Part I

Introduction

Chapter 1

Introduction

Mobile robots are one of the most major research area in robotics. Ultrasonic sensors are the most major sensor for the mobile robots. However, many people including myself have ever felt frustration on its short ability when we try to apply ultrasonic sensor to mobile robots' environment recognition. I thought that mobile robot could be able to do wider various things easily if the ultrasonic sensor was improved. This was the reason why this research started.

In this chapter, I will describe mobile robots and ultrasonic sensors briefly, and overview previous researches which attempted to improve conventional ultrasonic sensors. After that, I will show a purpose and main results of this research and outline of this thesis.

1.1 Mobile robots and sensors

Mobile robots are robots which has ability to walk or to travel by themselves. Current application of the mobile robots are cleaning robots, guarding robots, carrying robots in a hospital or in a factory, moreover an amusements robot in a household. Now, robots are expected to live together with human in our life environment. For this purpose, the robots should cope with our normal daily living environment which is not specially prepared for robots. Such typical environment is two-dimensional indoor environment where we are living. As the first step of its capability, mobile robots should be able to move safely in the two-dimensional indoor environment.

External sensors are necessary for safe motion of mobile robots which move in unstructured environment in order to understand around the robots. The robots using external sensors can avoid possible collision with surroundings or can realize intelligent motion using environmental information. The biggest characteristic of mobile robots is that its active or working space is more than hundreds times of its size. For that reason, it is extremely important to have external sensors for mobile robots to understand surroundings and to do real-time sensing while moving around.

There are touch-sensor, optic sensor, electro-magnetic sensor, acoustic sensor and so on, as external sensors of mobile robots to understand environment. Among those sensors, laser range sensor, radar sensor and ultrasonic sensor are known as sensors which can measure distance information for knowing geometric shape of environment [Everett 95]. Recently, image processing based sensor can extract environmental information including distance and becomes popular [Thorpe 90]. However, ultrasonic sensor is the most popular range sensor of mobile robot for indoor mobile robot to know its environment because of its simplicity.

1.2 Ultrasonic sensing

Comparing the other sensors, pulse-echo method ultrasonic sensor is small-sized, lightweight and safe for human. Because of that, pulse-echo ultrasonic sensors were used obstacle avoidance, wall following, positioning and environmental map generation in mobile robotics [Jones 93].

Here, after explaining conventional pulse-echo ultrasonic sensing, overviews of previous researches which tried to improve the sensing ability are shown.

1.2.1 Pulse-echo method

The pulse-echo ultrasonic sensor is a simple and low cost sensor, and consequently the most popular sensor for robotics applications. In the pulse echo method, a single pulse or a burst signal is input to the transmitter in order to emit an ultrasonic pulse. The reflected echo wave is converted to an electric signal at the receiver. Since the transmitter and receiver have a certain resonant frequency and bandwidth, the received signal can be considered as sine wave with certain duration. It can directly detect distance to a reflecting object just by measuring time interval from time when a pulse is transmitted till time when the echo is coming back. This time interval is called Time-Of-Flight (TOF) [McKerrow 90]. The distance to the reflecting object is calculated as follow:

$$L = \frac{1}{2} \cdot \frac{TOF}{c}. \tag{1.1}$$

where, L is distance to the object, TOF is measured Time-of-flight and c is speed of sound which is about 340 m/s in the air (Fig.1.1).

This pulse-echo ultrasonic sensor which can measure distance easily can be constructed simply at low cost, therefore various products of pulse-echo ultrasonic sensing kits are sold [Polaroid 91] [Everett 95].

The direction of the object is estimated based on heading direction of the transducer. The ultrasonic transducer can be assumed to emit a spherical wave front, but its intensity is dependent on angle from the normal direction of the transducer. This intensity distribution is called "ultrasonic beam" and its shape depends on the input frequency. Usually, transducers are designed to concentrate most of the beam energy into the main lobe. The intensity as a function of angle is called the directivity of the beam.

In the case of a circular disk transducer emitting single frequency waves, the width of the main lobe is given by:

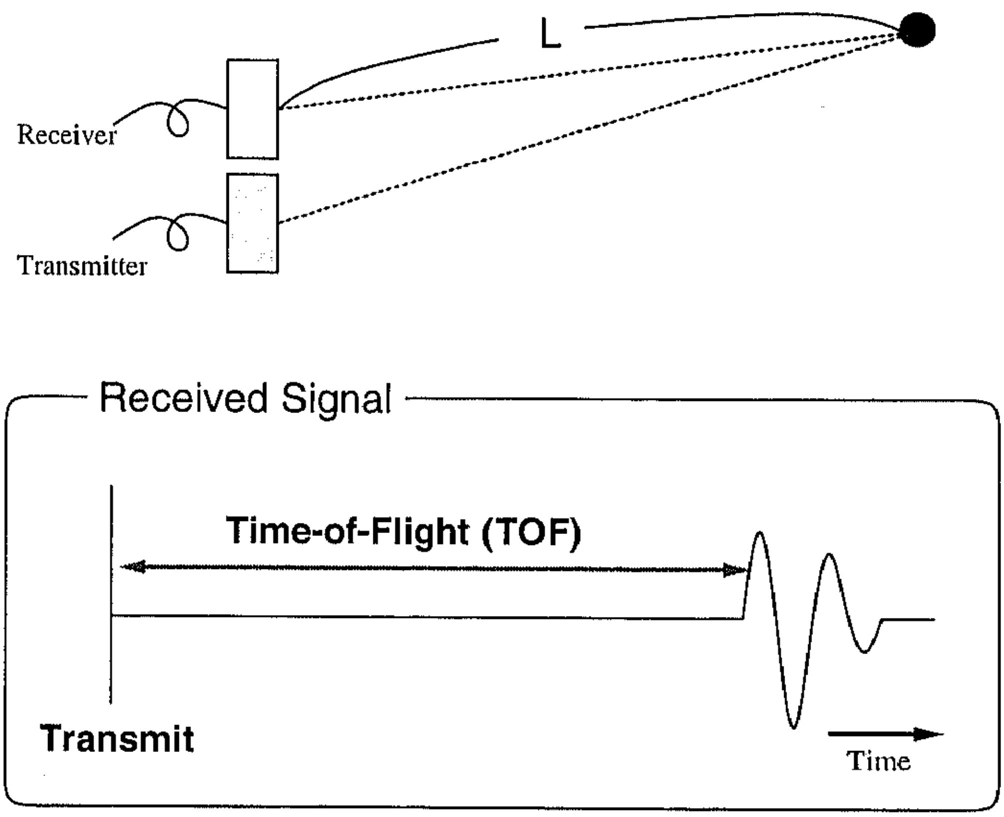

Figure 1.1: Pulse-echo method ultrasonic sensor. L is distance to the object, TOF is measured time interval between transmit and receive.

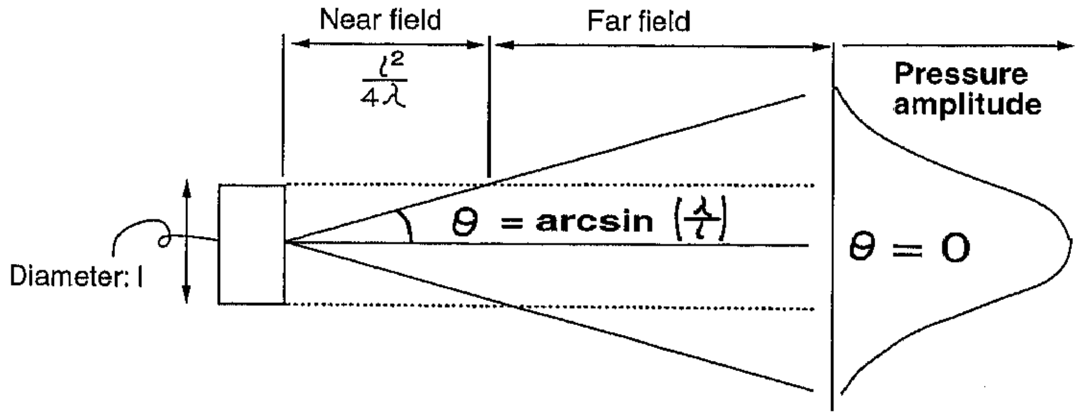

Figure 1.2: Directivity

$$\theta = arcsin(\frac{\lambda}{l}). \tag{1.2}$$

where, l is transducer diameter and λ is wave length.

This formula shows how the width of the main lobe depends on frequency and diameter of the transducer (Fig.1.2) [McKerrow 93b] [Kinsler 82].

Theoretically, this formula is only effective at far field which satisfies

$$r_{far-field} > \frac{l^2}{4\lambda}. \tag{1.3}$$

where, l is transducer diameter and λ is wave length (Fig.1.2). However, since ultrasound used in the air is frequency from 25 kHz to 70 kHz, and diameter of ordinal transducers are also from 1 cm to 5cm, the far field start at a few centimeter from the transducer thus only far field is used in the mobile robots application.

According to formula (1.2), Larger transducer or higher frequency should be used to make the beam sharper. However, there are limitation of size to put on the robot, and also, considering attenuation, frequency should be lower than several tens kHz to propagate in air. Hence, generally ultrasonic sensors which satisfied those conditions are used. The directivity is about 30 $\sim$ 60 degrees and it is not sufficiently sharp to measure the direction of objects. Therefore the accurate direction to the reflecting object is not possible to measure with conventional ultrasonic sensors,

Even though this bad accuracy of directivity, ultrasonic sensors are widely used for mobile robots because of its simplicity.

