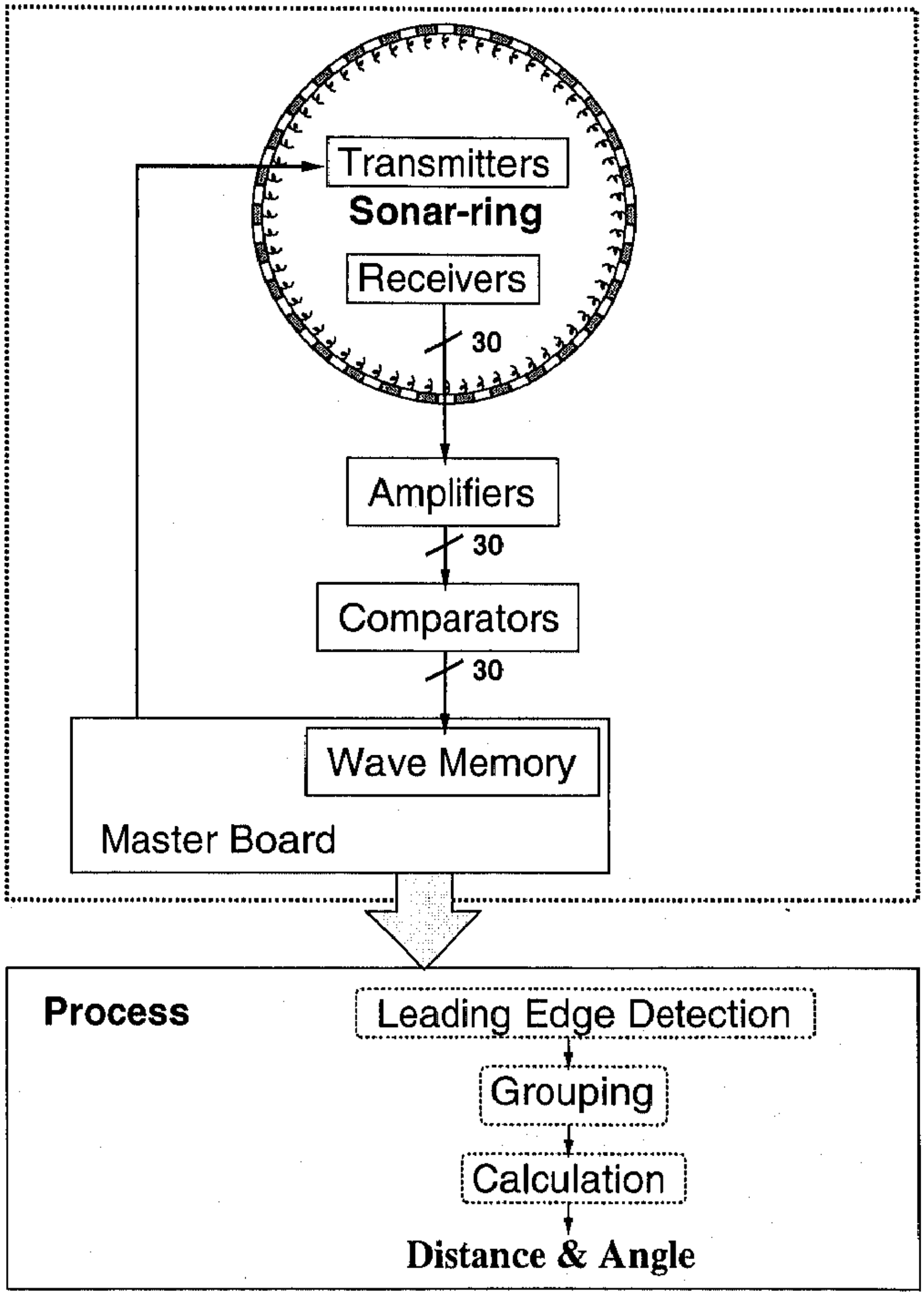

Figure 8.1: System architecture of the direction measurable sonar-ring.

Figure 8.2: Robot with the direction measurable sonar-ring system.

when using transmitter and transmitter pair or receiver and receiver pair. An examples of received echo wave is shown in Figure 8.6(a)-(d), and its frequency spectrum is shown in Figure 8.6(e)-(h). Transmitter was driven 270 volt 25 microsecond pulse, and the direct signal was received at distance 1m from the transmitter. From Figures 8.6, I found that when same type transducers are used for both transmitting and receiving, the frequency characteristics is sharper and the beat is reduced. According to this result, I decided to employ transmitter devices pair to avoid the beat and to get sufficient power in this system.

The transducer has polarity, as shown in Figure 8.4, it depends on direction the material is set how mechanical energy is translated into electrical energy. Therefore, it is important to know the direction of the polarity and use the same polarity for using multiple transducer simultaneously and to achieve accurate measurement.

8.2.3 Omni-directional transmission

In this method, transmitting one ultrasonic pulse to omni-directions equally at the same time is required. However, conventional ultrasonic transducers on the market have specific directivity because of their shapes. There are a few special transducers or techniques which can transmit a pulse omni-directionally [Toray] [Aoyagi 95], but they are not suitable for being mounted on the robot because of its big size or the insufficiency of power. Therefore, I propose to place wide directivity transmitters on the circumference intimately and to drive all the transmitters simultaneously.

In this way, the resultant ultrasonic wave can be assumed as being emitted by a single point source located at the center in two dimensions. Difference of power in direction exist due to interference, however it is not so large and does almost not effect on the measurement of TOF. Moreover transmitters are placed on the circumference closely and the phase difference in direction are small. Therefore bias time which correspond to distance from center of circumference to the position of transmitter can be added to assume all transmit signals are transmitted from the center. As the result, it is possible to assume there is a single point source in two dimensions.

Technically, all transmitters should be connected in the same polarity, and all transmitter circuit is connected electrically and driven at the same time. Input signal to all transmitter is about 270 V single pulse. The transmitter circuit diagram is shown in Figure 8.7.

8.2.4 Receivers

Since likewise conventional ultrasonic sensor, output signal from receivers are needed to amplify, all receivers are independently connected to amplifiers in parallel. Then, the amplified received signal is compared with a threshold value to make binary signal. This is because using a threshold is the simplest way to detect leading edge of the echo, and simplicity of each circuit is extremely important for using multiple circuits in parallel.

In the receiver circuit, simple base band wave given by the receiver transducer is amplified without detecting envelope for the purpose of keeping wave information. This wave

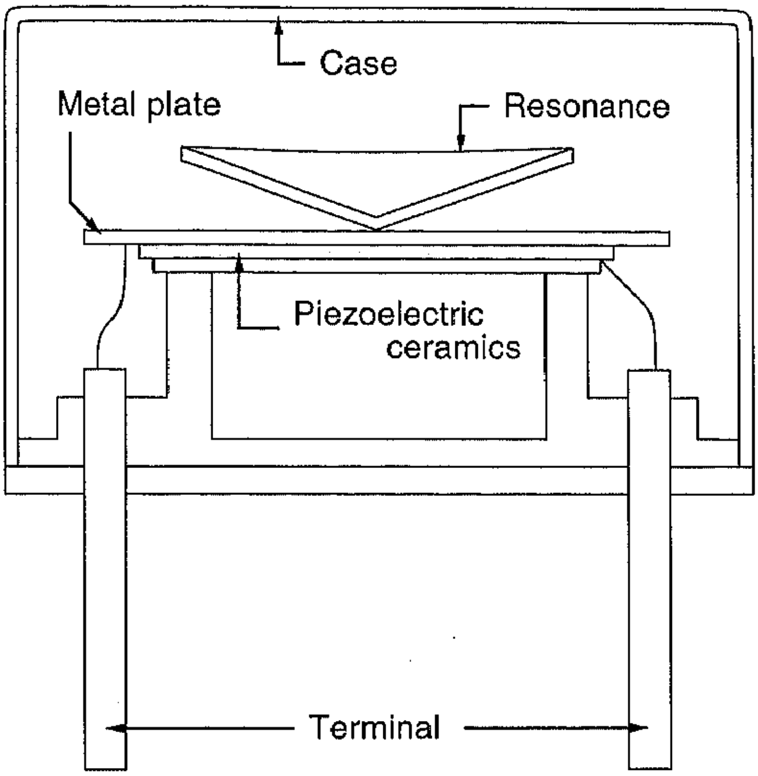

Figure 8.3: Piezo-electric ceramics type transducer.

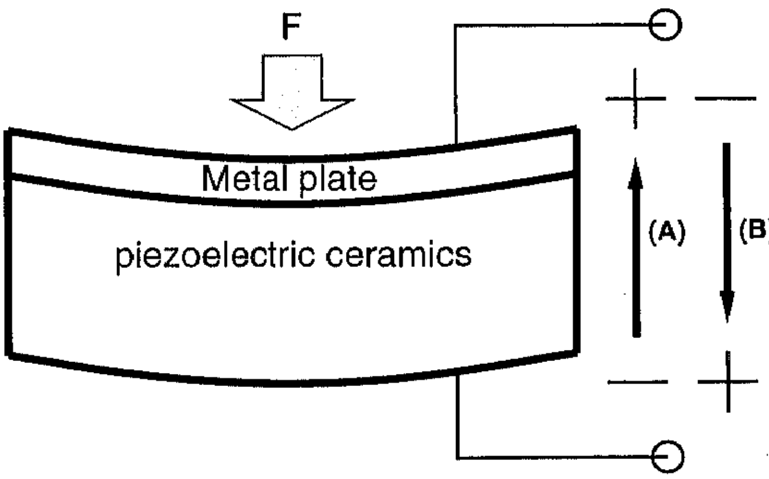

Figure 8.4: Piezo-electric ceramics type transducer. Piezo-electric ceramics has polarity.

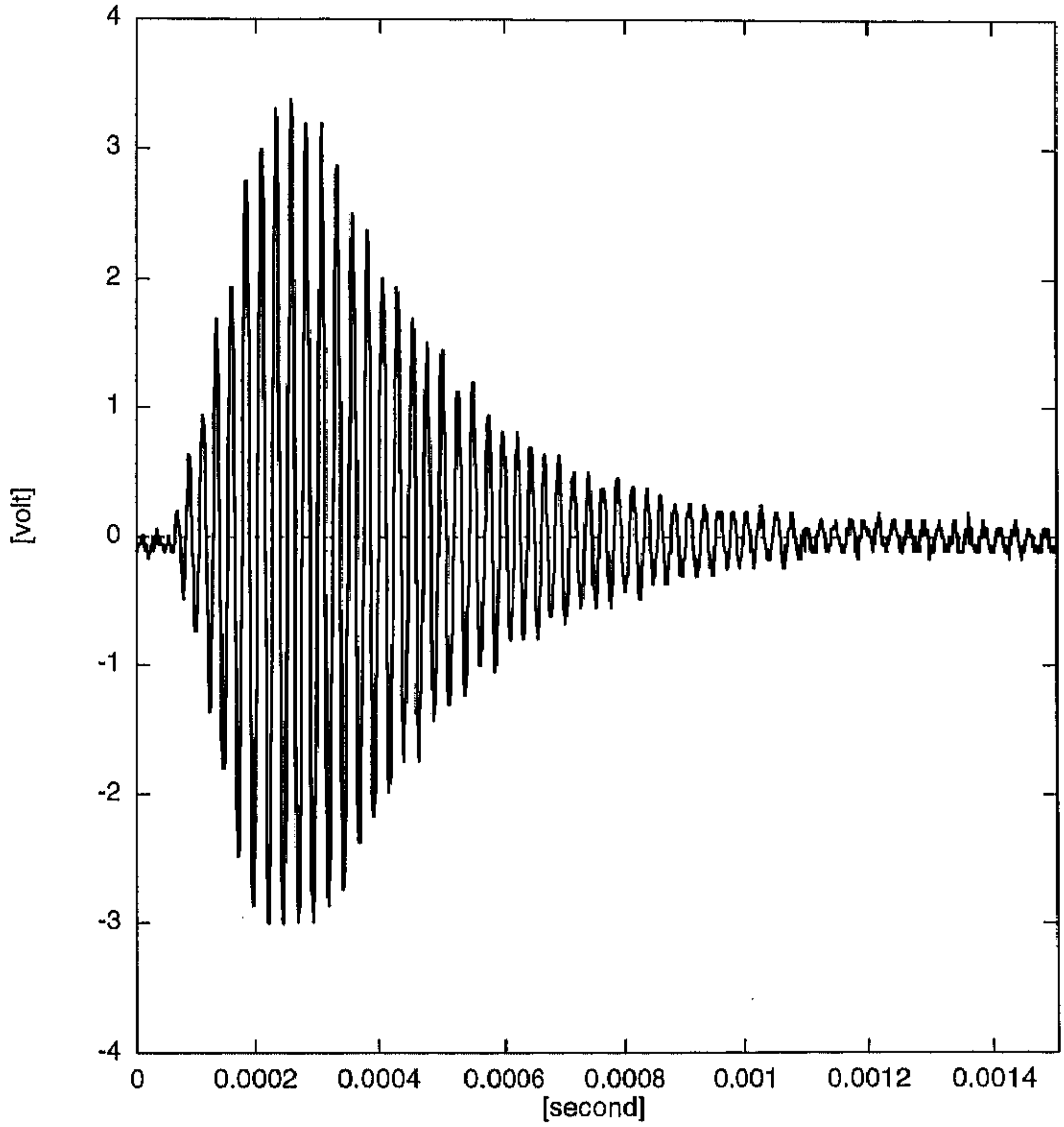

Figure 8.5: Sample received wave which was reflected on a pole at distance 1 meter when a transmitter was driven by a single pulse.

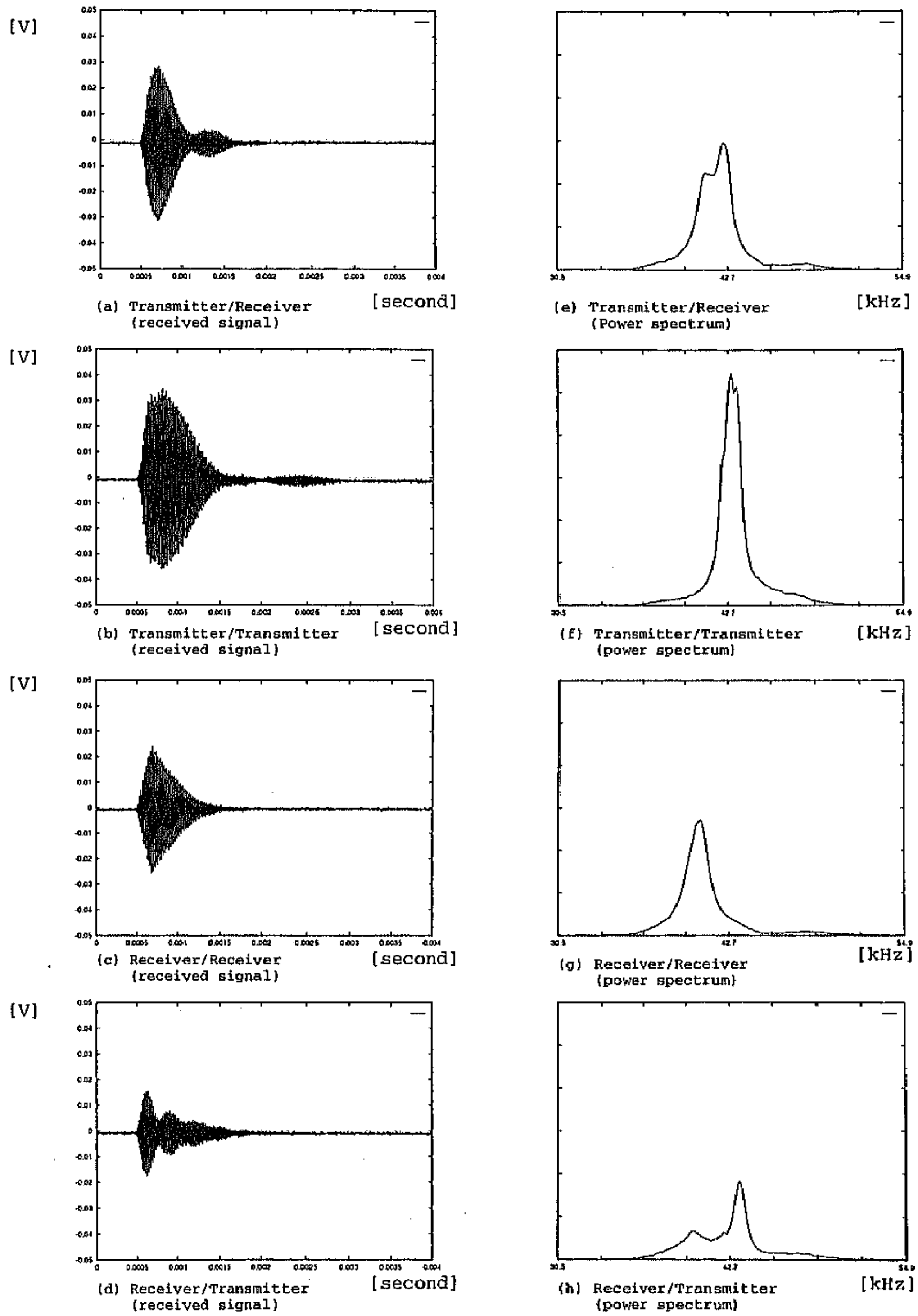

Figure 8.6: Received signal of transducers difference.

information is used for one wave length error correction explained in the next section. After that the amplified signal is compared with a threshold value at a comparator. The threshold value varies depending on time after transmitting pulse to avoid noise at near distance, especially direct wave from transmitters [Ohno 95].

