A Study on World Map Building for Mobile Robots with Tri-Aural Ultrasonic Sensor System

Hyoung Jo Jeon and Byung Kook Kim

Department of Electrical Engineering
Korea Advanced Institute of Science and Technology
373-1 Kusong-dong, Yusong-gu, Taejon 305-701 Korea

Abstract

A new tri-aural ultrasonic sensor system is suggested to build more accurate world maps for mobile robots with less scanning. In ordinary single sensor systems, the inherent beam-width of sonar transmitter causes ambiguity in sensing direction. Dual sensors may be used to discriminate plane and corner with several scans. However, the proposed method uses triple sensors, and achieves more accuracy with less scanning. Simulation studies and experimental results reveal the performance of the proposed method.

1 Introduction

In the area of mobile robot navigation, recognizing environments and building world maps are necessary. Among several range sensors, the ultrasonic sensor is most popular, because it has advantages of low cost, small size, low power, and simple hardware construction. However, it has major disadvantage, the inherent beam width of sonar, which causes ambiguity in sensing direction.

The beam-width of sonar transmitter causes mismatches between the line-of-sight and the real location of object. To reduce these mismatches, several methods are suggested such as grid analysis in the systematic sense to solve the misinterpretation of data[1], probability function including uncertainty of data[2][3], etc. Nevertheless, there are still problems such as errors that have the dimensions of grid, scanning time requirements, etc.

In the generation of a world map, it is useful to discriminate environment into planes, corners, and edges. An edge can be detected only when the angle between the line-of-sight of transducer and the location of edge is small. So, an edge can be easily differentiated from corner or plane[4][5]. However, using the simple dot map method, plane and corner can't be distinguished as shown in Fig. 1. To overcome this problem, Bozma and Kuc proposed a method discriminating corner and plane with a single sonar sensor[4], by parameterizing the arc formed when the sensor scans across an object. However, in this method multiple scannings are required at two different positions.

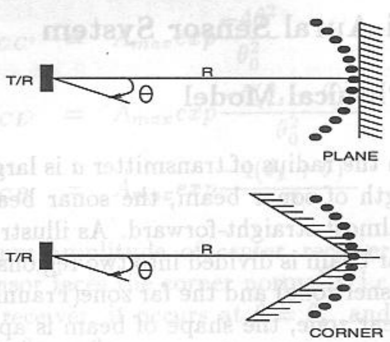


Figure 1: TOF dot patterns of a single transducer produced by the plane and corner reflectors.

On the other hand, a method using two sensors is suggested by Barshan and Kuc[6]. In this method single location of mobile robot is enough to discriminate corner and plane, by using amplitude information as well as time information(TOF). Also it is usable for the full range of sensor angles where reflected signal can be detected. Nevertheless, at least two scans are required in the same location. Since one of features of sonar is slower propagation velocity than other media such as laser, vision, etc, increase in scanning time results in slow recognition of environment.

In fact, a study about tri-aural sensor system is already proposed by Peremans and Campenhout[7]. They also utilize three ultrasonic sensors, one transmitting and three receiving. In this method, it is sufficient to distinguish an edge or a plane/corner with one measurement, but, still it needs at least two measure-

IEEE International Conference
on Robotics and Automation
0-7803-1965-6/95 $4.00 ©1995 IEEE

ments with different locations to discriminate a plane and a corner.

In this paper, a new tri-aural ultrasonic sensor system is suggested, which can recognize its environment more precisely with less scanning. The central sensor acts as both transmitter/receiver, and left and right side sensors act only as receivers. As described in Section 2, by considering oblique angle characteristics and using triple sensors, only one measurement is necessary to discriminate a plane and a corner. In addition, triple receivers achieve the correction of errors in sensing direction[8].