1.2.2 Improved pulse-echo methods – previous research

Whereas basic pulse-echo ultrasonic sensor explained before, there are several research which try to improve those sensor to get better information. Here some representing methods are explained.

Electronic beam scanning by transducers array

This method uses transducers array. Direction of ultrasonic pulse transmission can be controlled by controlling phase of input signal to each element owing to interference of ultrasonic wave. In another case, received signal at each element are added with suitable time-delay for each, and consequently generate sharp beam. Those method are application of method used in electronic controlled antenna to ultrasonic sensor [Sato 72].

When N pieces of elements whose individual directivity is $A(a)$ are aligned at distances d and all pieces were driven at the same amplitude, directivity of transmitter array $E(a)$ is:

$$E(a) \simeq A(a)\frac{\sin N(\frac{\pi d}{\lambda}\sin(a) - \frac{\delta}{2})}{\sin(\frac{\pi d}{\lambda}\sin(a) - \frac{\delta}{2})}. \tag{1.4}$$

where a is bearing angle, d is distance between two elements, λ is wave length of input signal and δ is phase difference. This beam takes peak at bearing angle a is satisfied following:

$$\frac{d}{\lambda}\sin(a) - \delta = 0. \tag{1.5}$$

As the result, direction of the beam can be controlled by controlling δ, without moving transducer itself.

This method is much used in medical ultrasonic sensors [Kawabata 89]. Application of this method to robot sensor were tried in [Takanashi 91] [Webb 96]. However this method has some technical problems – manufacturing transducer array is difficult, huge hardware are required in total because individual transmitter/receiver circuit including delay circuit for each elements are required, it takes time to scan because sound speed in air is slower than in liquid. As the result, this method does not come to implement on mobile robots.

Use of multiple receivers

This method uses TOF and multiple receivers. Transmit a pulse from a single transducer and receive the echo by multiple receivers simultaneously, and measure TOF at each receiver. The most important point in this method is to overlap beam of multiple receivers and to receive the same echo by multiple receivers simultaneously. As the result, the echo from the same place can be detected by multiple receivers. The reflecting place can be calculated using TOFs measured by different receivers based on a principle of triangulation.

For example, when the reflecting point is enough distant comparing distances among receivers, direction can be found as follow [Nagashima 92]:

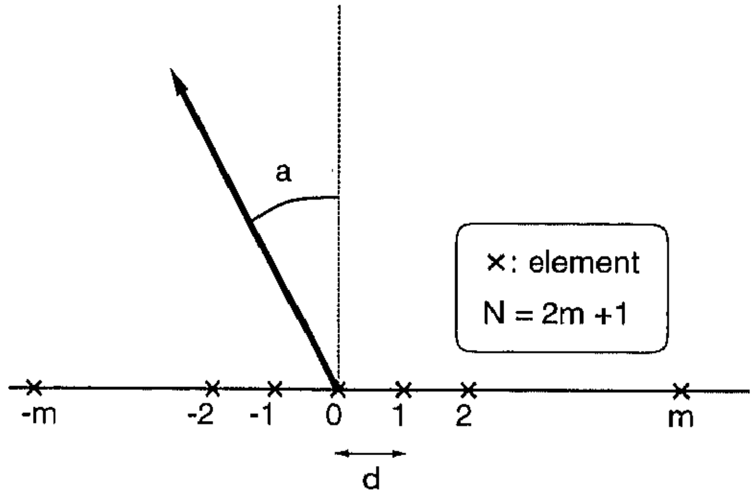

Figure 1.3: Electronic beam scanning method. N pieces of elements are aligned at distance d a is beam angle.

$$a \simeq sin^{-1}(\frac{TOF_{diff}/c}{d}). \tag{1.6}$$

Where, a is measured direction to reflecting point TOF_{diff} is difference of Time-of-flight, c is speed of sound and d is distance between receivers (Fig.1.4).

Furthermore, using TOFs measured by multiple receivers and the ultrasound propagation path model [Kuc 87], there are some approaches to find shape of reflecting target object, for example classifying the object into plane, corner and edge [Barshan 90] [Barshan 92] [Bozma 94], or estimating diameter of the object [Peremans 94], etc.

In this method direction of the reflecting point can be found. In a word, this method can measure not only distance but also accurate direction to the reflecting point. However this method has some problems – measurable area is narrow because only area where beam of multiple receivers are overlapped can be measurable area. Thus, mechanical rotation of the sensor head are required to measure wider area. Moreover, mechanical scan takes time, not only because sound speed in air is slower than in liquid, but also Mechanical motion require extra time. As the result, this method does not suitable to use for mobile robots while moving.