The receiver circuit diagram is shown in Figure 8.8. It is also important to connect uniform polarity of transducers.

8.2.5 Omni-directional horn

An omni-directional horn was attached to avoid echoes from the robot itself or the ground. The horn effect to sharpen directivity and concentrate the power in the vertical axis, consequently it become possible to measure longer distance. Theoretically, a longer in length and wider in the cross-section of opening horn makes beam sharper [Murata 93].

Drawings of omni-directional horn is shown in Figure 8.9 and 8.10. Length was decided to be the longest considering size of the robot and transducers ring, opening was decided considering beam width of transducer, and exponential shape was selected, because it is one of the most popular shape [Negishi 92]. There are 60 holes to set transducers on a circumference which radius is 11cm, and transmitters and receivers are placed alternately. The material is polystyrene-form, and metal plates are attached top and bottom to support strength (Figure 8.11) [1].

8.2.6 Time-of-flight measurement

For measuring the TOF of each echo signal, the leading edge is detected. The leading edge gives the first rising part of echo wave. Since the proposed method is using the differences of leading edges among the different receivers, the accuracy of the TOF is very important in this method (Figure 8.12.) Thus, even when a narrow-band transducer is used, the echo signal should be amplified in the base band and should reach the comparator directly without envelope detection. Compared with wave shape processing methods, the circuit and process of this method is simpler and smaller. Since the proposed method uses multiple receivers simultaneously, simplicity of each receiver is important to reduce the total amount of circuitry. Therefore, TOF is time from transmission to leading edge of echo in this system.

8.2.7 30 channel 1bit wave memory

This new sonar-ring system have to achieve following two points simultaneously:

- Receive echo signal by multiple receiver simultaneously.
- Detect multiple TOFs in received signal at each receiver.

[1]This horn was produced by Mr. Eiji Koyanagi.

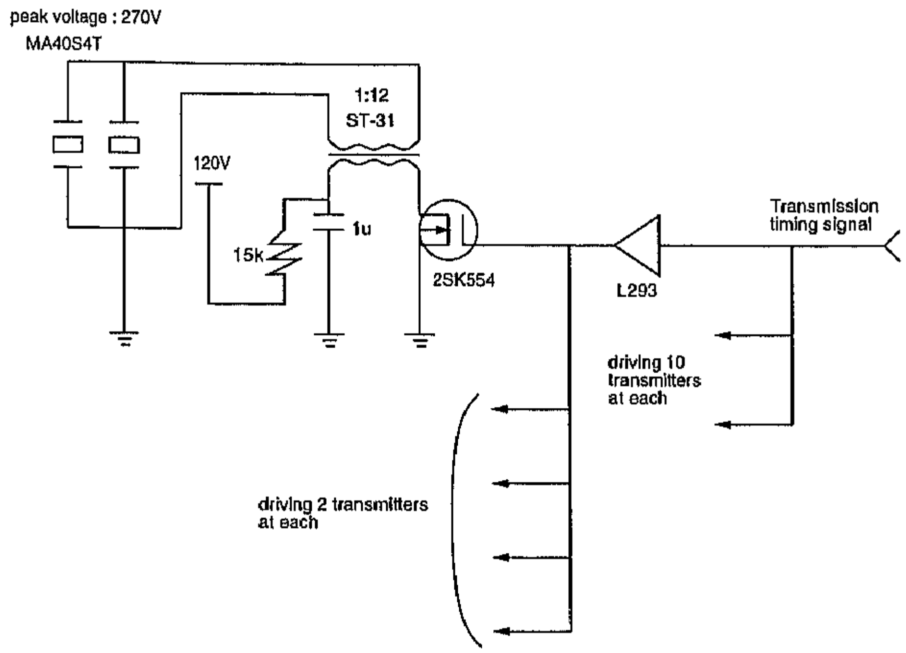

Figure 8.7: Transmitter circuit.

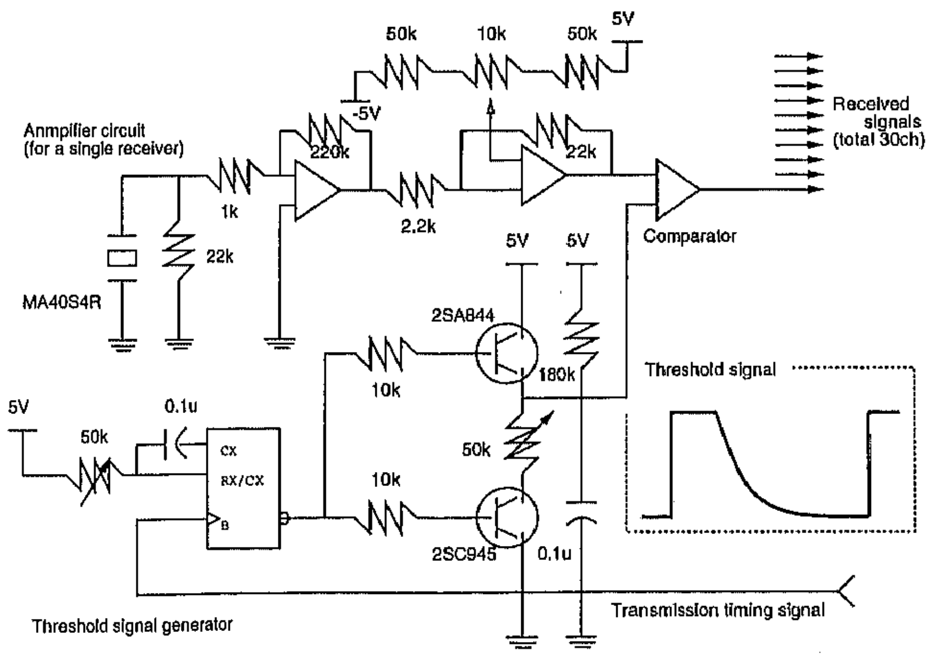

Figure 8.8: Receiver circuit.

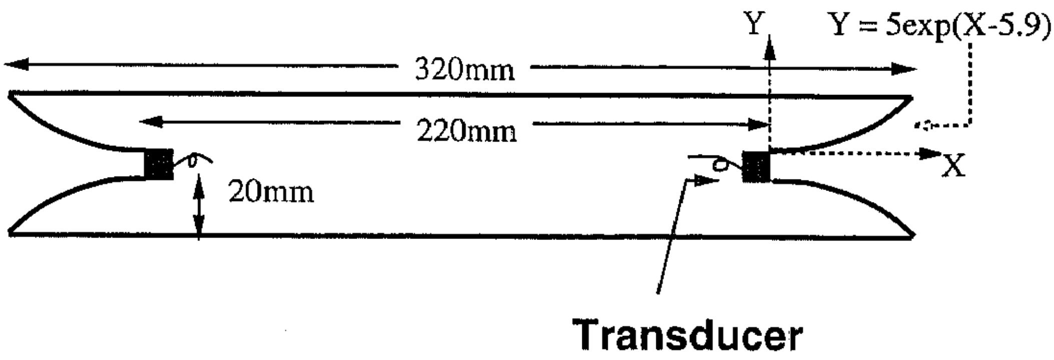

Figure 8.9: Omni-directional horn. (Side view)

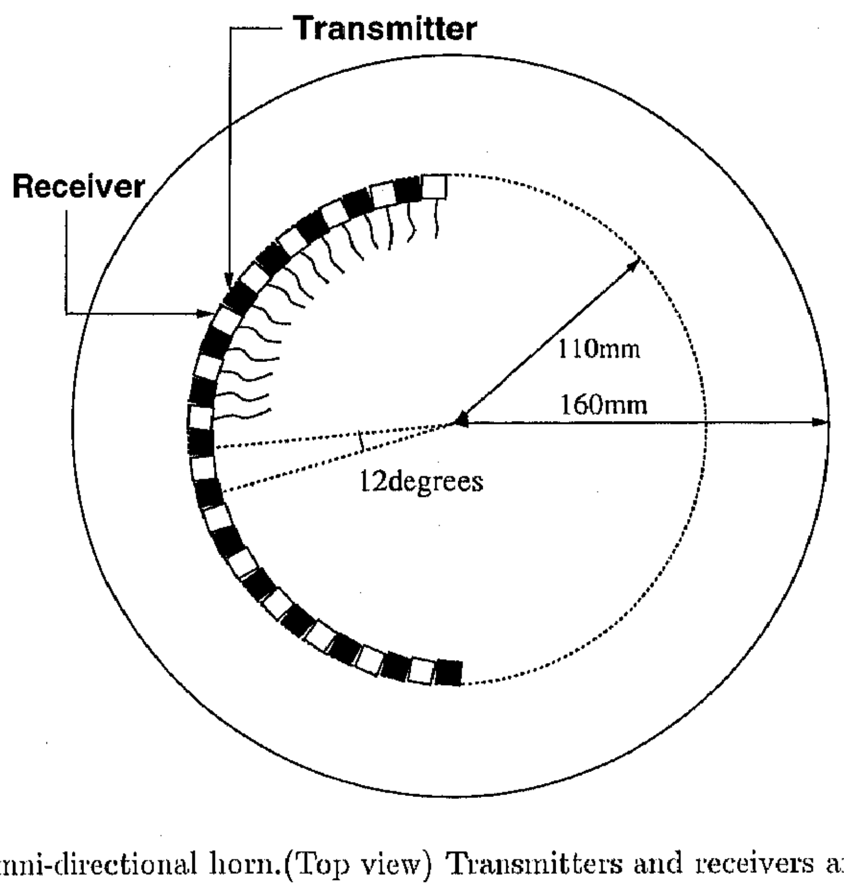

Figure 8.10: Omni-directional horn.(Top view) Transmitters and receivers are placed alternately.

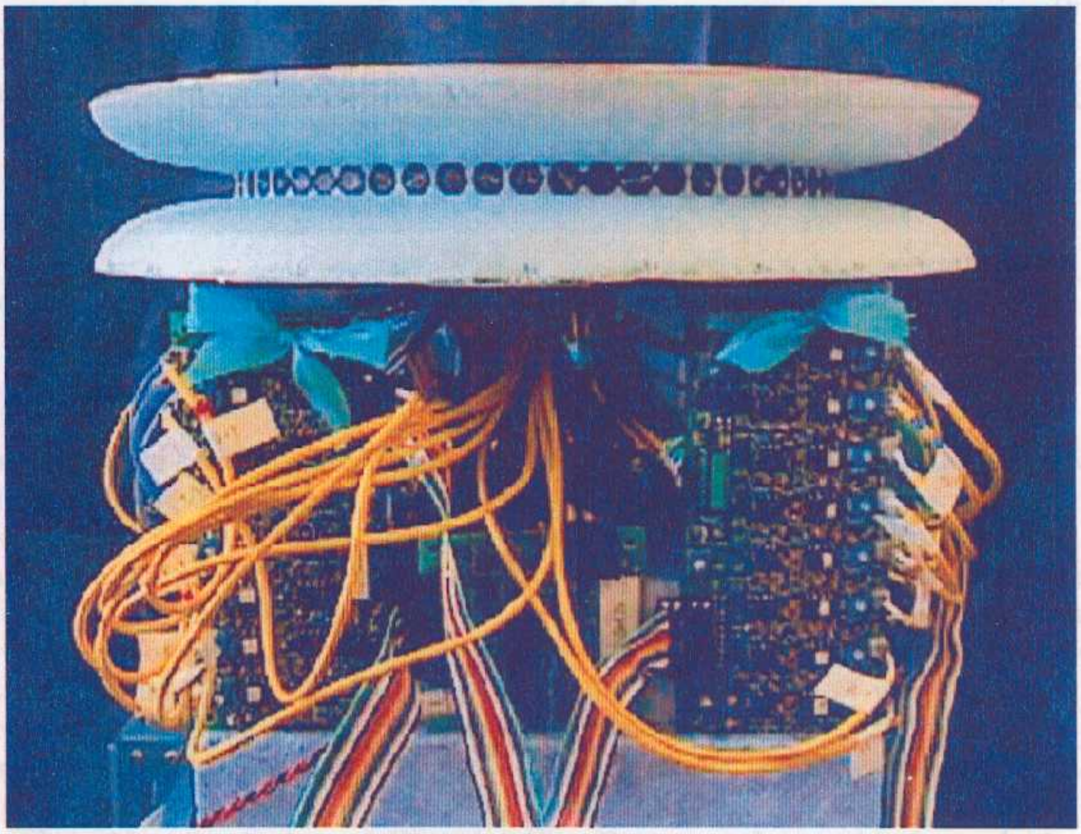

Figure 8.11: Omni-directional horn and its circuits.

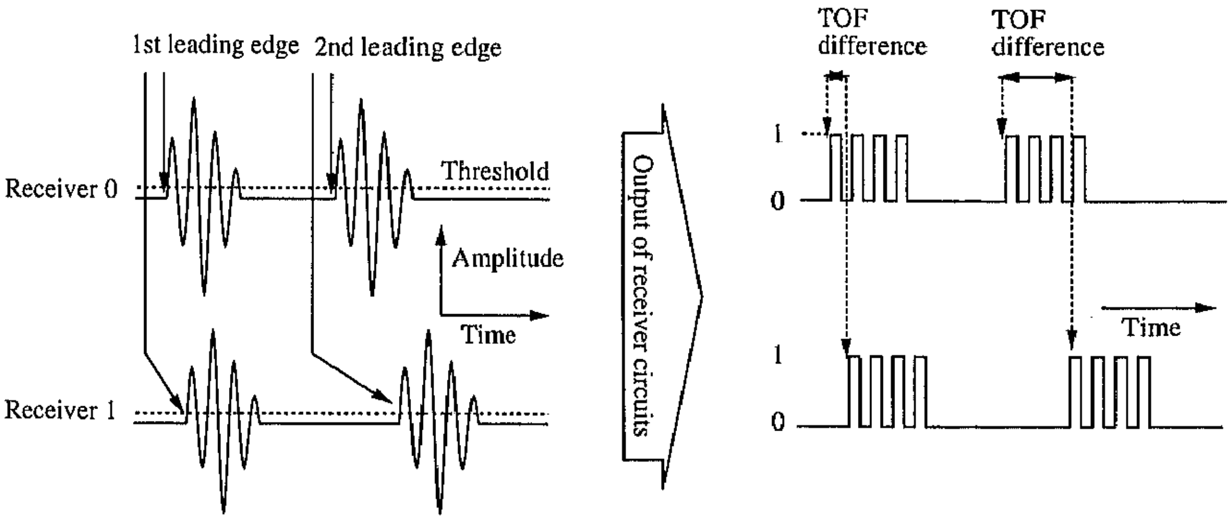

Figure 8.12: Informations of leading edges are detected by a threshold. So that, the differences of Time Of Flight can be measured from the binary data.

It is impossible to satisfy by conventional circuit for pulse-echo method which stops a timer by the first coming back echo.

Use of wave memory is one of solution for detecting TOFs of multiple echoes. Multi channeled wave memory is required to detect TOFs of multiple receivers simultaneously. Furthermore, it is necessary to mount on the robot to use it during the robot is moving. However, it is not necessary to have ordinal regular wave memory which has large capacity at each channel, and when number of channel increase, size of which get very huge. Consequently, it became difficult to implement it on the robot.

As explained, use of a threshold value is useful to detect leading edges easily. When the threshold value is used to detect the leading edges, the signal is already binarized and it is just a one bit at each channel (Figure 8.12). Consequently, one bit for each channel is enough capacity when leading edges of echoes are detected by using a threshold value.

Accordingly, I constructed a memory system which can simultaneously record 30 channels wave data which is binarized by a threshold at receiver circuit in parallel. The system assigned one bit for each receiver and 30 bits from 30 channels data are written on the memory as one word simultaneously. A counter which increment each 1 microsecond (1MHz) is attached for generating address signal. This is a binary wave memory with 30 channel for 32k words within 1 microsecond sampling (measurable range is 5m) as shown in Figure 8.14. This memory can access from CPU anytime but writing received data (Figure 8.13). The circuit was implemented on the main board of the robot which uses Transputer as CPU (Figure 8.15). This system can record 30 receivers data in parallel, and it is possible to implement and use on the robot easily.

8.3 Software

At first, TOFs are measured by detecting leading edges from data of 30ch 1bit wave memory which has been explained above. TOFs of multiple echoes from multiple objects should be detected at each channel in this method. Those detected multiple TOFs at each receiver are grouped corresponding to each object. And then, reflecting points on each object are calculated at each group. Here, I explain each part of these process, and process to treat one wave detection error.