2 Tri-Aural Sensor System

2.1 Physical Model

When the radius of transmitter a is larger than the wavelength of sonar beam, the sonar beam is transmitted almost straight-forward. As illustrated in Fig. 2, a sonar beam is divided into two regions of the near zone(Fresnel zone) and the far zone(Fraunhofer zone). In the near zone, the shape of beam is approximated as a cylinder with radius a, and this zone is extended to the distance of $\frac{a^2}{\lambda}$. In the far zone, the beam diverges with half angle θ_0 as

$$\theta_0 = sin^{-1}\frac{0.61\lambda}{a} \qquad (1)$$

In fact, the region we are interested is the far zone,

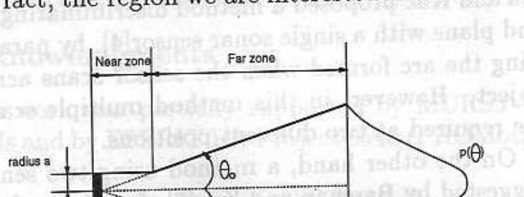


Figure 2: Beam Pattern

where the pulse is transmitted as like a plane wave. The amplitude pattern can be described as[6]

$$p(\theta) = p_{max}exp\frac{-2\theta^2}{\theta_0^2} \qquad (2)$$

The amplitude has a Gaussian form with standard deviation of $\theta_0/2$.

As depicted in Fig. 3, when a pair of identical sensors are used as one for transmitter, and another for receiver, the amplitude of signal arrived at the receiver is described as a product of two beams, given as[6]

$$A(\theta_1, \theta_2) = A_{max}exp\frac{-2\theta_1^2}{\theta_0^2}exp\frac{-2\theta_2^2}{\theta_0^2} \qquad (3)$$

where θ_1 and θ_2 are the oblique angles of the transmitter and the receiver, respectively. A_{max} is the amplitude that is observed when $\theta_1 = \theta_2 = 0$, that is, the transducers are pointed at each other.

Assuming that the reflectors are composed of smooth surfaces that act like mirrors, a transmitting/receiving (T/R) transducer can be viewed as a separate transmitter(T), and a virtual receiver(R').

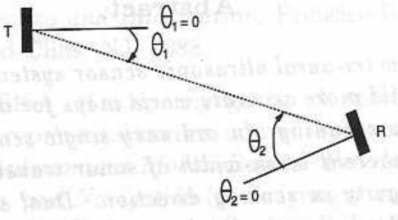


Figure 3: A pair of identical transducers

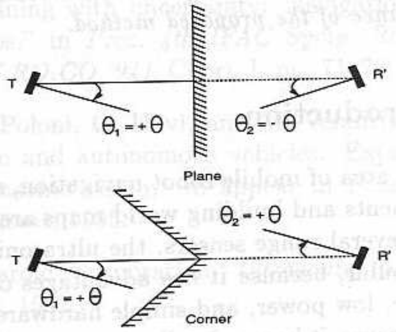


Figure 4: Reflection model of plane and corner

As illustrated in Fig. 4, for the reflection from a plane, measured angle in the clockwise direction is $\theta_1 = \theta$ whereas $\theta_2 = -\theta$. Also for a corner, $\theta_1 = \theta_2 = \theta$. Substituting these values in Eq. (3) yields the same amplitude characteristics for both plane and corner[6].

$$A(\theta) = A_{max}exp\frac{-4\theta^2}{\theta_0^2} \qquad (4)$$

2.2 Plane/Corner Differentiation Algorithm

As indicated by Eq. (4), plane and corner cannot be differentiated with a single transducer. Hence, to discriminate corner from plane, the difference in the sign of θ of the virtual receiver must be exploited by using multiple sensors. For this purpose, we propose a tri-aural sensor system where the central sensor acts both as transmitter/receiver, and left and right side sensors act only as receivers, as depicted in Figs. 5 and 6.

Using this configuration, amplitudes $A_{CC'}$, $A_{CL'}$,

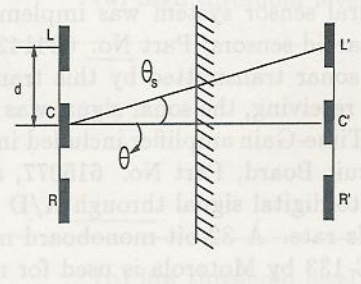


Figure 5: Tri-aural sensor system

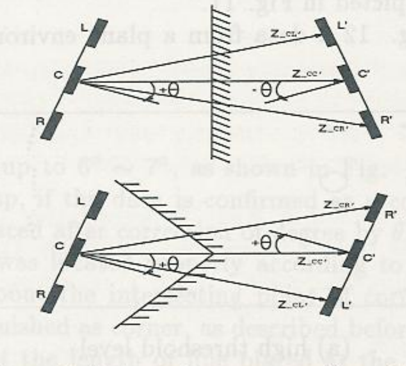


Figure 6: Tri-aural sensor configuration

$A_{CR'}$ can be obtained and exploited for the differentiation procedure as shown in Fig. 7. The corresponding ranges $Z_{CC'}$,$Z_{CL'}$,$Z_{CR'}$ will be used for determining the inclined angle θ later. Amplitudes of reflected signal received by two side sensors are the same for plane, and not the same for corner, when varying the inclination angle θ.