Echo wave form analysis

This method capture received signal into wave memory and analyze the wave signal trying to get information about target objects. The echo wave form is affected by transmit/receive transducer, propagation substance (air), character and shape of reflecting objects, etc. These

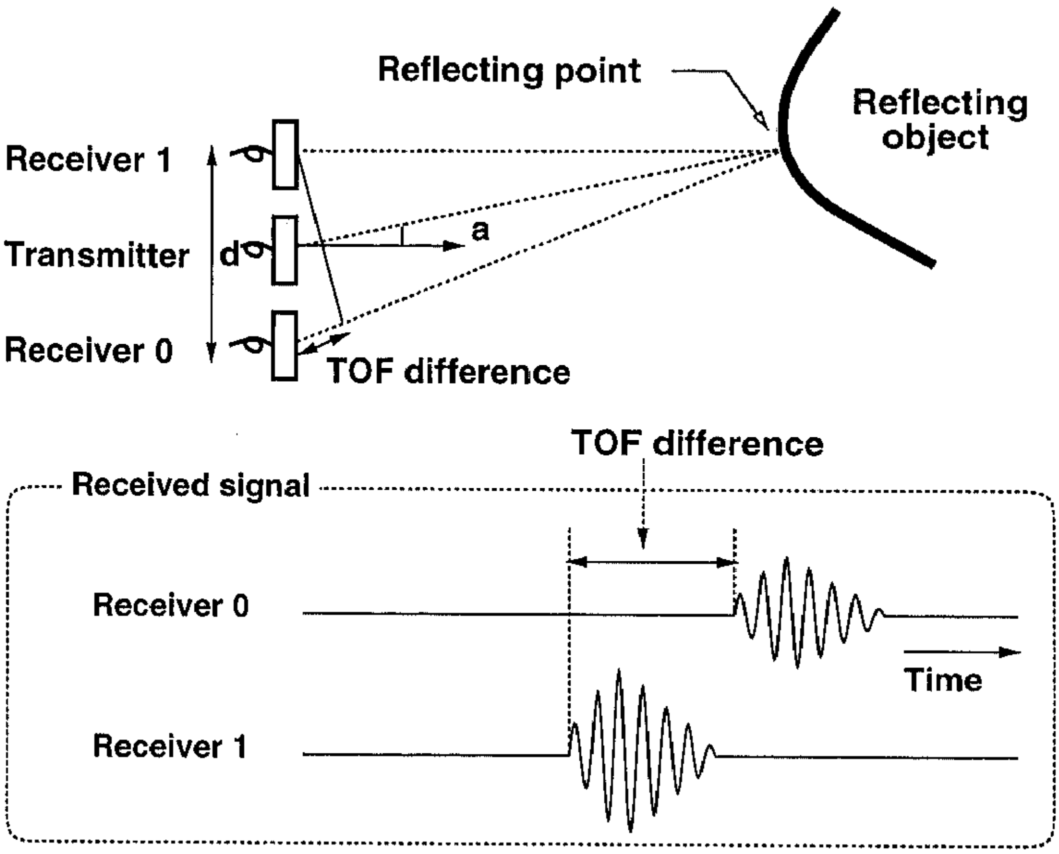

Figure 1.4: Accurate direction measurement by using TOF difference.

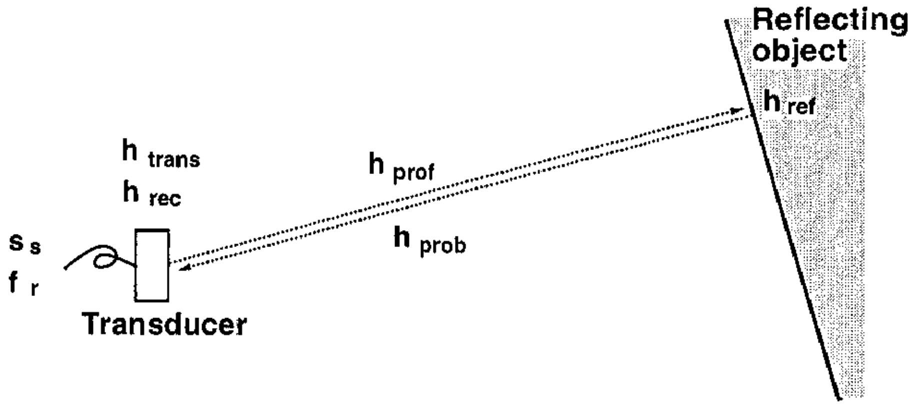

Figure 1.5: Linear propagation model

can be considered by linear superposition model [Kuc 87] [Sasaki 92]. Received wave form can be given as follow in the model:

$$f(t) = s(t) * h_{trans}(t) * h_{pro_f}(t) * h_{ref}(t) * h_{pro_b}(t) * h_{rec}(t). \quad (1.7)$$

where, $*$ demotes convolution, s(t) is excitation signal given to the transmitter and $h_{symbol}(t)$ are linear impulse responses due to the each part.