8.3.1 Multiple echoes detection

For the purpose of detecting objects in the full directions, it is necessary to detect echoes from multiple objects, not only from the nearest object in each receiver. This is also very important to detect second and third objects, in case of using wide directivity transducers. Because possibility of more objects are in the beam width increase.

Leading edges are detected from binary wave signal. The binary wave signal is generated at receiver circuit from output of receiver and a threshold at receiver circuit as explained part of receiver, and is time sequence signal starting with a transmission signal.

The first leading edge, leading edge of the first echo, can be detected as same way as conventional ultrasonic sensors. The time which the wave signal turn high firstly is the time of the first leading edge (Figure 8.16).

It is necessary to detect end of the fist echo block to detect the next leading edge. In this system, envelope of the received echo is not detected for the purpose of keeping wave information, consequently the end of the echo block can not be detected directly. However, frequency of transducer is known and the binary wave signal remains the frequency information. For that reason, it can be regard the first echo block has ended when the low level continued for more than half wave length period in time since the signal turned from high to low. After detecting the end of the first echo, the next echo can be detected by the same method as the first one.

A deficiency of this method is that overlapping of echoes causes hiding of reflecting points which are near by. The size of the hidden area is depending on the directivity of the each receiver and the duration of the echo pulse and it might not be small. This makes it difficult to apply this system to more complicated environment. This is a kind of occlusion problem in ultrasound sensing, and this problem is discussed at part of discussion later.

8.3.2 Correspondence to objects

Multiple receivers are used simultaneously and multiple TOFs are detected by each receivers in this system, and accurate reflecting points are calculated from difference of TOFs reflected

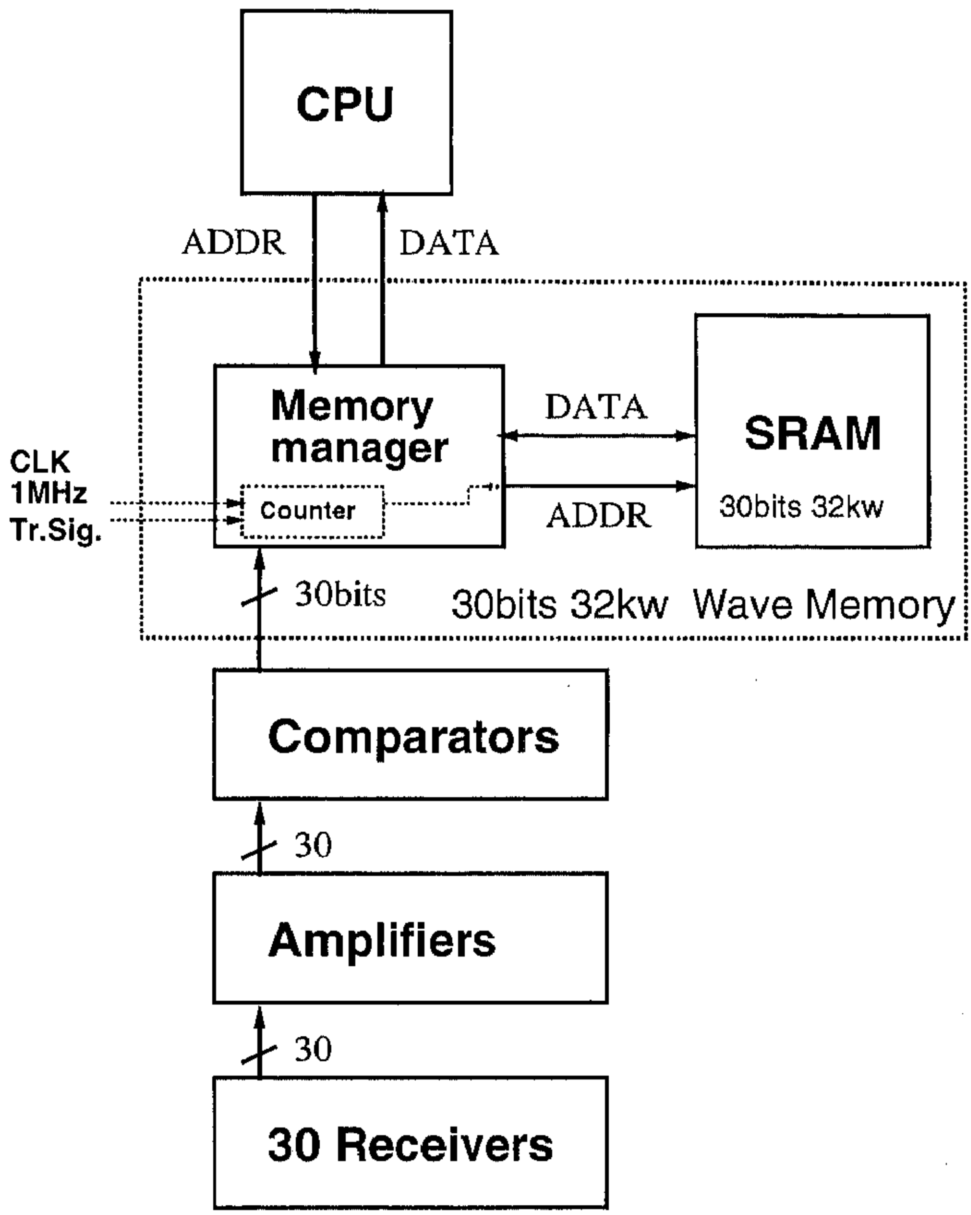

Figure 8.13: A 30ch 1bit wave memory system.

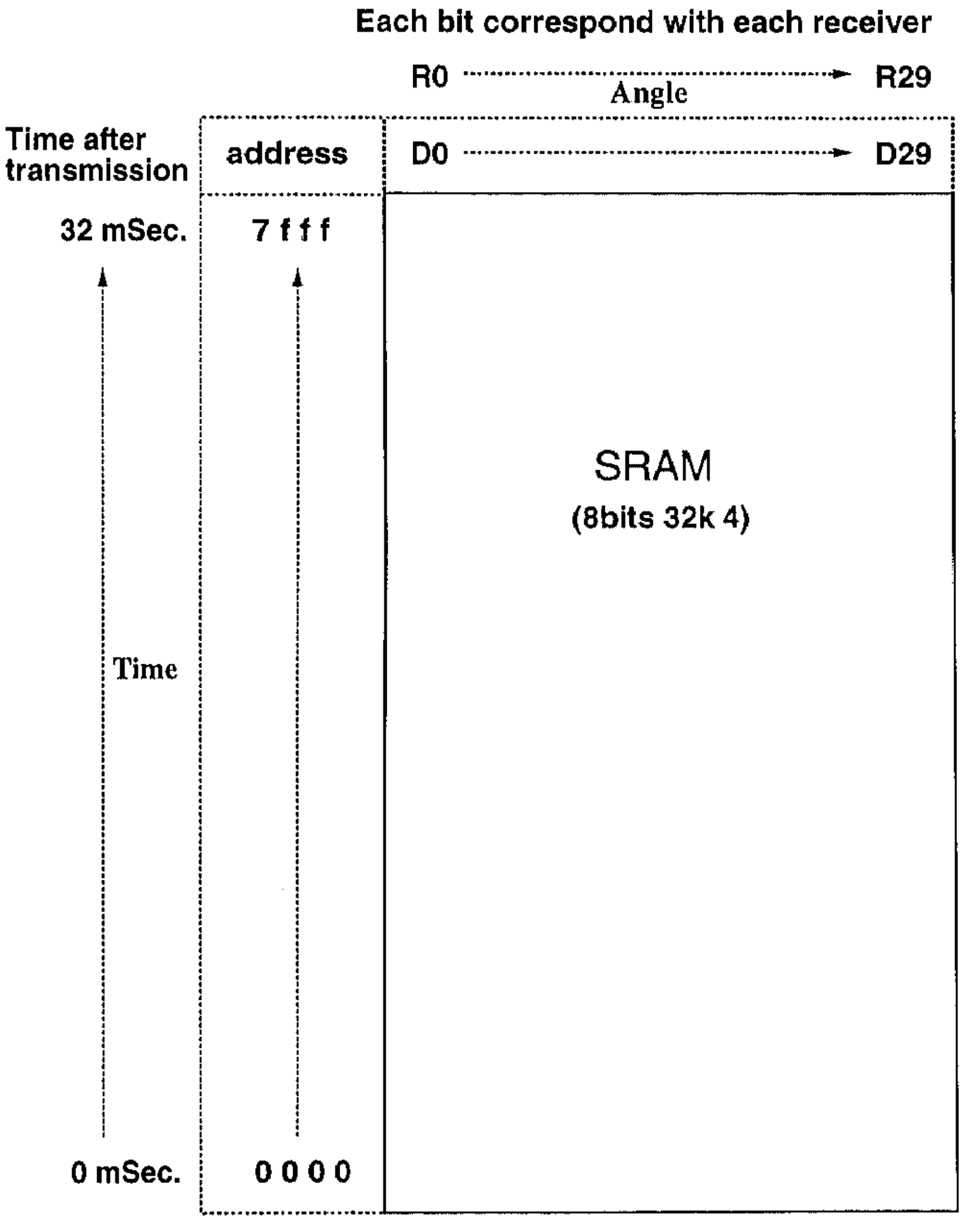

Figure 8.14: A 30ch 1bit wave memory system.

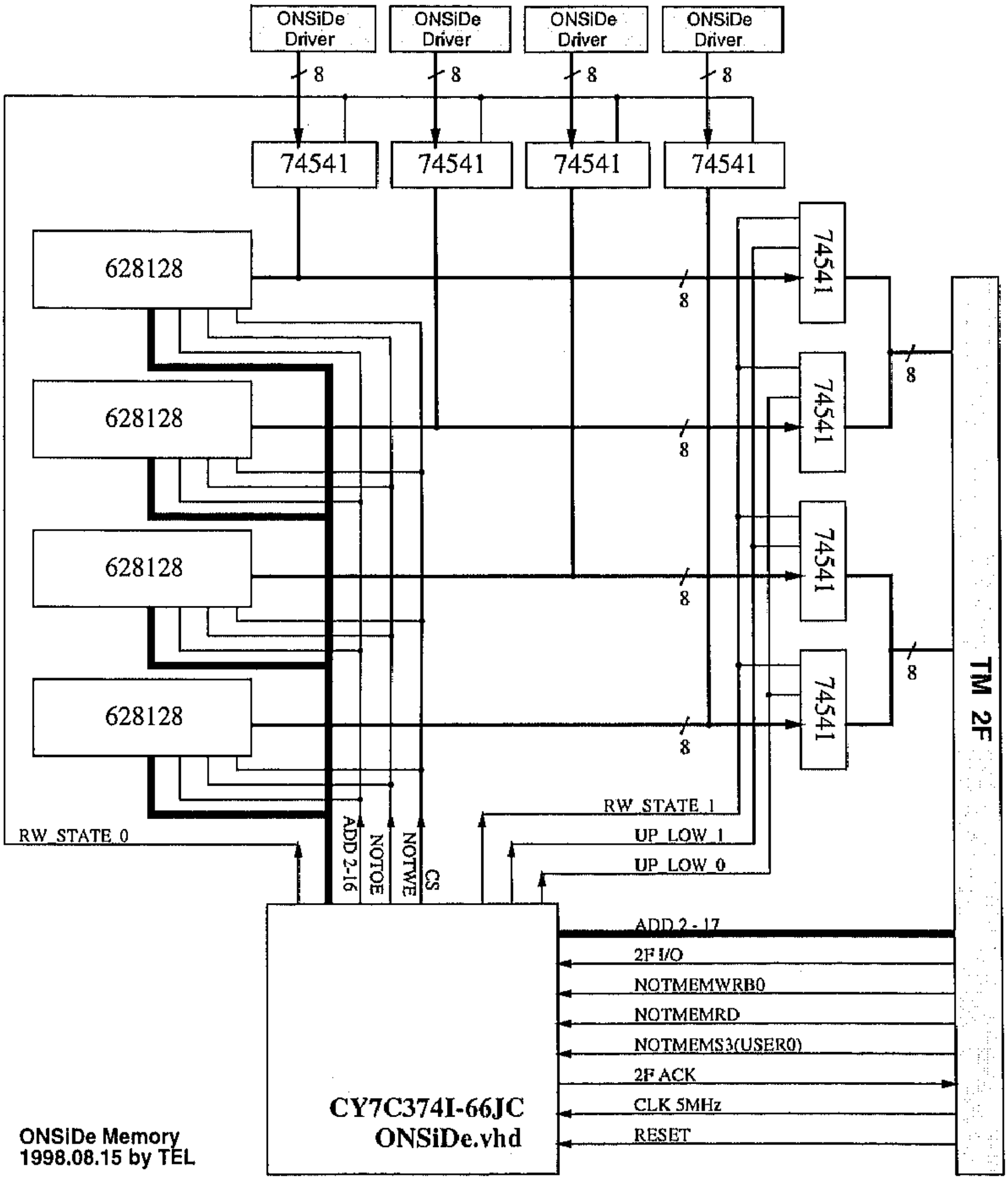

Figure 8.15: A 30ch 1bit wave memory system (detailed diagram.)

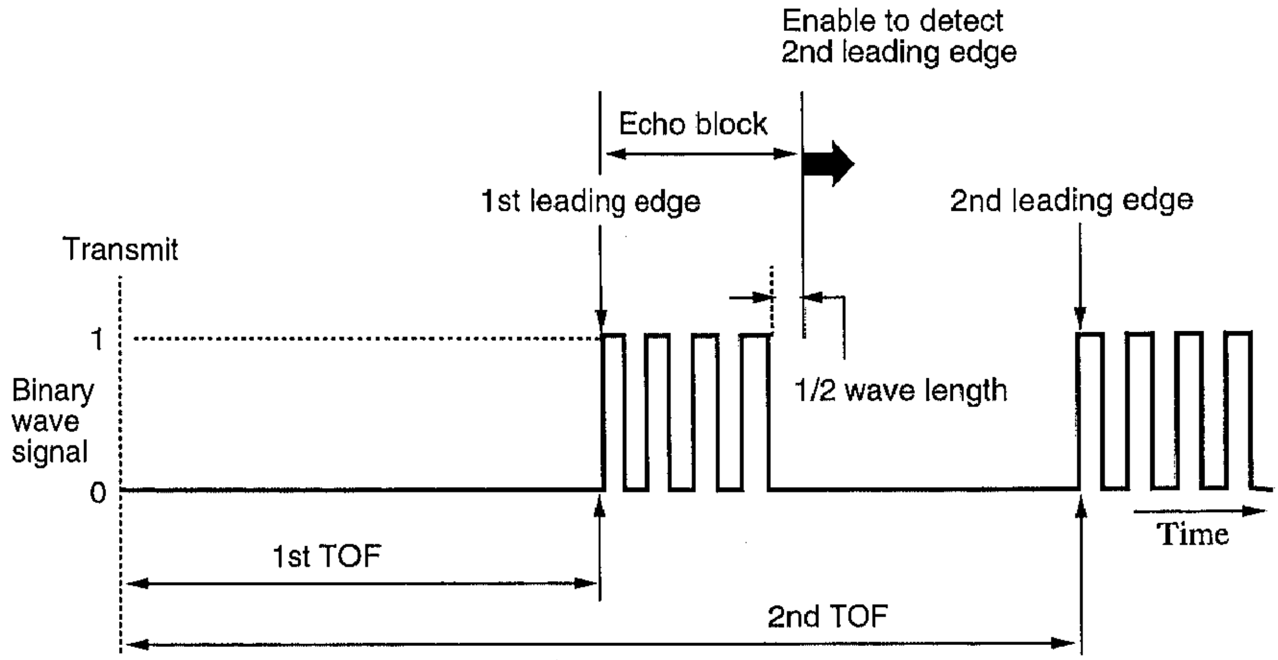

Figure 8.16: Multiple TOF measurement from memory data using leading edges.

from the same object and detected at different receivers. In order to calculate the reflecting point, TOFs should be grouped corresponding to the reflection object (Figure 8.17).

The TOFs of echoes which were detected by all receivers should be classified into groups, one for each reflected object (Figure 8.17). For this purpose, TOFs measured at receivers are grouped by using the conditions that the difference of TOFs of the neighbor receivers are less than ε, at first. Here, with considering one wave length error which is explained in the following section, $\varepsilon = 1.25T + T_0$. Where T is one cycle time of the ultrasound wave, and T_0 is the TOF difference between two receivers. They are candidates for a TOFs group which are coming back from the same object.

Then, those TOFs are checked whether they are coming back from the same object by fitting with formula for calculating distance and angle which explained in the next section. If the data of the TOFs group do not fit with the formula, select those TOFs only which fit, and redefine the TOFs group which can be assumed coming back from the same object.

8.3.3 Calculation : distance and angle

Based on the assumption that the reflecting object has the property of specular reflection, the propagation pass of ultrasound is modeled using the ray-tracing method [Kuc 87] (Figure 8.18). Then we apply the model to the proposed sonar-ring. Transmitting an ultrasonic pulse to all directions is regarded as a transmission from a single point source in two dimensions.