For a plane, we get

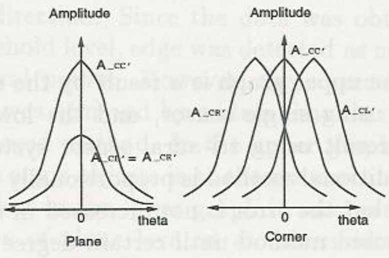


Figure 7: Amplitude graphs

$$A_{CC'} = A_{max}exp\frac{-4\theta^2}{\theta_0^2} \quad (5)$$

$$A_{CL'} = A_{CR'} = A_{max}exp\frac{-4\theta_s^2}{\theta_0^2}exp\frac{-4\theta^2}{\theta_0^2}$$

where

$$\theta_s = tan^{-1}\frac{d}{2R}$$

The maximum amplitude of each transducer occurs at $\theta = 0$, that is, when the sensor system faces the plane normally. Rotation of the transmitter decreases amplitude.

For a corner, we get

$$A_{CC'} = A_{max}exp\frac{-4\theta^2}{\theta_0^2} \quad (6)$$

$$A_{CL'} = A_{max}exp\frac{-4(\theta_s-\theta)^2}{\theta_0^2}$$

$$A_{CR'} = A_{max}exp\frac{-4(\theta_s+\theta)^2}{\theta_0^2}$$

The maximum amplitude of center receiver occurs when the sensor faces the corner normally, i.e., $\theta = 0$. For the left receiver, it occurs at $\theta = \theta_s$, and for the right receiver $\theta = -\theta_s$.

When a noise is present, the actual amplitude

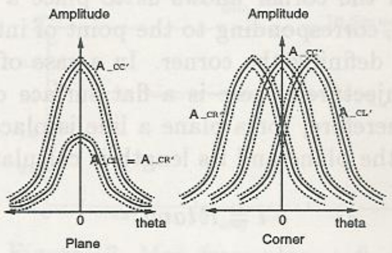


Figure 8: Amplitude graphs with noise effects

measurement shows statistical variation that can be modeled by additive random noise n.

$$A_{meas}(\theta) = A(\theta) + n \quad (7)$$

The noise can be described by a probability density function having zero-mean and variance σ^2. Amplitude curves incorporating noise are redrawn in Fig. 8.

The following equation is applied to discriminate corner from plane in wider range of θ.

If $|A_{CL'} - A_{CR'}| > 6\sigma$, then the object is a $CORNER$ (8)

For the near range of $\theta = 0$, a corner cannot be differentiated from plane in this proposed method. However, after multiple scans with different sensor directions as described in Section 2.3, a line is placed whose length is proportional to θ for the plane, and a dot is placed for the corner. Hence, plane and corner can be discriminated for all angles.

2.3 Range and Direction

It is assumed that the environment is composed of only corners, planes, and edges. To estimate the value of θ, we employ the three range measurements from three transducers as

$$\begin{aligned} Z_{CC'} &= 2R \\ Z_{CL'} &= \sqrt{4R^2 + d^2 - 4Rdsin\theta} \\ Z_{CR'} &= \sqrt{4R^2 + d^2 + 4Rdsin\theta} \end{aligned} \tag{9}$$

From the above equations, R and θ are calculated as

$$R = \frac{Z_{CC'}}{2} \tag{10}$$

$$\theta = sin^{-1}\frac{Z_{CR'}^2 - Z_{CL'}^2}{4dZ_{CC'}} \tag{11}$$

However, the angle of the surfaces defining one corner with respect to the transducer line-of-sight cannot be determined due to the physics of reflection.