The each impulse response is analyzed as follows: $h_{pro_f}(t)$ and $h_{pro_b}(t)$ are due to propagation in forward and backward direction between the transmitter/receiver and the reflecting object, respectively. $h_{ref}(t)$ is due to the reflection at the surface of the object. $h_{trans}(t)$ and $h_{rec}(t)$ are due to the ultrasonic transmitter and receiver, respectively. Here, when propagation substance is air, $h_{pro_f}(t)$ and $h_{pro_b}(t)$ can be known beforehand. $h_{trans}(t)$ and $h_{rec}(t)$ can be known by character of each transducer. At the result, $h_{ref}(t)$ can be found by analyzing the wave form. Hence, theoretically, it became possible to know not only distance but also various information as like shape or character of the target object. As the result, several attempts have been done to extract the property of the reflecting object after estimating the function $h_{ref}(t)$ by signal processing technique.

However this method has a problem – it is not easy to get information as like shape or character of target object directly from the function $h_{ref}(t)$. Consequently only methods generating template function with respect to wave form by simulation beforehand [Kleeman 95] or using amplitude as additional information [Stanley 97] are proposed.

Use of CTFM

Moreover, as a method capturing all wave form, there is a method using Continuous Tone Frequency Modulation (CTFM). CTFM ultrasonics use a wide-band transducer, and trans-

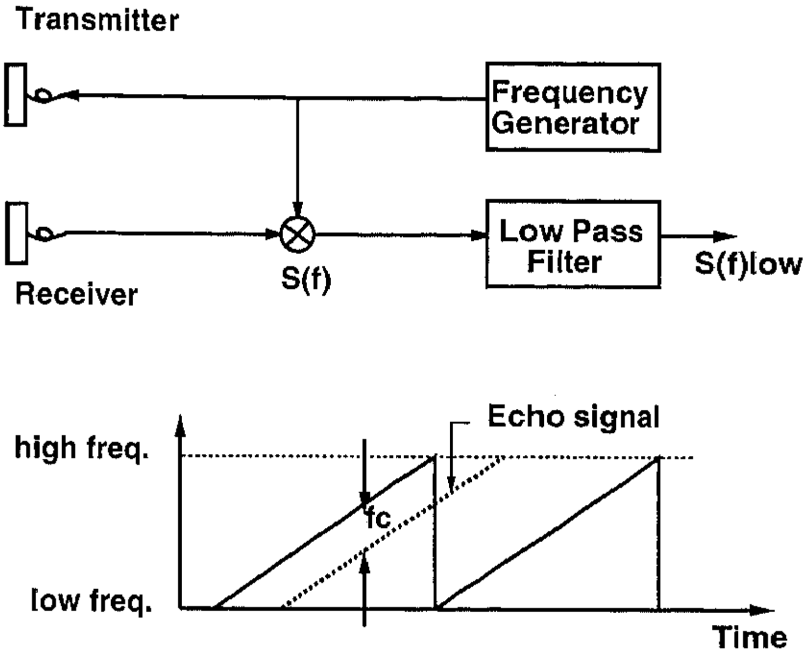

Figure 1.6: CTFM method.

mits continuous sinusoidal frequency modulated wave whose frequency changes linearly. The wave travels to the subject and is reflected back to the receiver. The amplified received wave is multiplied with the transmitting signal, and generate beat signal with transmission and reception. The beat signal is low pass filtered and extracted only envelop which express frequency difference of two signals. This frequency difference correspond to time difference from transmission to reception. Hence, it is possible to measure TOF of received echo signal by frequency analysis. As regards using TOF, this method is same as ordinary pulse-echo method.

This method was originally proposed in an aiding system for people who has difficulty in visibility [Kay 74]. It also interested since that bats are naturally using the similar method.

A strong point of this method is high resistant to noise, because continuous transmission can give larger energy than just transmitting a single pulse.

However this method has some problems – frequency analysis is required to displays the distance information by frequency, frequency modulated transmit signal is required, wide band transducer which can transmit and receive the modulated frequency is required. Consequently precise hardware are required. Recently, improvement signal processing hardware as like DSP, it started realizing to use environment recognition in robotics [Harper 94] [Polits 98].

1.3 Indoor environment

To design a realistic mobile robot, analysis and understanding the environment where the robot lives, is very important. Especially, the property of the surrounding relating with the used sensor should be considered as well. Considering that, I will discuss properties of indoor environment from a point of view using ultrasonic sensors.

1.3.1 Specularity

When an ultrasonic sensor is utilized in indoor environment, relatively smooth surface of the walls or other artificial objects are expected reflecting targets. The roughness of such surfaces is generally less than the order of one millimeter. On the other hand, the wavelength of ultrasound used for such robotic applications in the air is typically between 5mm and 15mm (frequency from 25kHz to 70kHz). Therefore, since these variations in surface smoothness are generally small compared to the wave length, it can be regarded as a mirror for ultrasonics. In addition, such an object has an acoustic impedance completely different from that of air, resulting in total reflection of the ultrasonic signals.