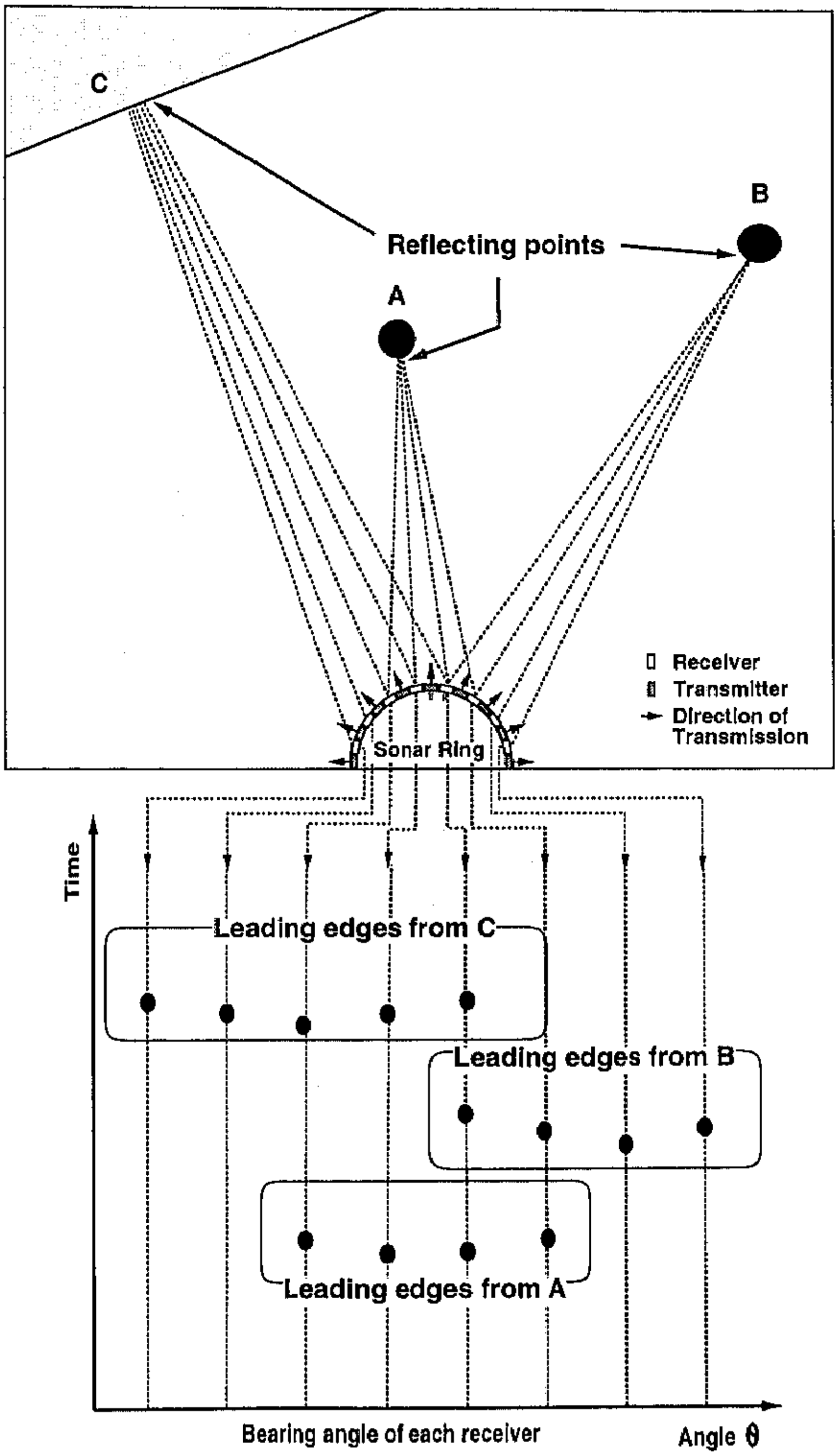

Figure 8.17: Relationships between reflecting points in an environment and observed echoes at each receiver. The bottom graph shows received echo signals at each receiver which are lined in bearing angle θ. The echoes coming back from a same object are appear close in time among close receivers.

Here, we assume that the reflecting object is located at direction θ_0 and distance L from the center of the sonar-ring.

Case I – a point reflecting object in two dimensions (eq. a corner edge of the wall): The propagation path of the ultrasound from the center of the ring to a receiver placed at direction θ via the reflecting object is modeled as shown in Figure 8.18(a), the propagation distance from transmitter to receiver is given as follows:

$$d_{point}(\theta) = \sqrt{L^2 + R^2 - 2LR\cos(\theta - \theta_0)} + L - R. \tag{8.1}$$

R is the radius of the sonar-ring.

Case II – a plane reflecting object : The propagation path can be considered using the mirror model as shown in Figure 8.18(b). The propagation distance is equal to the distance from transmitters of a virtual sonar-ring located at symmetrical point of the real receiver, and is given as follows:

$$d_{plane}(\theta) = \sqrt{(2L)^2 + R^2 - 4LR\cos(\theta - \theta_0)} - R. \tag{8.2}$$

Those formulas are approximated to Formula (8.3), when $L \gg R$ and $|\theta-\theta_0|$ is reasonably small, eg. $|\theta - \theta_0| < 45$degrees.

$$\begin{aligned} TOF(\theta) &= d_{approx}(\theta)/c \\ &= \frac{2(L-R)}{c} + \frac{LR}{c(2L-R)}(\theta - \theta_0)^2. \end{aligned} \tag{8.3}$$

where c is the velocity of sound.

Consequently, when the TOF for the same object are measured at several receivers, the distance and direction to each reflecting object are calculated by finding the appropriate values of L and θ_0 of Formula (8.3). The concrete processes are as follows.

The TOFs of echoes which were detected by all receivers should be classified into groups, one for each reflected object (Figure 8.17). For this purpose, TOFs measured at receivers are grouped by using the conditions that the difference of TOFs of the neighbor receivers are less than ε, at first. Here, with considering one wave length error which is explained in the next section, $\varepsilon = 1.25T + T_0$. Where T is one cycle time of the ultrasound wave, and T_0 is the TOF difference between two receivers. They are candidates for a TOFs group which are coming back from the same object. Then, those TOFs are checked whether they are coming back from the same object by fitting with Formula (8.3). If the data of the TOFs group do not fit with Formula (8.3), select those TOFs only which fit, and redefine the TOFs group which can be assumed coming back from the same object.

Calculate angle and distance to the reflecting point by fitting TOFs of the same objects with Formula (8.3), and finding L and θ_0 (Figure 8.19). Fit the formula to TOFs which are measured more than three receivers using the least squares.

8.3.4 One wave length error

In this method, the same wavefront of the reflected echo must be detected by different receivers when measuring the TOF using the leading edge, for an example, the difference

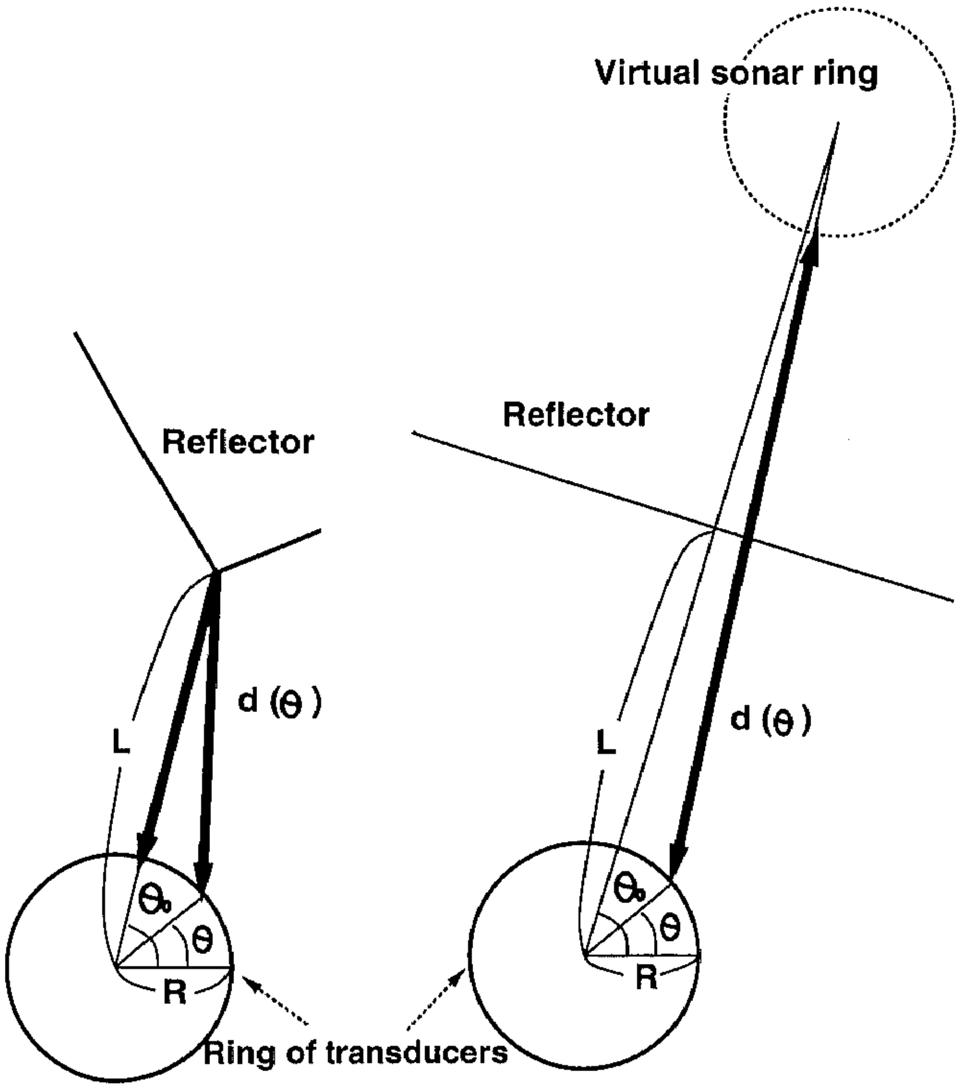

Figure 8.18: Ultrasound propagation model. When a target is a point reflecting object as like pole or edge, propagation pass of ultrasound is shown in (a). When a target is a plane reflecting object as like wall, propagation pass of ultrasound is shown in (b).

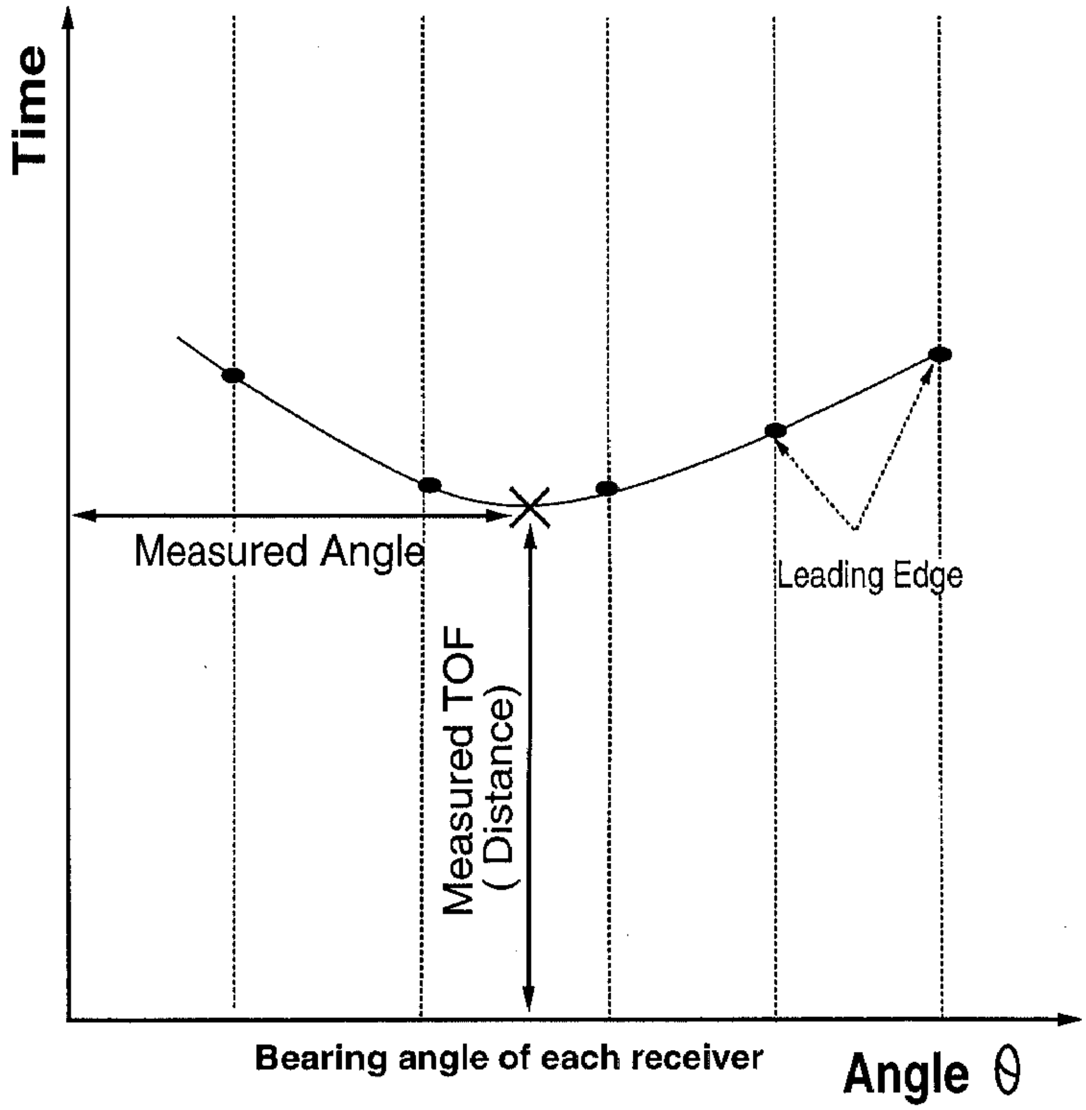

Figure 8.19: Measured bearing angle and distance are a minimum point of quadratic function fitted with detected leading edges. Bearing angle and distance are calculated using Formula (8.3).

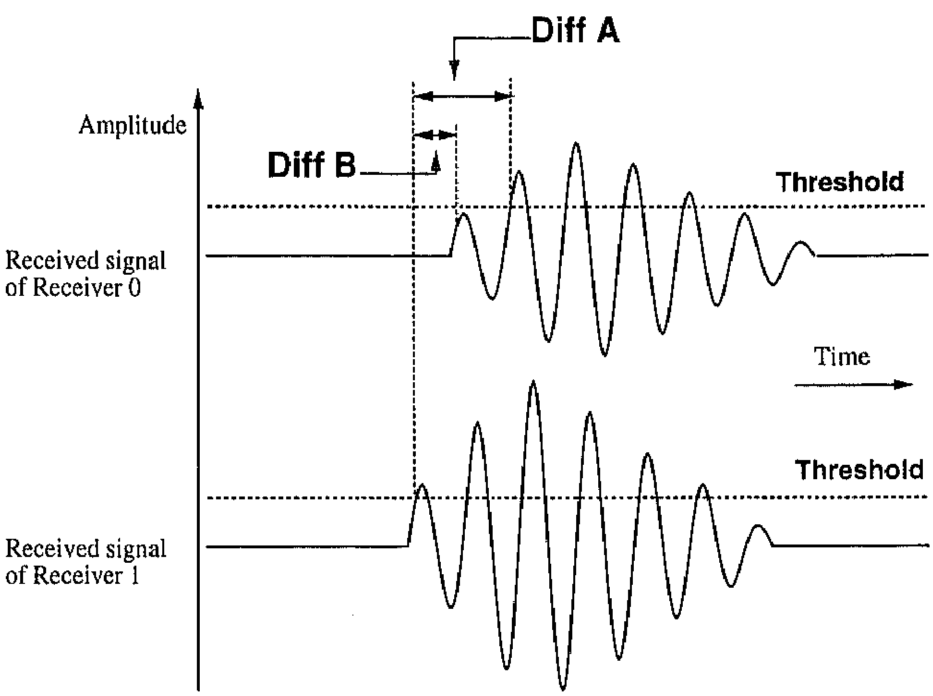

Figure 8.20: To measure the accurate bearing angle, the difference of the corresponding leading edges should be measured between the receivers (Diff B). The difference of the received echo amplitudes between the receivers causes the failure to detect the corresponding leading edges (Diff A).

"Diff B" in Figure 8.20 should be detected. When the leading edges are detected with a threshold level, small amplitude difference at each receiver can cause one ultrasonic wave length detection error "Diff A," as shown in Figure 8.20. Since, this type of error is discrete as shown in Figure 8.20, the difference between "Diff A" and "Diff B" is almost equal to an integer times wave period. Therefore, it is easy to detect and correct a few wave length errors with a good reflection model when more than three receivers detect the echo (Figure 8.21).