For a corner, the oblique angle θ between the transducers and the corner allows us to place a dot on a sonar map, corresponding to the point of intersection of surfaces defining the corner. In a case of plane, it can be conjectured there is a flat surface of certain length. Therefore, for a plane a line is placed at the surface of the plane and its length is calculated as

$$l = Rtan\theta \tag{12}$$

As mentioned in Section 1, the reflected signal from edge is detected when the oblique angle is small, and the amplitude of reflected signal is smaller than the other cases. Therefore, for an edge or a corner, a dot is placed. For a plane, which is the last case, a line is placed.

3 Simulation and Experimental Results

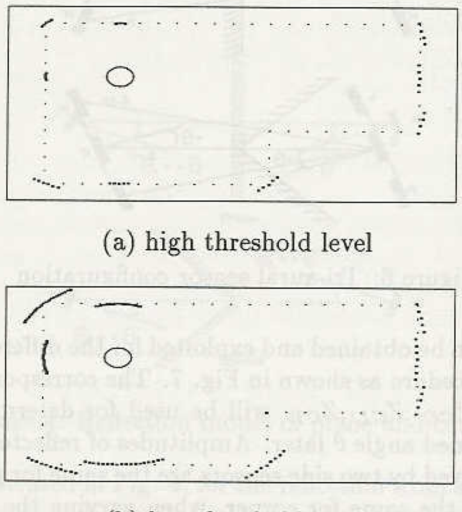
For simulation, impulse response simulation model is used[5]. In Fig. 9, a simulation result of single sonar system(a traditional method) is depicted, and the upper graph (a) is the case of using high threshold level, and the lower one (b) is for using low threshold level. In this graph, the error is increased with lower threshold level.

Fig. 10 is the graph when using the tri-aural sensor system. It shows a dot for detecting a corner, and a solid line for detecting a plane or failing to detect a corner. The solid line has the length of Eq. (12). In this case, in spite of using low threshold level the error is not increased, but, the detectable region is increased. Hence, more accurate recognition of environment is achieved.

The tri-aural sensor system was implemented using three Polaroid sensors, Part No. 604142 [9]. The frequency of sonar transmitted by this transducer is 50kHz. After receiving, the sonar signal was amplified by the Auto-Time-Gain amplifier included in Polaroid Ranging Circuit Board, Part No. 615077, and finally converted to digital signal through A/D converter with 312.5kHz rate. A 32-bit monoboard microcomputer MVME 133 by Motorola is used for main processing, and connected to IBM PC via RS-232C for editing, compiling, downloading the program as well as user interface. The set-up of experimental equipment is depicted in Fig. 11.

In Fig. 12 a data from a plane environment is plotted. The upper graph is a result by the traditional method using single sensor, and the lower graph shows the result using tri-aural sensor system. The error of traditional method is proportionally increased as θ grows, but the error is not increased in the graph of the proposed method until certain degree of angle, about $12° \sim 15°$ which is similar to simulation.

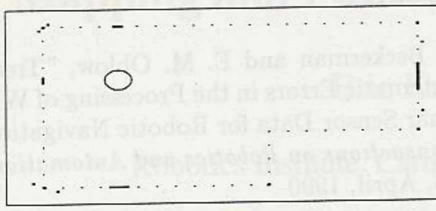
For a corner environment, the degree error was cor-



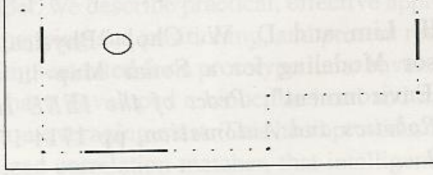
(a) high threshold level

(b) low threshold level

Figure 9: Global map using one sensor with different threshold



(a) high threshold level



(b) low threshold level

Figure 10: Global map using tri-aural sensor system with different threshold

rected up to 6° - 7°, as shown in Fig. 13. Making the map, if the data is confirmed as a corner, a dot was placed after correction of degree by θ, and if not, a line was located properly according to θ. The region about the intersecting point of corner was not distinguished as corner, as described before in Section 3.2, but the length of line placed at the intersecting point was shorter than the result from the traditional method. Hence, it is enough to describe the point of intersection of surfaces defining the corner.