For these reasons, reflection of ultrasonic wave in such environment can be regarded as specular. Since the transmission and detection of ultrasonic waves occur at the same point in the pulse echo method, the direction of ultrasonic wave propagation is normal to the reflecting surface. So, it can be assumed in such environment that the ultrasonic reflecting characteristics of the surface are expected to be almost identical and independent of the reflecting object.

1.3.2 Reflecting points

The conventional pulse-echo method sometimes implicitly assumes that the environment returns the ultrasonic echo from any direction irrespective of the incident pulse direction. However, this is not correct in most indoor environment. since most reflective objects appear specular to ultrasonic frequencies.

Specularity implies that the reflecting position is surface of the wall which is perpendicular to incident direction or curved surface of a convex corner (Fig.1.7). That is, geometrically, the ultrasonic wave reflects from locally minimum point. This fact means that the nearest point in the environment is a reflecting point, and it corresponds to the first part in the echo signal. Consequently, in the indoor environment shown Fig.1.8, ultrasonic echo is coming back to the robot only from points shown by $\times$. Essentially, it is impossible to know existence of other part of wall. On the other hand, if the direction of the reflecting point is accurately detected, it will be the good information for recognizing the environment.

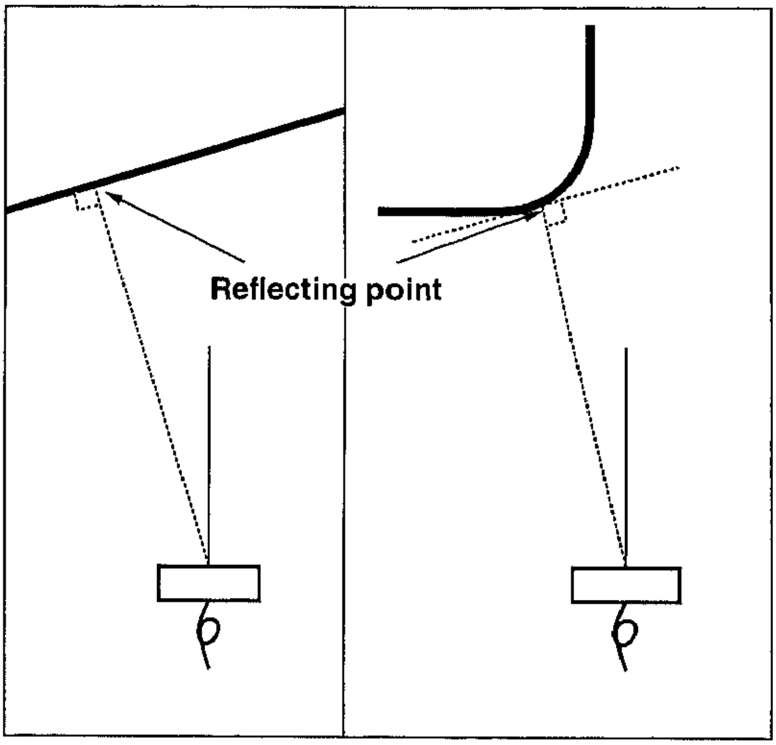

Figure 1.7: The bearing angle to the reflecting point is showing the perpendicular direction of the nearest point.