8.4 Summary

In this chapter, I explained the system design of the proposed fast and accurate direction measurable sonar-ring sensor to implement on the real mobile robot. This system is constructed by the hardware parts and the software parts. As for the hardware, the mobile robot itself, the transducers, the omni-directional transmission circuits, the simple parallel

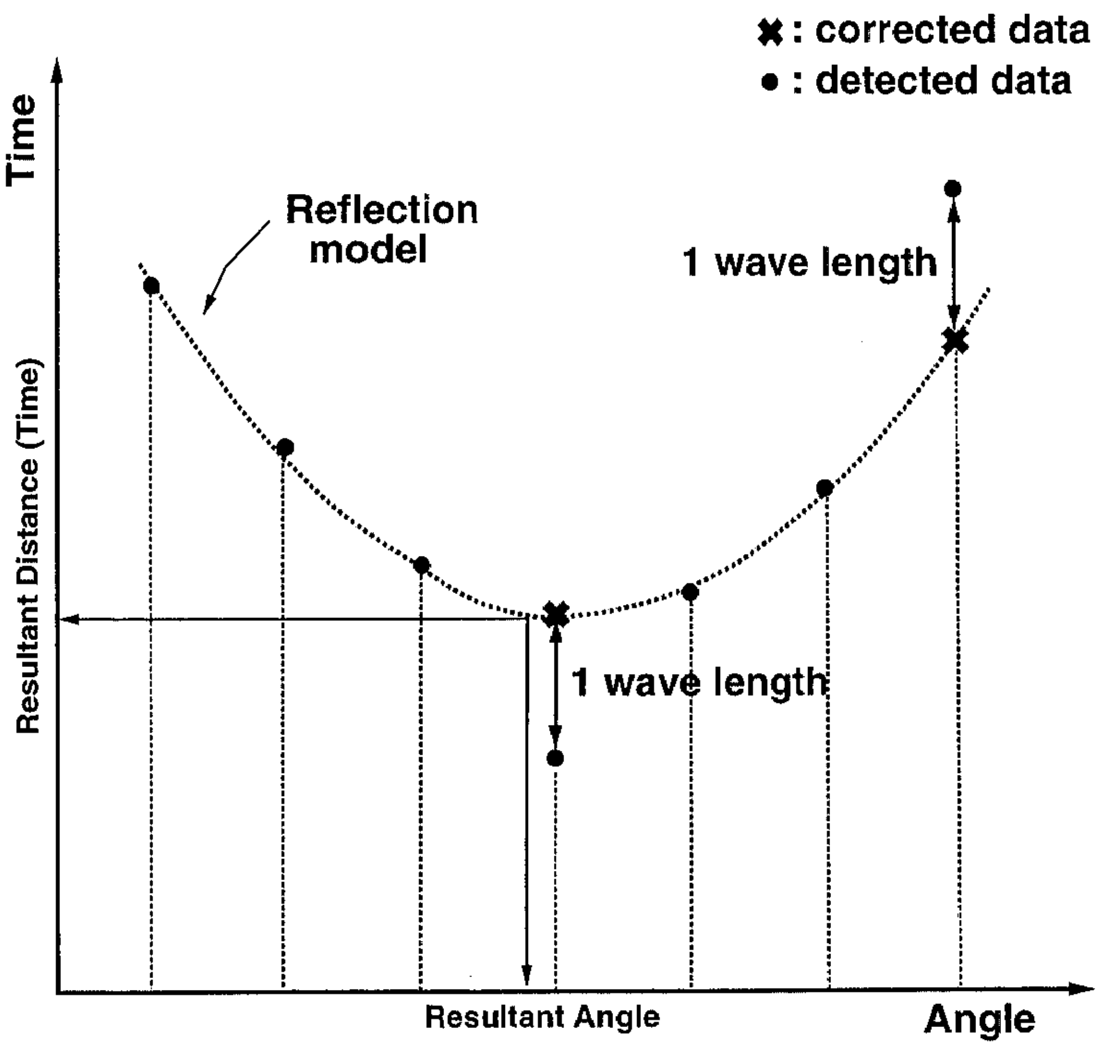

Figure 8.21: One wave length error can be corrected by reflection model.

receiver circuits, the special horn which designed to avoid reflection from the robot itself and from ground and the small sized 30ch 1bit wave memory are necessary. Also, as for software process, to measure TOFs, to detect multiple objects, to calculate accurate positions of each object, to overcome the expected errors are necessary.

I have implemented this system on a mobile robot and experimental result which used this system are shown in a following chapter.

Chapter 9

Experiments of direction measurable sonar-ring

In this chapter, the experimental results of effect of the horn and omni-directional transmission are shown at first, and an experiment showing bearing angle measurement accuracy is explained. And then I will show two types of environment recognizing experiments at simple environment placing boards and poles and at real corridor in our university building, which were performed to know its ability of application.

9.1 Evaluation experiments

I examined effect of originally designed omni-directional horn and omni-directional transmission by driving all transmitter simultaneously, at first. And then, I evaluated directional accuracy which is a strong point of this system. Processing speed is also discussed.

9.1.1 Omni-directional horn

Effect of omni-directional horn which has been designed to reduce reflection from the robot itself and ground was tested comparing power of transmission from a single transmitter with the horn and without the horn. A single transmitter was driven by 270 Volts pulse. Direct wave of the transmission was received at distance from the transmitter. The peak voltage of the received signal was measured scanning the receiver to horizontal direction and vertical direction at distances as shown in Figure 9.1(c).

The result is shown in Figure 9.2. Comparing results measured at front of both transmitter, I could observe the voltage with horn is higher which means that it is succeds to concentrate the power into the middle part. Moreover, in case of not using horn, comparing results on horizontal and vertical directions, they are same as shown in Figure 9.2(a)(c). However, they are very different in case of using the horn (Figure 9.2(b)(d)), and it is successfully concentrating the power into two dimensions of the ring which transducers are placed.

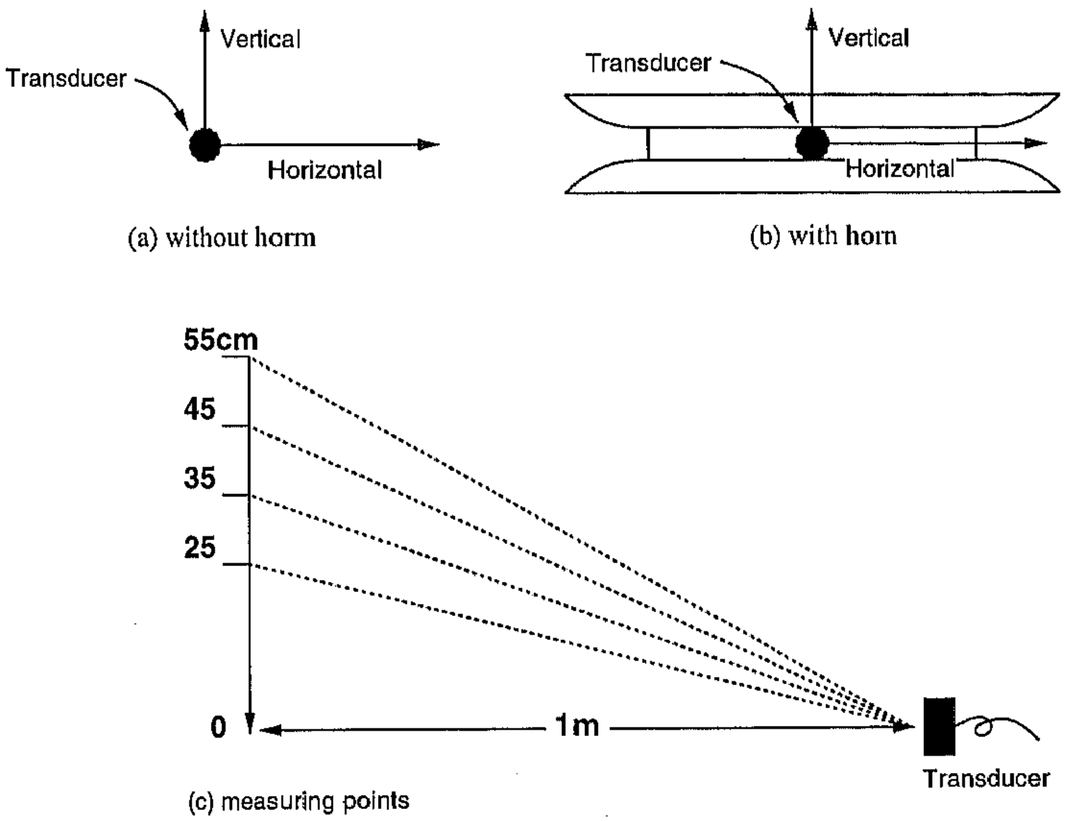

Figure 9.1: Evaluation of horn. Direct wave of the transmission was received at each point shown in (c). Definition of vertical and horizontal directions with respect to transducers are shown in (a) and (b).

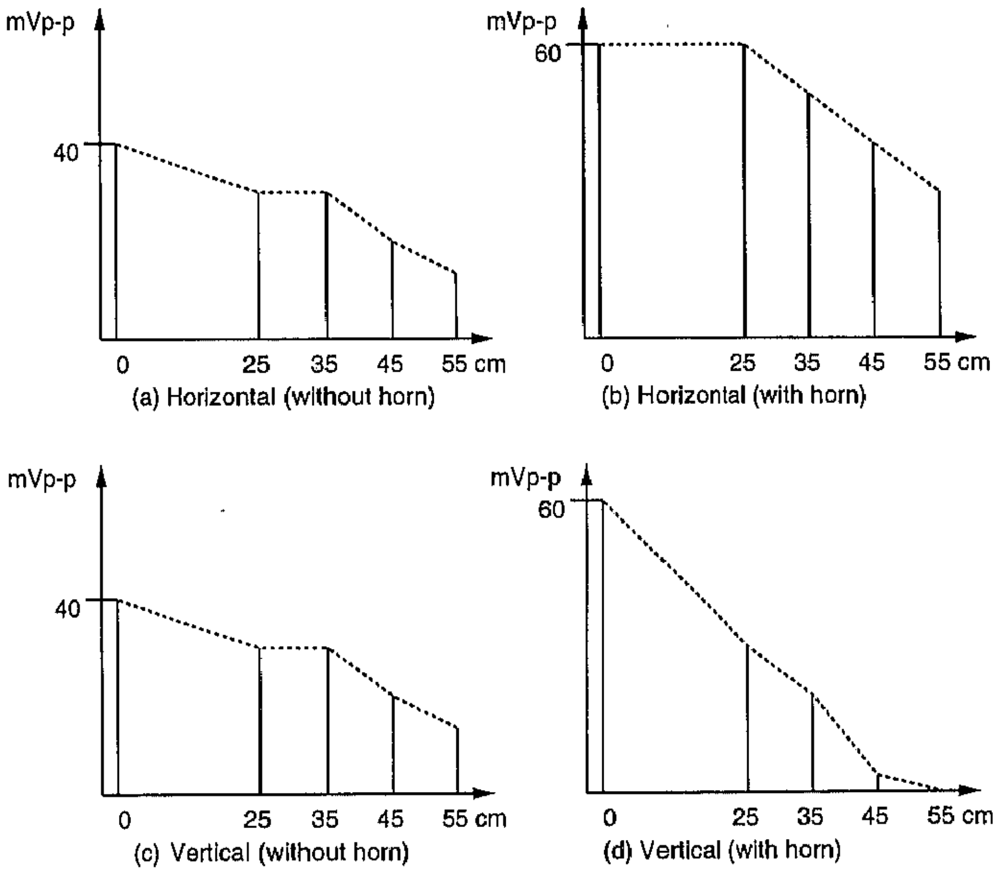

Figure 9.2: Experimental result of horn efficiency. (a) and (c) are showing peak voltage of direct wave transmitted without using the horn. (b) and (d) are showing peak voltage of direct wave transmitted with the horn in horizontal and vertical direction scan respectively.

9.1.2 Omni-directional transmission

For knowing the ultrasonic pulse is transmitted radially, the direct transmission was received at distance 1.5m from the center of the robot. In this experiment, 30 transmitters connected electrically was driven as explained at the part of hardware. As the result, according to the rotation of the robot, there were about two times difference of amplitude, but there were not phase difference.

9.1.3 Accuracy

For evaluating directional accuracy, a columnar object which is 50 millimeters in diameter was placed at distance 1.5 meters and the robot with the sonar-ring was rotated every one degree for 60 degrees and measured directions at each point.

The experimental result is shown in Figure 9.3. The horizontal direction shows rotation angle of the robot and vertical direction shows measured angle of direction in this experiment. According to an experimental result maximum error of bearing angle measurement was ±0.8 degrees and RMS value of it was 0.41 degrees.

9.1.4 Processing speed

Considering how long it require to complete one cycle measurement – this also means how long it takes to measure all around the robot because this system can measure all around the robot in a single measurement cycle, processes can be divided into following three steps.

1. Wait echo signal – It is about 30 milliseconds which corresponding about 5 meters in propagation distance. Received signals are written in memory simultaneously. It is impossible to reduce this time because it depends on speed of sound.

2. Detect leading edges – It needs to scan all memory data which is 32bits 32 kiloword once to detect leading edges, and it extract maximum about 100 points leading edge data. It is not necessary to do any extra process for the data, hence this part is almost equal to memory access time.

3. Calculate – It finds reflecting points using about 100 points data.

As the result, the first, the second and the third steps process can be done in 30 milliseconds, and at latest case one cycle takes 60 milliseconds after transmission. In case of using two memory sets alternately, it is also possible to update the data each 30 milliseconds. Considering speed of indoor mobile robots, it is possible to say real-time operational system.

9.1.5 Discussion

In this section, fundamental validity of the proposed system were examined by experiments. Effectiveness of omni-directional transmission and good accuracy of directional measurement

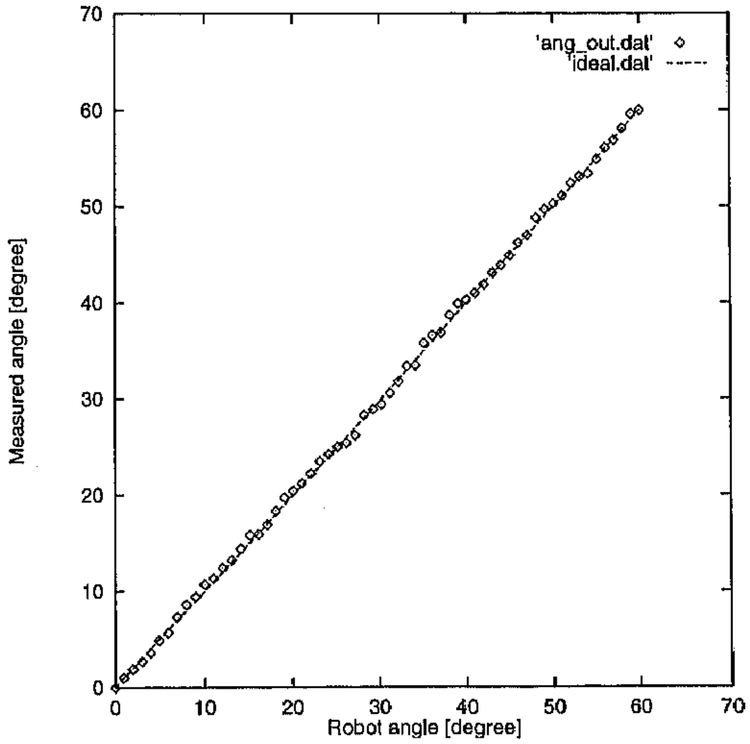

Figure 9.3: Measured bearing angle in the prototype system. The horizontal axis shows rotating angle of the robot and the vertical axis shows measured angle.

were confirmed by experiments, and also processing time was discussed and concluded as it is possible to do real-time operation.

Furthermore, I would like to discuss an occlusion problem which can not be avoid in pulse-echo method ultrasonic sensing and whether it is possible or not to distinguish shape of the object using difference of propagation models, because they are frequent asked questions.

Occlusion in ultrasonic sensing

As shown in the section of hardware, echo signal has its duration for a certain period in time. When two reflecting objects are distant enough, echoes from them are observed as two independent echoes. However, when two reflecting points are near by, a leading edge of echo might be hidden by duration of another echo, and in this case, the hidden leading edge can not be detected, and consequently it fail to detect the reflecting point. This is essentially unavoidable problem and we can say this is occlusion problem in pulse-echo ultrasonic sensing.

The shape of received echo wave in pulse-echo ultrasonic sensing is strongly dependend on input signal and transducer [Kuc 87]. Even a single pulse is an input signal, it is impossible to avoid duration of echo signal because of transducer.

For example, MA40S4 transducer which is used in this system was driven 270 Volts single pulse, and received the echo from a pole at distance 90 cm from the transducer is shown in Figure 9.5. This echo signal has duration for about 1 m-second, which correspond to about 17 cm. In this case, it should be distant more than 17 cm in distance from transducer for detecting another echo with this receiver.

As explained before, a single pulse-echo ultrasonic sensor can not get directional information. For that reason, occlusion area can be shown as in Figure 9.4. Where, W is beam width of transducer, and D is distance calculated from duration of echo. The occlusion area can be defined as fan-shaped area A. This means, because of existence of the pole, it become impossible to detect other objects in the fan-shaped area A.

Object shape recognition

Potential of object shape recognition is discussed with experiments. This topic is not main function of this system, but this is an answer for frequently asked question – whether it is possible or not to distinguish shape of the object which reflecting point is on, because a quadratic function approximated propagation model of plane and point reflector is used in this system.

As explained before, based on an assumption that reflecting objects have property of specular reflection, propagation passes of ultrasound are modeled using the ray-tracing method [Kuc 87] (Figure 9.6).

In case of a point reflection as shown in Figure 8.18(a), the propagation distance from transmitter to receiver is given as follows:

$$d_{point}(\theta) = \sqrt{L^2 + R^2 - 2LR\cos(\theta - \theta_0)} + L - R. \tag{9.1}$$

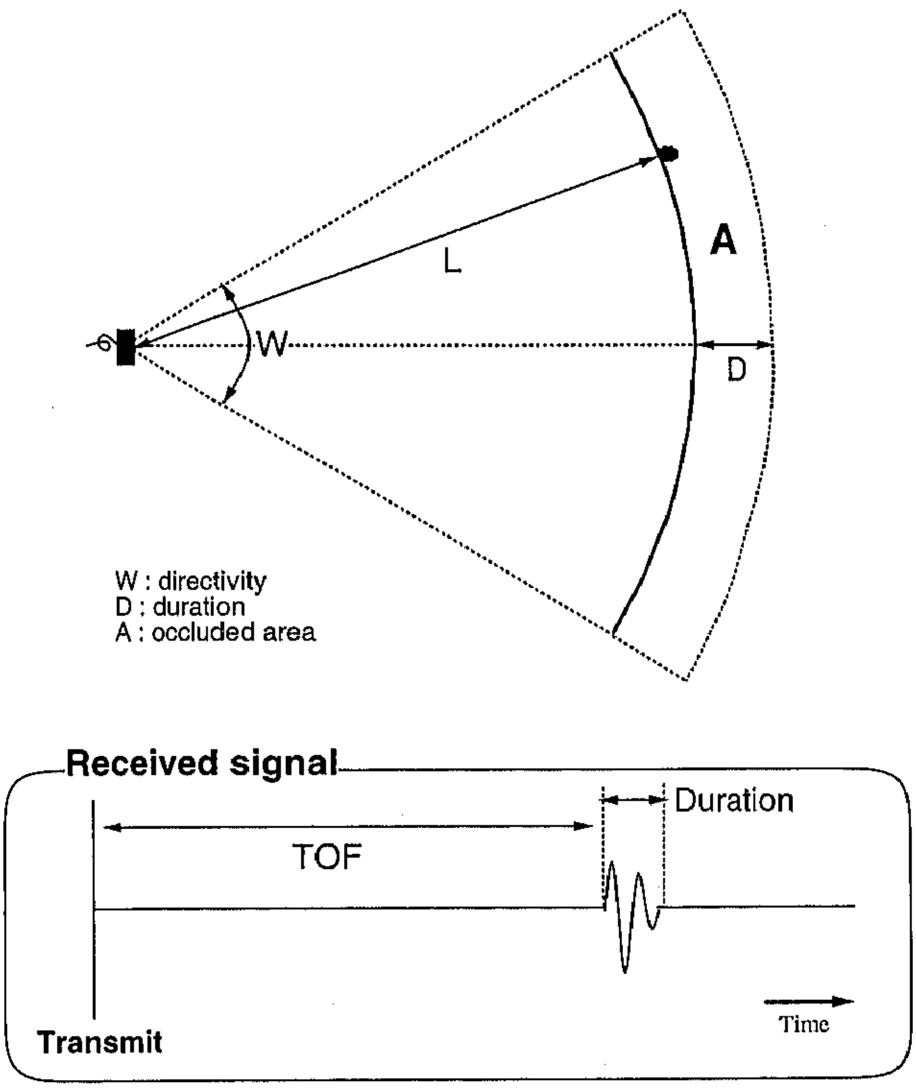

Figure 9.4: Occluded area depends on duration of the echo and directivity of the transducer.

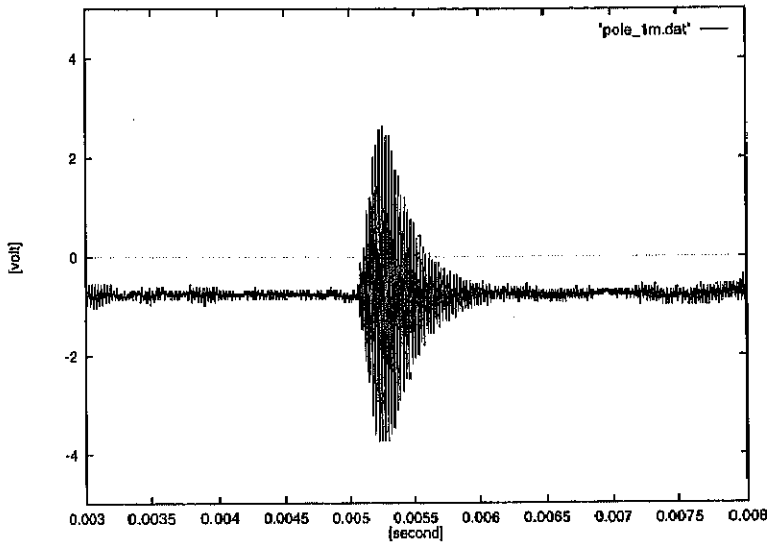

Figure 9.5: Received echo single from a pole at distance 1m from the sonar-ring.

R is the radius of the sonar-ring. Here, we assume that the reflecting object is located at direction θ_0 and distance L from the center of the sonar-ring.

In case of a plane reflection as shown in Figure 8.18(b), The propagation distance is equal to the distance from transmitters of a virtual sonar-ring located at symmetrical point of the real receiver, and is given as follows:

$$d_{plane}(\theta) = \sqrt{(2L)^2 + R^2 - 4LR\cos(\theta - \theta_0)} - R. \tag{9.2}$$

When we assume an object which is a point reflector or a plane reflector is existing in front of this sonar-ring which receivers are placed at each 12 degrees, and 5 receivers received the echo from the object. When the object is existing at distance from 0.5 meters to 3 meters, from the sonar-ring, average calculated difference between the two models, a point reflector and a plane reflector, are shown in Figure 9.7. The difference at distance 1m is about 1 microsecond. According to the result, it might be possible to detect the difference of the shape of the reflecting object.

Based on the simulation result, using a plane board and a thin pole, experiments to distinguish the shape of reflecting object has done. Five shortest TOFs were selected at each measurement and compared difference of similarity using the real experimental data and two models explained before. Average difference from the measured TOFs to two models are shown in Figure 9.9 and Figure 9.10.

This experimental result shows that in case of using a correct model, there are tendency that the error get smaller comparing the different one. However, the differences itself are not sufficiently large, and it became clear that it is difficult to use this difference to distinguish difference of the object.

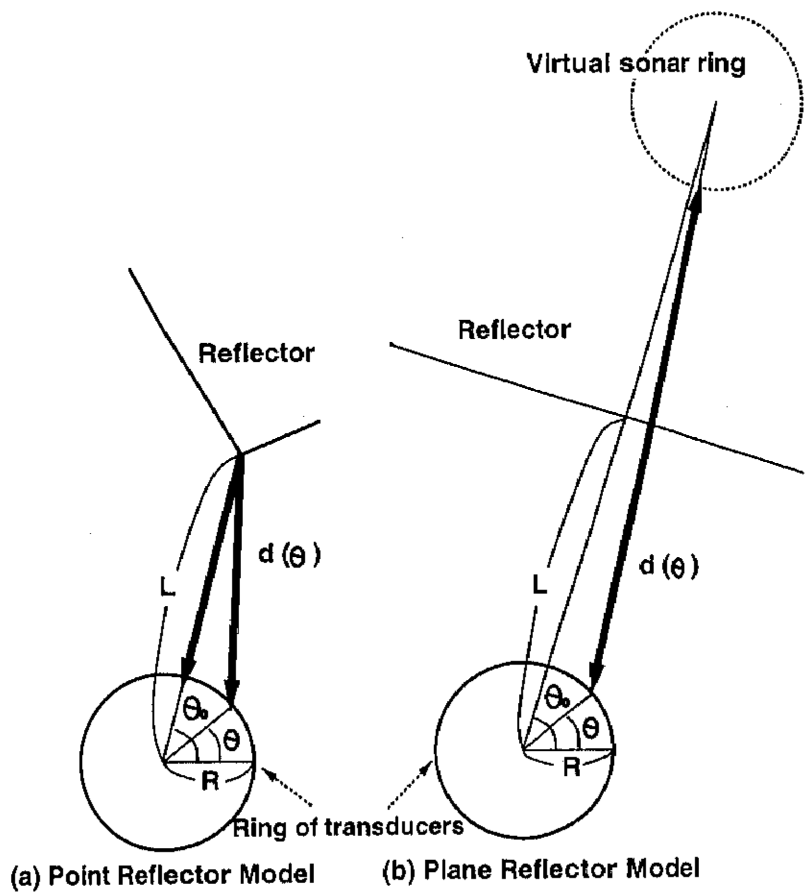

Figure 9.6: Ultrasound propagation model. When a target is a point reflecting object as like pole or edge, propagation pass of ultrasound is shown in (a). When a target is a plane reflecting object as like wall, propagation pass of ultrasound is shown in (b).

On the other hand, it became clear that using power strength of echoes can be more effective, than using this difference of propagation models. An experimental result compared number of receivers which could detect echoes according to difference of reflecting objects are shown in Figure 9.8. It is clear that reflection from wider object, as like a plane board or wall, is much stronger than thin object, as like a pole or edge. Consequently, as the result support, number of receiver reflect that strength of echo, and this information is much stronger to know shape of the object.

Conclusion on evaluation

Effectiveness of omni-directional transmission which is one of the biggest point of this system and omni-directional horn which designed to avoid reflection from robot itself and ground were confirmed by the experiments. Accuracy of directional measurement was better than 1 degree and it is sufficient for use to recognize environment in mobile robot. Real-time operation which is one of the most important thing in real mobile robot application was confirmed theoretically.

The occlusion problem which can not be avoid in pulse-echo method ultrasonic sensing explained by revealing relations of factors. It also made clear that when you want to add extra information as like shape of reflecting object, use of receiver number which could detect echo is useful in this system.

Considering those result of fundamental experiment, it can be conclude this system is satisfying requirements.

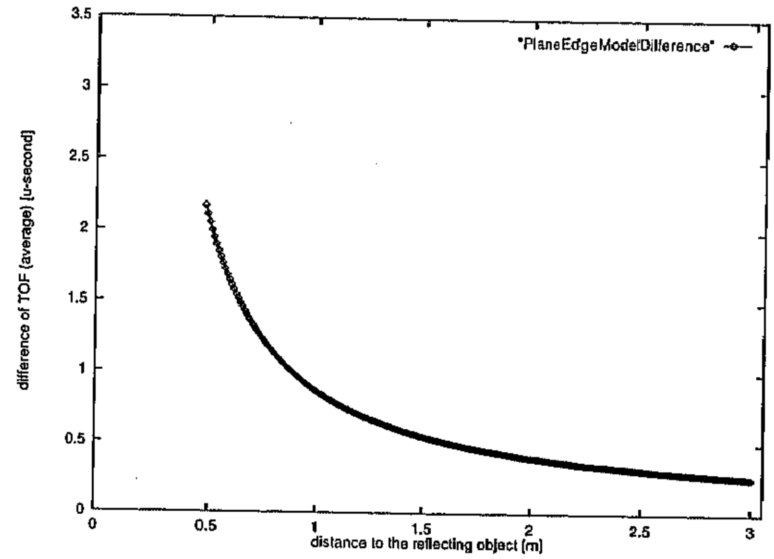

Figure 9.7: Simulation result of difference in models. Horizontal line shows distance to the reflecting object, and vertical line shows average calculated difference of two models, a point reflector and a plane reflector, when five receivers detected the echo from the object.

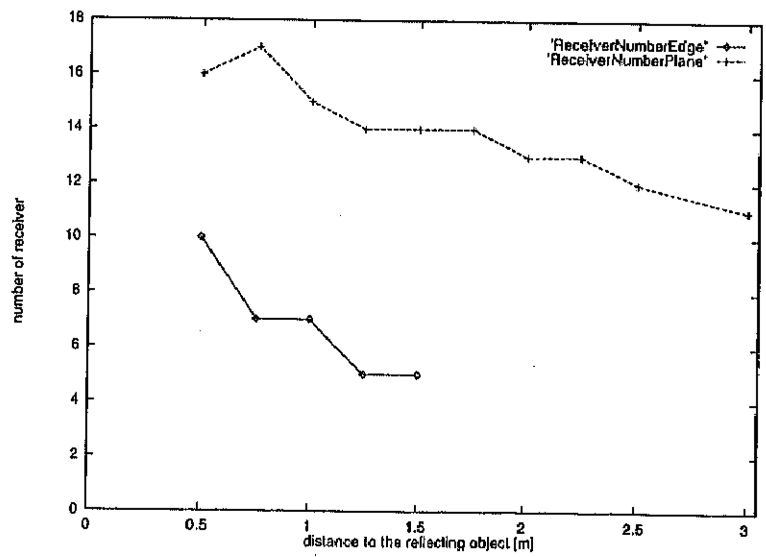

Figure 9.8: Number of receiver which detected echoes. Horizontal line shows distance to the reflecting object, and vertical line shows number of receivers which detected echo from the object. Upper line is a result using a plane board as reflecting object, and bottom one is a result using a pole.

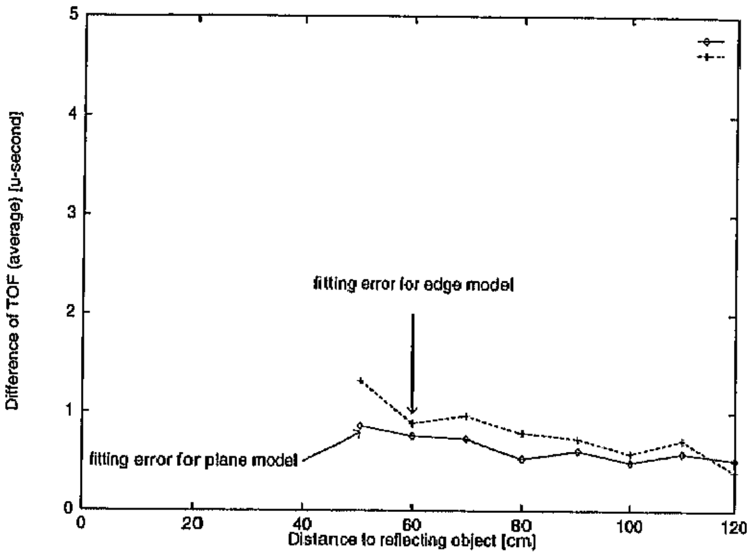

Figure 9.9: Fitting error in case of using a plane reflector.

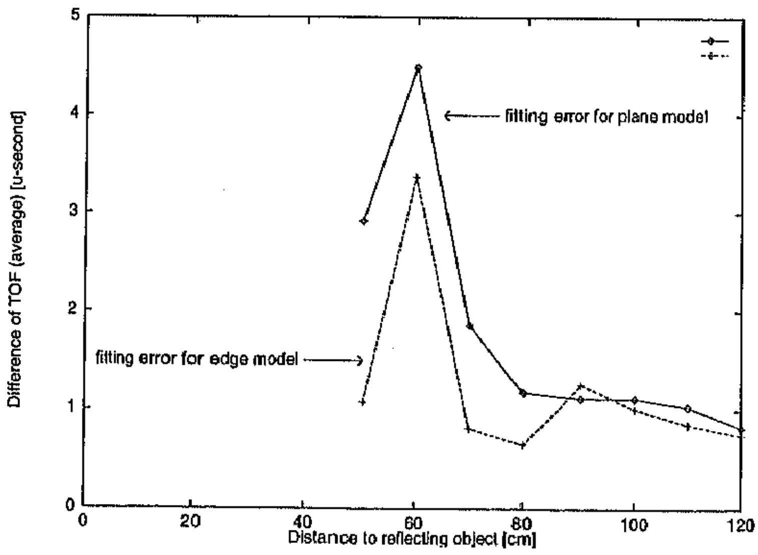

Figure 9.10: Fitting error in case of using an edge reflector.

9.2 Environment recognizing experiments

Using this proposed system which has implemented on a mobile robot, experiments to recognize environment is done for studying potential of real applications at simple environment placing boards and poles and at real corridor in our university building.