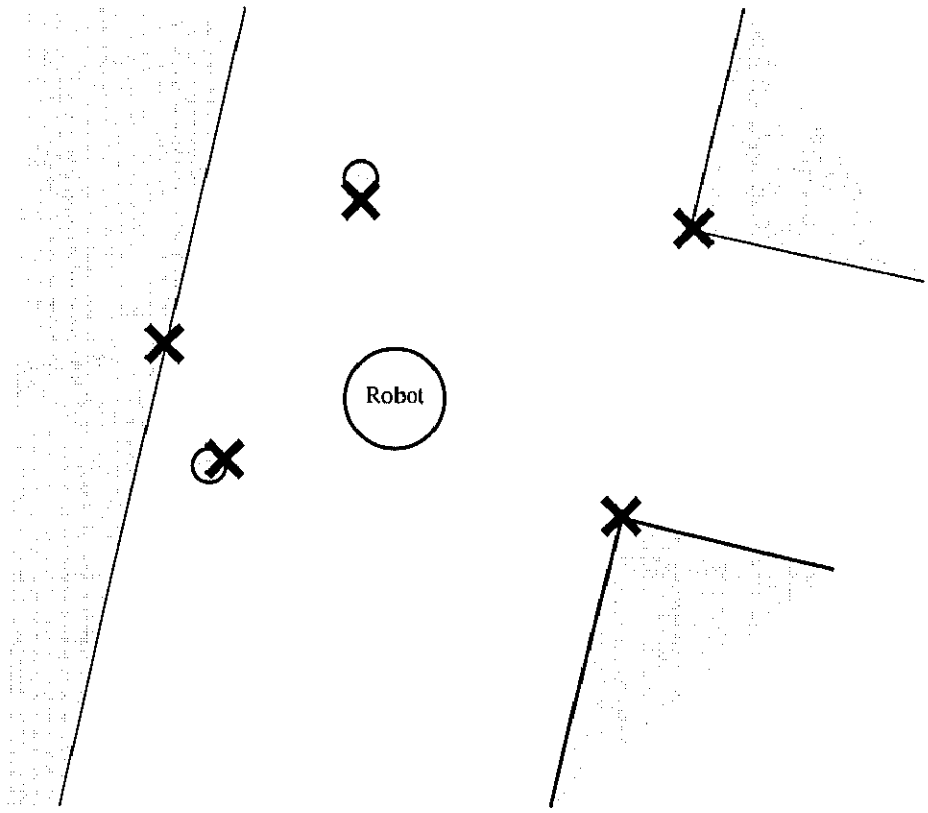

Figure 1.8: Examples of reflecting points in environment.

1.4 Requirements for mobile robots ultrasonic sensors

As explained above, external sensors for mobile robots are extremely important to know surroundings for mobile robots. Requirement for those sensors in practical use are [Everett 95]:

- **Real-time operation** – The update frequency must provide rapid, real-time data.
- **Size** – The physical size and weight of the system should be practical with regard to intended mobile robot.
- **Power consumption** – The power requirements should be minimal in keeping with the limited resources on board a mobile robot.
- **Simplicity** – The system should be low-cost and modular to allow for easy maintenance.
- **Field of view** – Should be wide enough with sufficient depth of field to suit the application.
- **Accuracy and resolution** – Both must be in keeping with the needs of the given task.

Furthermore, as explained before, pulse-echo method ultrasonic sensors have advantages as follows:

- Distance to a reflecting object can be measured in real-time.
- Small and light.
- Simple and low-cost.
- Safe for humans. (Comparing laser sensor and so on, ultrasound is safe for humans. When robots are coming into our life environment, safety is important.)

As we can see, pulse-echo ultrasonic sensors are really suitable sensor for mobile robot.
In spite of those advantages, conventional pulse-echo ultrasonic sensor is insufficient in directional measurement accuracy, thus the robot can not move relatively complicated environment just by measuring distance with a conventional ultrasonic sensor.

This is the reason why there are many research to overcome that deficiency by accumulating data while moving. Representative research of environment recognition using conventional ultrasonic sensors in mobile robots are: Map generation accumulating data on grid map with probability process using odmetry of the robot [Borenstein 91] [Borenstein 96] [Elfes 87] [Beckerman 90], Positioning accumulating data with probability process using odmetry of robot [Leonard 91] [Crowley 89] [Yamamoto98] [Anousaki 99], Finding possible passage complementing data by accumulated data [Nagatani 98] [Budenske 94], planning of sensing [McKerrow 93] and so on. Those research are trying to over come the biggest deficiency of conventional ultrasonic sensors – poor in directional measurement accuracy.

However there are limitation as long as using motion of the robot. Therefore development of good direction measurable ultrasonic sensors must be the most important for using ultrasonic sensors on mobile robots in practical use.

Among improved pulse-echo methods explained in section 1.2.2, beam forming method, TOF difference method and echo wave form analysis have potential to measure accurate direction than beam width. However, those methods are missing:

- Simplicity – beam forming method and echo wave form analysis require much larger circuit comparing conventional ultrasonic sensors.
- Field of view – beam forming method and TOF difference method are reducing measurable area, as the result those methods require to scan or mechanical rotation to get enough view.

Summarizing those point, direction measurable ultrasonic sensors which does not vitiate simplicity and field of view of conventional ultrasonic sensor are required as one of the most important problems in ultrasonic sensors for mobile robots.

1.5 Purpose of this research

Purpose of this research is development of highly efficient ultrasonic sensors for indoor mobile robots environment recognition. As explained before, many objects in indoor environment are specular for ultrasound wave used in the air. According to this specularity, reflecting region which corresponding to a leading edge of the echo are almost a point. That means, reflecting points in environment are showing quantitative information as like position of a corner or bearing angle of a wall, therefore accurate directional measurement to the reflecting point can give those information which are really useful for environment recognition. Therefore, development of good direction measurable ultrasonic sensors are the most important for using ultrasonic sensors on mobile robots. Moreover, simplicity and real-time operation are important for implementing on a real mobile robot and using this sensor while moving.

Accordingly, this research has aimed at development of ultrasonic sensing systems for indoor mobile robots which fulfill following points:

- Accurate direction measurable.
- Simple.
- Real-time operational.

1.6 Results of this research

For the purpose, two fast and accurate reflecting point measurable methods are investigated and studied, and their usefulness are confirmed in this research.