9.2.1 Experiments at Environment I

Setup

Experiments using plane and columnar objects were performed. Plane boards and columnar poles were placed as shown in (Figure 9.11), and robot was moved among them. Columnar objects were 45 millimeters in diameter. The robot moves and stops at each 10 centimeters and performs a measurement in repetition.

Result

Figure 9.12 shows the experimental result in a single measurement, which means this is measured by a single transmit/receive cycle. The robot is located at the origin of the coordinate axes. The experimental results show that the proposed sonar-ring sensor successfully measures the location of the reflecting points in the environment.

When the robot moves and stops at each 10 centimeters and performs a measurement in repetition, the result of measured reflecting points in this experiment is shown in Figure 9.13. The trajectory of the robot which is generated based on odometery data is along the y-axis starting from the origin of the coordinate system.

The proposed method could achieve accurate omni-directional measurements in a single transmit/receive cycle. And also while the robot moves, movements of the reflecting points according to the motion of the robot are observed. The measured reflecting points on the columnar reflectors remained at the same points. The measured reflecting points on the plane reflectors traverse along the surface of the plane reflectors according to the robot motion. Nevertheless, when the robot moves in perpendicular direction to the plane reflector surface, the measured reflecting points on it remain at the same point.

9.2.2 Experiments at Environment II

Setup

This experiment was performed at more realistic indoor environment. At corridor shown in Figure 9.16, two columnar objects which diameter is 50 mm are placed, and the robot robot moved among them repeating measurement at every 10cm for 2m.

Result

Figure 9.14 shows memory data of 30ch 1bit wave memory in this experiment. Figure 9.15 shows detected leading edges from the memory data and fitted functions on the leading edges. Figure 9.17 shows the experimental result from the data Figure 9.15 which is a result of a single measurement (a single transmit/receive cycle). The experimental results show that the proposed sonar-ring sensor successfully measures the location of the reflecting points in the real environment.

The result of measured reflecting points in this experiment is shown in Figure 9.18. The trajectory of the robot which is generated based on odometery data is along the horizontal-axis starting from the origin of the coordinate system. The measured reflecting points on the columnar reflectors and corners remained at the same points. The measured reflecting points on the plane reflectors traverse along the surface of the plane reflectors according to the robot motion.

9.2.3 Discussion

The proposed method could achieve accurate omni-directional measurements in a single transmit/receive cycle. Moreover, experimental results moving the robot showed in Figure 9.13 and Figure 9.18 can be said environmental map which is generated by fusing data of odometery and sonar-ring sensor, and it showed possibility to generate accurate environmental map only by accumulating the measured data without extra process. Consequently, the sonar-ring could work as required and could get accurate information all around the robot in a single measurement, and we can say the potential of the proposed system for recognizing the environment was confirmed in these experiments.

9.3 Conclusive discussion on the experiments

Usefulness of the proposed direction measurable sonar-ring sensor system has been confirmed by experiments. Originally designed omni-directional horn could focus power of ultrasound into two-dimensions as it satisfied the requirement. Moreover, omni-directional transmission by driving all transmitter simultaneously could transmit ultrasound to all directions. Directional accuracy was better than one degree and it confirmed strong point of this system in the real system. In the discussion about object shape recognition based on experimental result, it became clear that using number of echo detected receiver is more efficient. Processing speed of this proposed method can be less than 60 m-second and it can be real-time operation.

Using this proposed system which has implemented on a mobile robot, experiments to recognize environment was done for studying potential of real application at simple environment placing boards and poles and at real corridor in our university building. As the result, the proto-type sonar-ring could work as required and could get accurate information all around the robot in a single measurement, and it showed the potential of the proposed system for recognizing the environment.

Those experimental result showed the proposed method is actually useful.

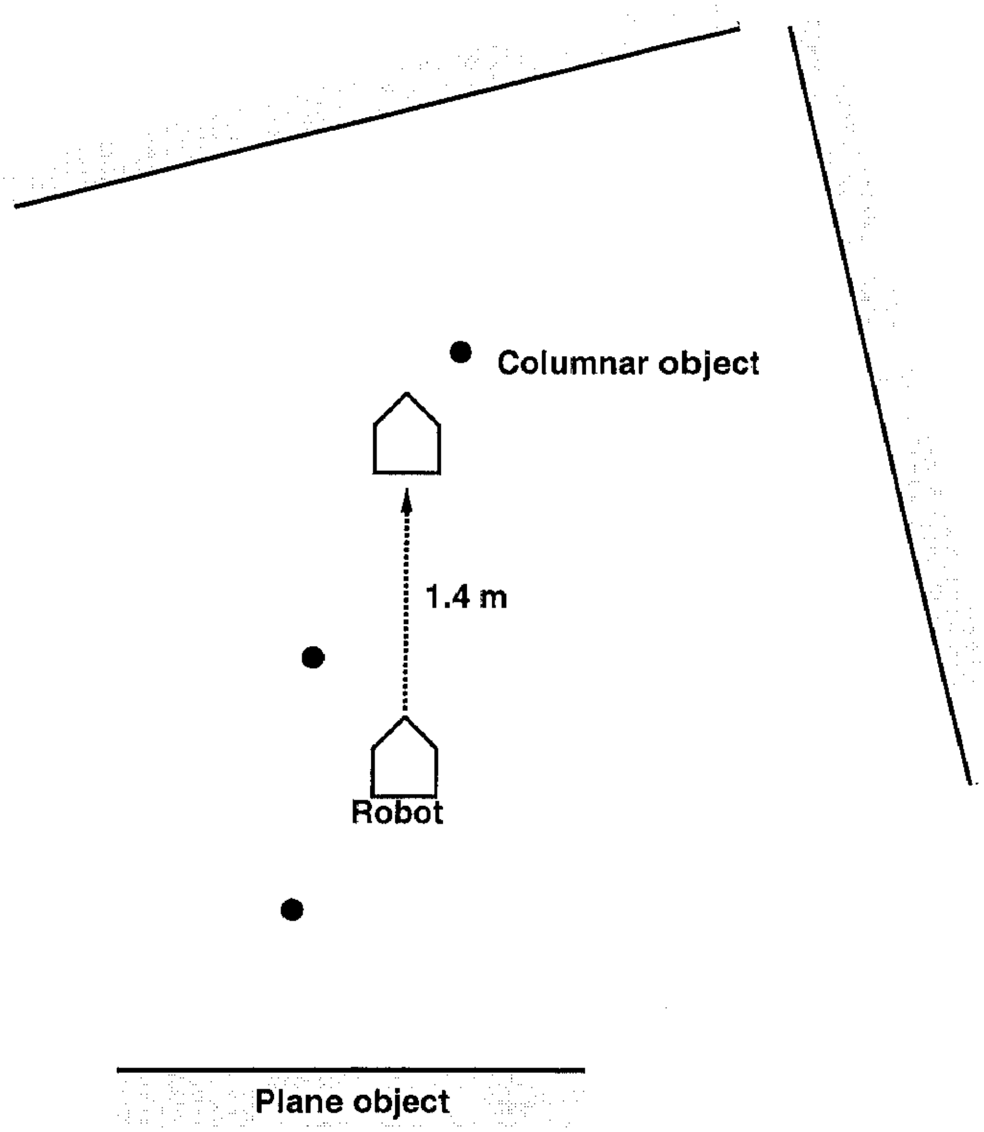

Figure 9.11: Experimental environment.

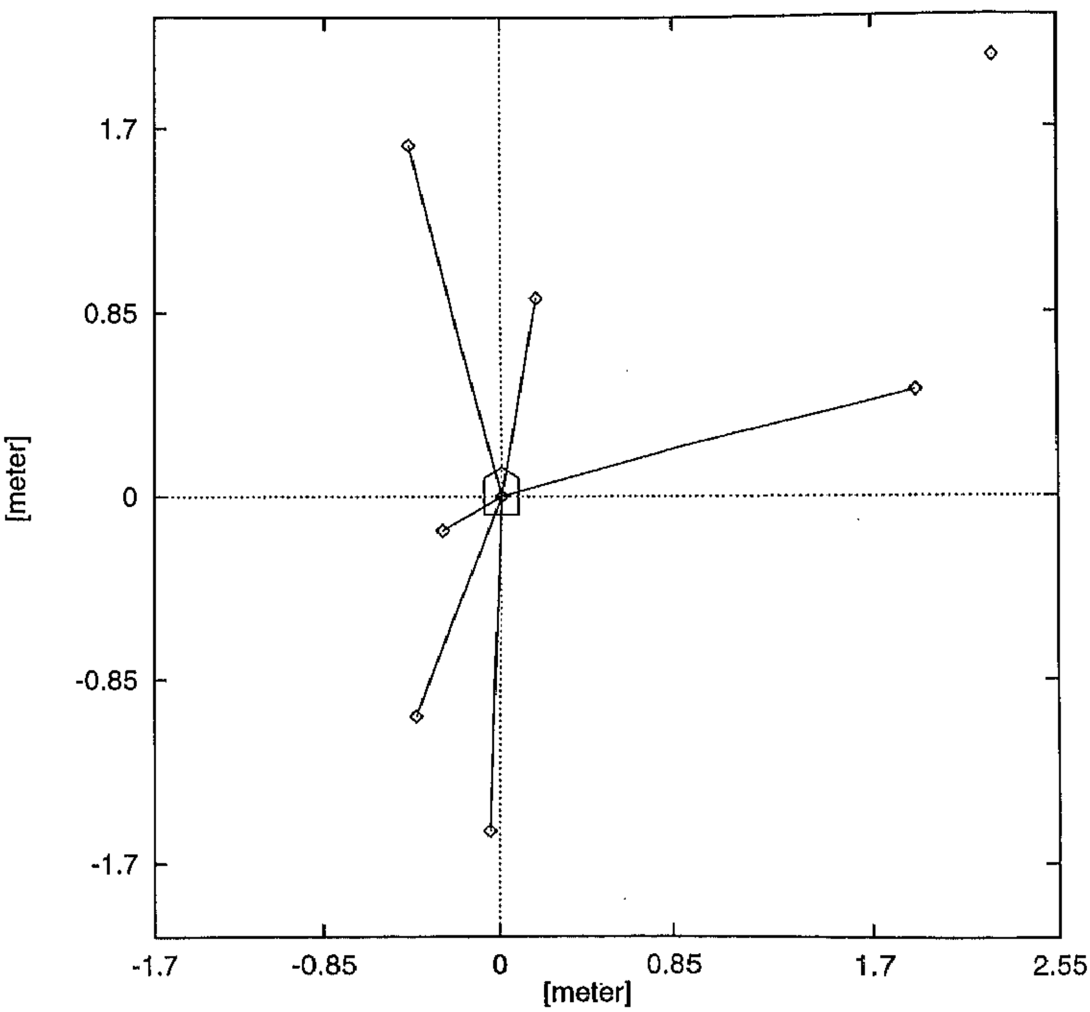

Figure 9.12: Experimental result in a single measurement. The robot is at the origin of the coordinate axes.

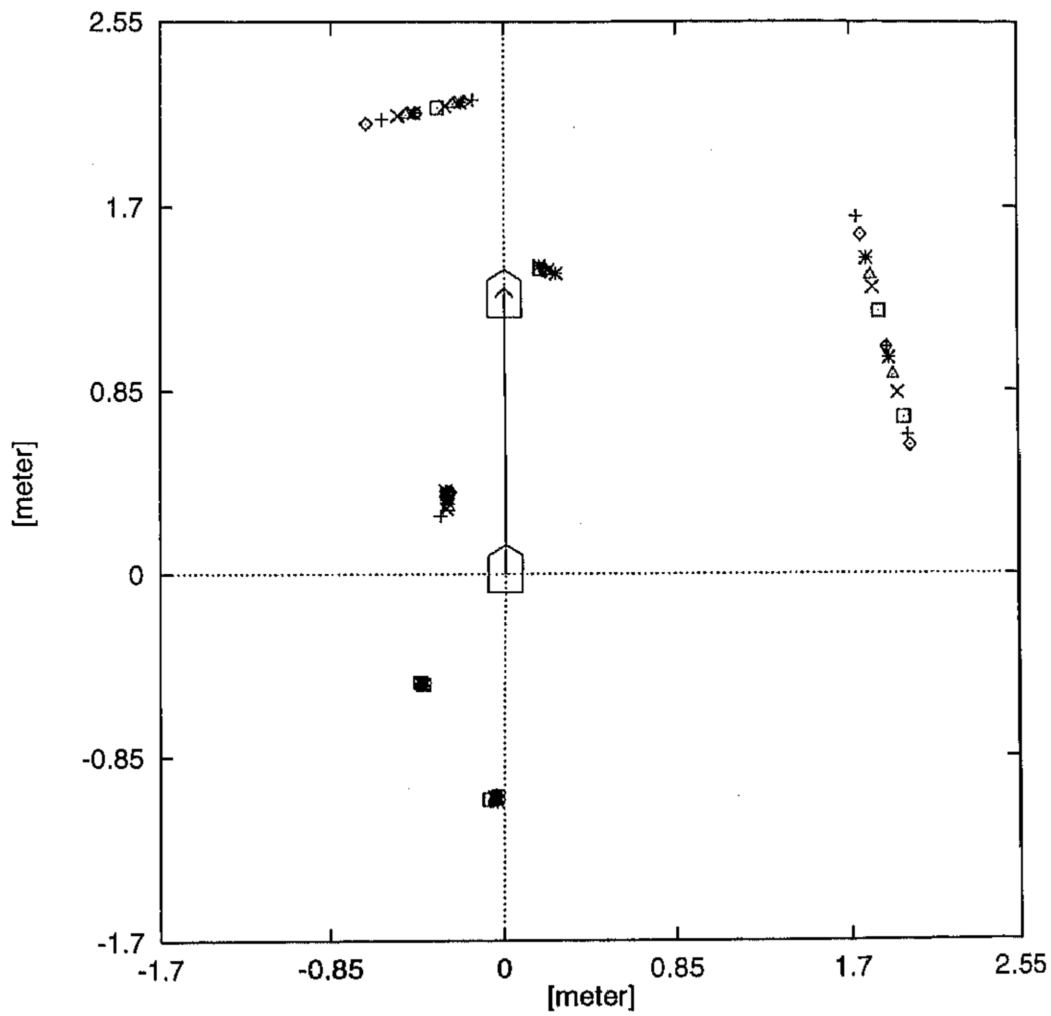

Figure 9.13: Experimental result. The robot moved along the y-axis starting from the origin of the coordinate axes.

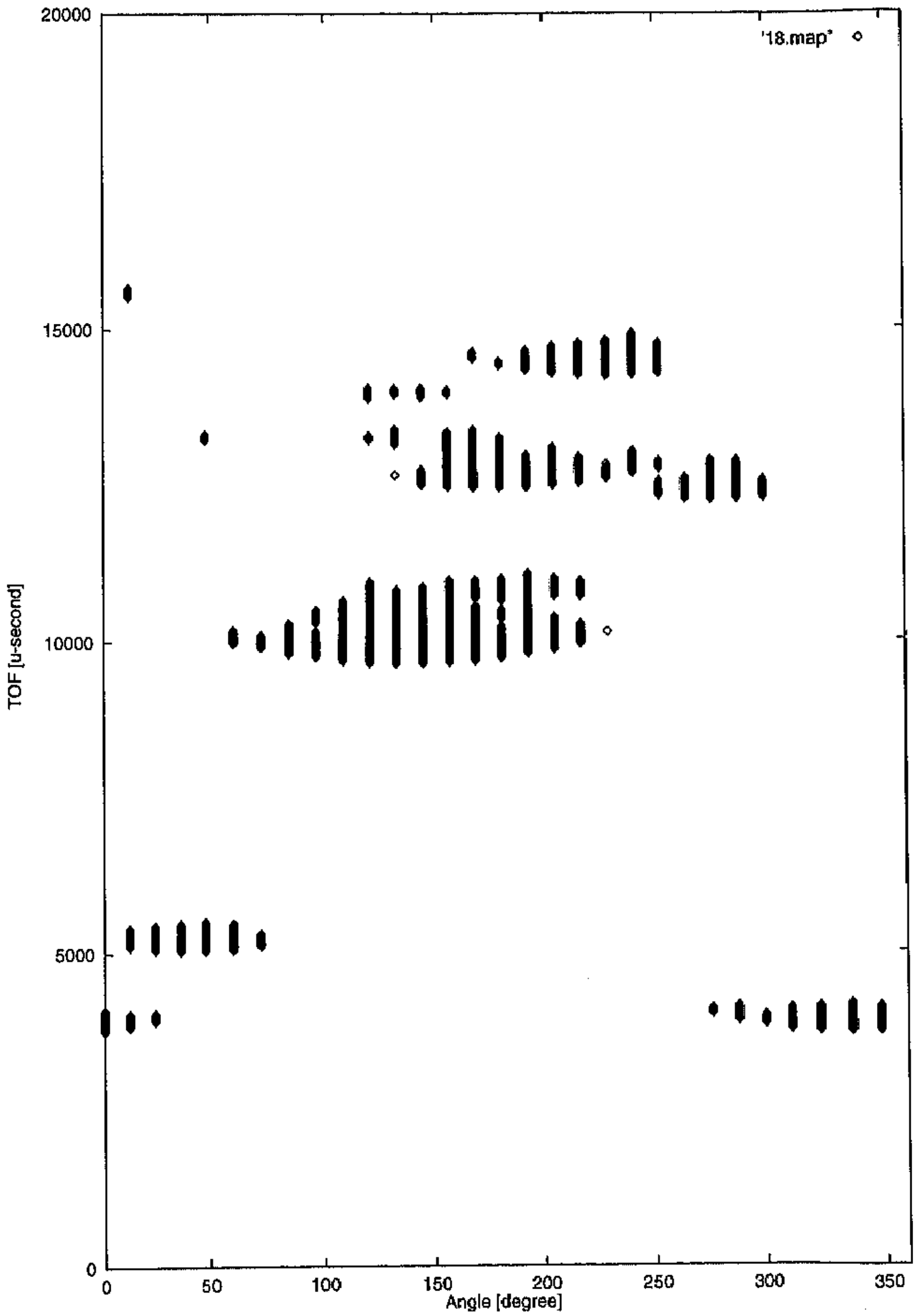

Figure 9.14: 30 channel 1bit wave memory data.

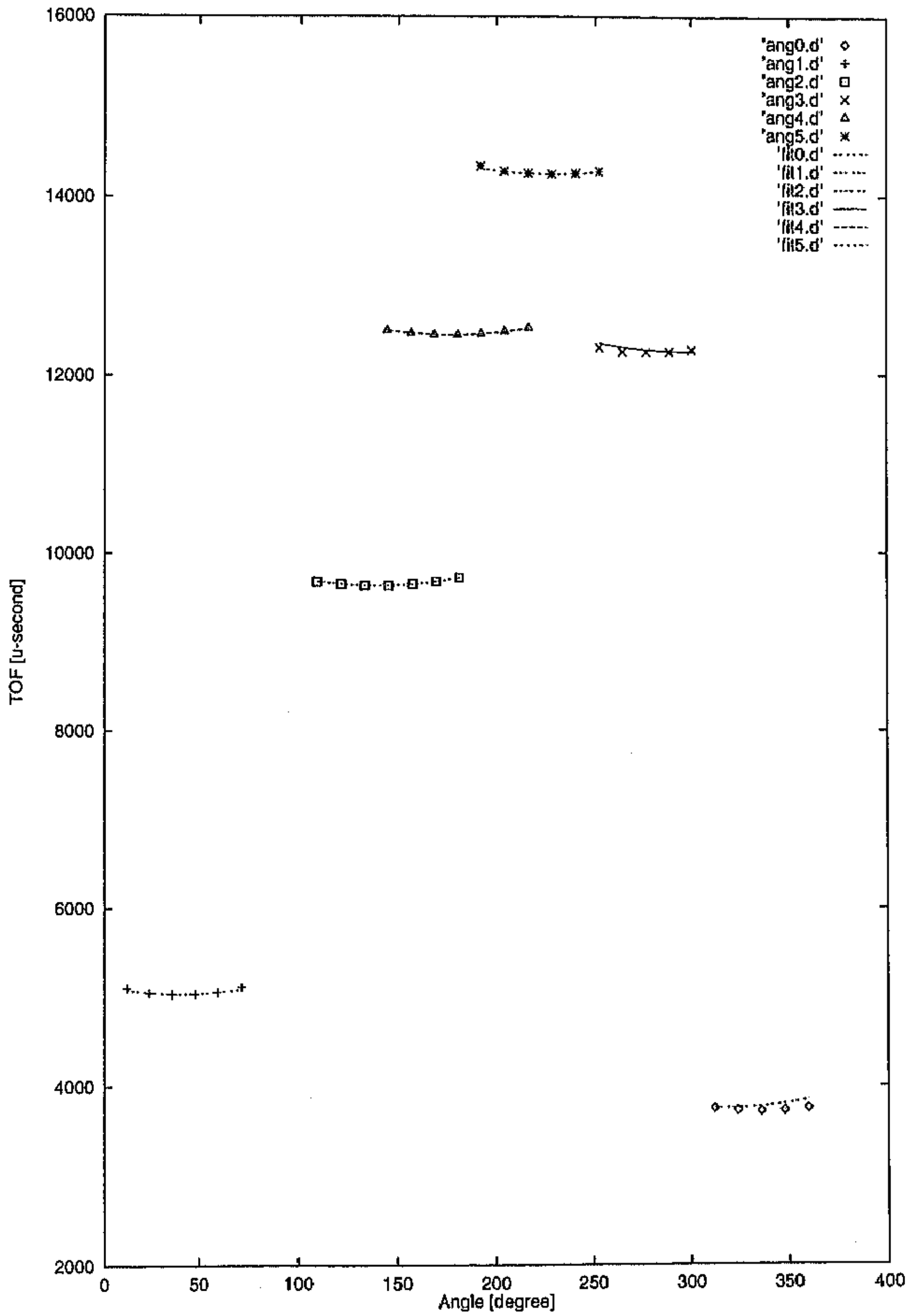

Figure 9.15: Detected leading edges and fitted functions.

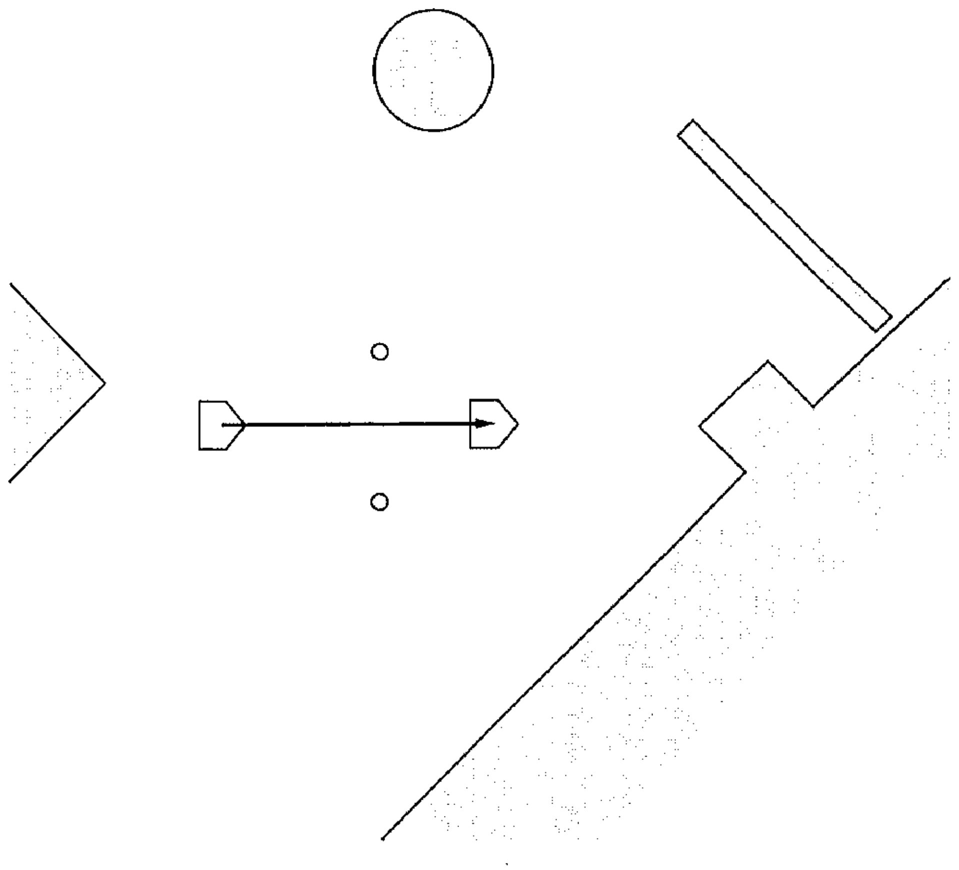

Figure 9.16: Experimental environment.

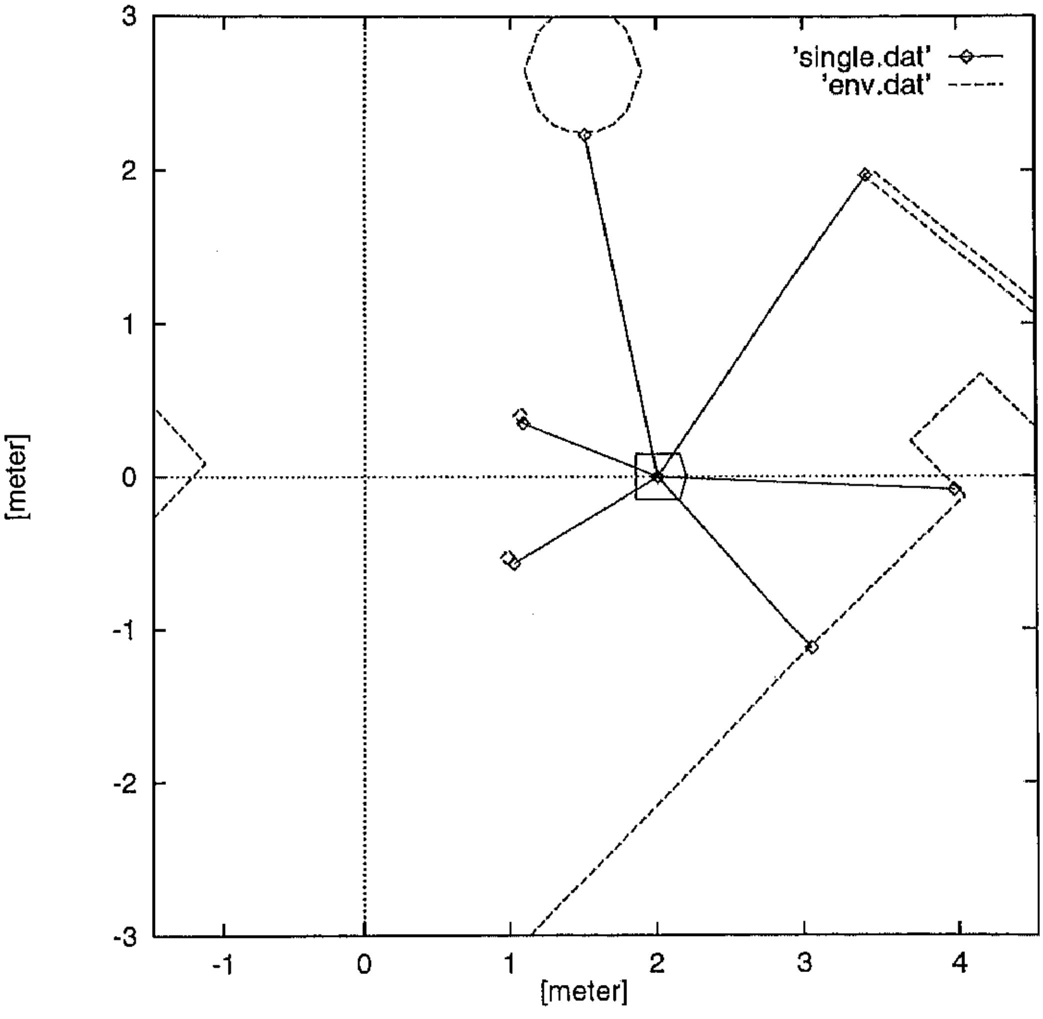

Figure 9.17: Experimental result in a single measurement.

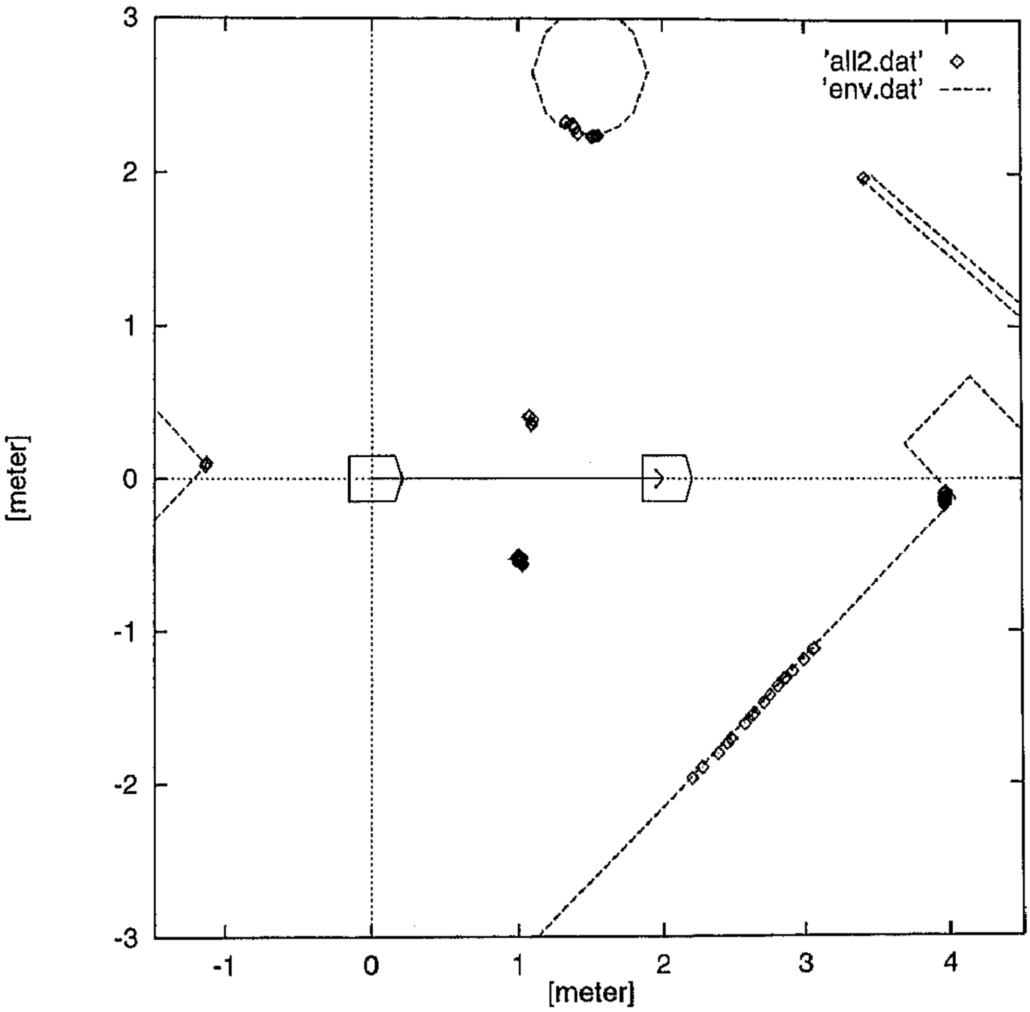

Figure 9.18: Experimental result with a robot motion. The robot moved along the horizontal axis starting from the origin of the coordinate axes.

Chapter 10

Conclusion to direction measurable sonar-ring

At the end of this part, I will discuss about the proposed method, and then conclude this part.

10.1 Discussion

Here, I will discuss merits, a limitation and applications of this method.

10.1.1 Merits

The proposed new sonar-ring sensor has following advantages:

- Wide measurable area of sonar-ring sensor.
- Measurement of all around the robot in a single transmit/receive cycle.
- Accurate directional angle measurement of the adapting multiple receiver. Consequently, it is possible to measure reflecting points on a wall, a pole, a corner and so on.
- Detection of multiple reflecting points in a single measurement.

These property and its usefulness were confirmed by experiments.

10.1.2 Limitation

A limitation of this method is occlusion problem which is overlapping of echoes causes hiding of reflecting points which are near by. The size of the hidden area is depending on the directivity of the each receiver and the duration of the echo pulse and it might not be small. This makes it difficult to apply this system to very complicated environment. This problem is caused by the natural property of ultrasonic wave, so it is impossible to eliminate this occlusion area fundamentally. Consequently, when using this type of sonar-ring, the user has to know this limitation.

10.1.3 Future works

Following problems can be proposed as future works:

- Sensor data fusion
  - with odometery data as shown in the experiments. It is possible to generate an environment map only accumulating reflecting points data based on odometery data.
  - with omni-directional vision using accurate directional information. Reflecting points data include distance and direction are obtained only sparsely, however vision data especially omni-directional vision using a special mirror can can provide segment information of the environment. Hence, it is possible to compensate for each other based on directional information.
- Adding other information – The amplitude of received signal may be a useful information added to the proposed system. In case of using the proto-type hardware given in this part, the receiver number which detected an echo can represent the amplitude of the echo. Using this information, it may be possible to estimate shape of the target object. This will help to know geometrical information.

10.2 Conclusion

In this part, I proposed a new sonar-ring for a mobile robot, which can perform fast and accurate measurements. The proposed system employs simultaneous transmissions/receptions of all directions for fast measurement, and accurate bearing angle measurements by using the difference of time-of-flight. And then, it could achieve an accurate omni-directional measurement in a single transmit/receive cycle. The potential for recognizing the environment by the proposed sensor system was confirmed in the experiments.