With respect to the approach in this research, a characteristic point is that the system is made as a closed system including from sensor device which is entrance of information to output which can be apply for various tasks of mobile robots. Moreover, the sensing system is constructed sufficiently to apply for various tasks by making sure of modularity.

Those two methods studied in this research are as followed.

1.6.1 Bearing measurement by a single transducer

This method achieve fast and accurate bearing measurement by a single ultrasonic transducer using characteristics that the center frequency of echo signal depends on direction which the echo comes back from.

It was known that received echo signal of pulse-echo method ultrasonic sensing depends on transducers, shape of reflecting object, distance to the object and direction to the reflecting point. Among them, direction to the reflecting point strongly influences the central frequency of echo signal independently of the shape of the reflecting object and distance to the object. Considering this point, we can use this property for accurate directional measurement.

Based on this idea, accurate directional measurement method to a reflecting point utilizing the frequency directional dependency is invented. The accurate direction to the reflecting point can be measured concretely by following methods:

- Central frequency is measured by using zero-crossing time interval of the echo wave, for achieving fast measurement.
- Preparing look-up table beforehand and using it at the measurement stage, because relationship between frequency and direction reflecting point are not be expressed by simple function.

Possibility of directional measurement to a reflecting point by using the frequency directional dependency is confirmed at first, by fundamental experiment which investigated frequency dependency on direction, shape and distance to a target object. Moreover, the result which shows directional frequency dependency was explained with linear ultrasound propagation model.

I implemented the system on a mobile robot, and verify the usefulness of this method by experiments. The influence of object shape on measurement was investigated and the result was compared with other methods. Moreover, effectiveness of the proposed method on a mobile robot is confirmed by wall following experiment using implemented sensing system.

1.6.2 Direction measurable sonar-ring

It is important to get wide field of view in a single measurement for environment recognition of mobile robots. This method achieved this purpose. In this research, I realized a sonar-ring which can measure multiple reflecting points existing around a robot with good directional accuracy in a single measurement.

Specifically, this new fast and accurate sonar-ring is designed using following ideas:

- Extending TOF difference explained before, simultaneous reception of a single transmission by multiple receivers achieve accurate position measurement of reflecting points based on a triangulation principle.
- All around a mobile robot are made field of view by placing transducers on a circumference.

This new sonar-ring realizes fast and accurate measurement by following four factors:

- Transmit an ultrasonic pulse radially and simultaneously.
- Receive the echoes with plural wide beam receivers on the circumference, consequently, measure all around the mobile robot by a single measurement.
- Accurate distance measurement is achieved by pulse-echo method ultrasonic sensing. Accurate directional measurement is achieved by using TOF difference measured by multiple receivers.
- Detecting multiple echoes at each receiver, consequently achieve to detect multiple objects in a single measurement.

The robot with the new sonar-ring becomes to be able to do following what was not be able to be done by using a conventional sonar-ring.

- It is possible to measure all around the mobile robot in a single measurement and to detect multiple reflecting points simultaneously.
- It is possible to measure accurate position of reflecting points on walls, poles, corners in environment.

A new sonar-ring based on those idea was implemented on a real mobile robot. Experiments investigating fundamental efficiency are done to confirm its usefulness. At the result, it was ascertained that the investigated system can measure multiple reflecting points all around the mobile robot accurately in a single measurement. Moreover, experiments on environment map generation is done to confirm usefulness of this method for actual environment recognition for a mobile robot, and it substantiated its usefulness.

1.7 Thesis outline

The following two fast and accurate direction measurable ultrasonic sensing methods which explained above are proposed with experimental results in following part II and III:

- Fast and accurate bearing measurement by a single transducer using frequency directional dependency.
- Fast and accurate reflecting points measurable sonar-ring using multiple transducers, TOF difference.

At Part II (Chapter 2 - 5), the fast and accurate bearing measurement by a single transducer is described. Frequency dependency on direction is explained using ultrasound propagation model at first. After that, an accurate bearing measuring method using the frequency dependency is proposed. Usefulness of this method is shown by experimental result using a mobile robot which implemented the proposed method, then conclude this method.

At Part III (Chapter 6 - 10), the fast and accurate direction measurable sonar-ring sensor is described at first. Conventional ultrasonic sensor, sonar-ring, direction measuring method and multiple object detection are explained as background of the new sonar-ring. After that, the fast and accurate direction measurable sonar-ring sensor based on those background is proposed. Then system design of the new sonar-ring to implement on a real mobile robot is described. Usefulness of this sonar-ring is shown through experiments using a mobile robot which implemented the proposed sonar-ring system, then conclude this method.

As the results of this research, that a mobile robot can detect useful environmental information by detecting accurate position of reflecting points using proposed ultrasonic sensor. At Part IV (Chapter 11), based on those result, effectiveness and limitation on effectiveness and limitation on this research whose purpose in improving ultrasonic sensing system for indoor mobile robot is discussed before concluding this thesis.