In Fig. 14, an experimental result at a corridor is shown, as a general case being composed of complex reflectors. The sensor system is located in the center of the corridor. The surface of corridor is not so smooth, which causes some diffused reflections. Comparing with the two previous graphs, the discrimination was not accomplished enough for longer distance, but the accuracy of map was improved by the correction of direction. Since the data was obtained using low threshold level, edge was detected as not one point but several points. However, the correction of point location was achieved by certain amount of degrees in the proposed method. In the upper graph, it was detected as some objects is at the bottom and the left of middle, but in the lower graph it was corrected. Also the shape of plane located at left-middle and right-middle was detected more correctly in the proposed method.

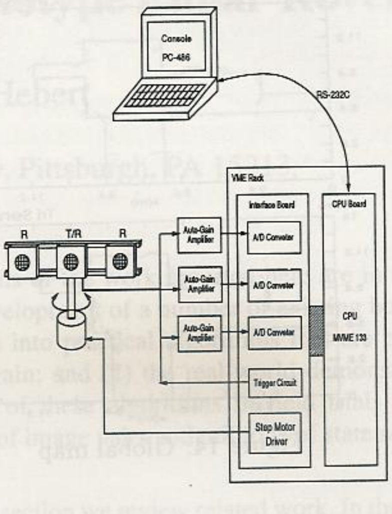


Figure 11: Block diagram of experimental equipments

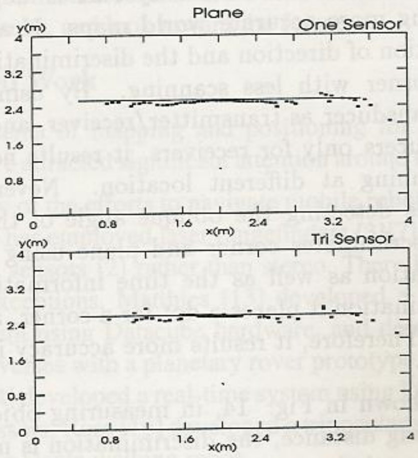


Figure 12: Map from plane reflector

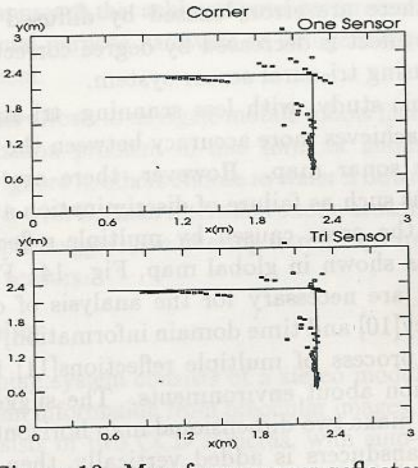


Figure 13: Map from corner reflector

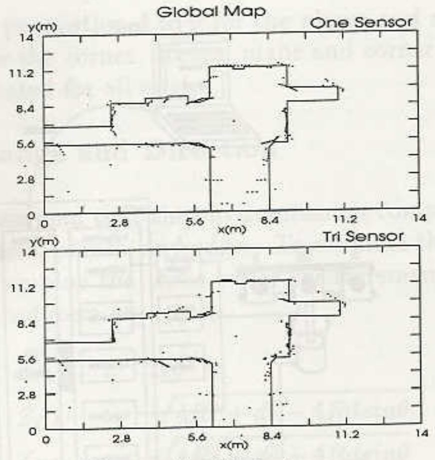


Figure 14: Global map

4 Concluding Remarks

A new tri-aural sensor system is developed for building more accurate world maps. It achieves the correction of direction and the discrimination of plane and corner with less scanning. By using the central transducer as transmitter/receiver, and both side transducers only for receivers, it results no additional scanning at different location. Nevertheless, it achieves detecting the oblique angle of the reflector and discriminates corner and plane using amplitude information as well as the time information. After discrimination it places a dot for a corner, a line for a plane. Therefore, it results more accuracy in the map making.

As shown in Fig. 14, in measuring objects located at long distance, the discrimination is not accomplished, and there is not so much difference from single sensor system. However there are some improvements on the measurements of plane reflectors. Besides, there are errors caused by diffused reflection, but the effect is decreased by degree correction in the graph using tri-aural sensor system.

In this study, with less scanning, tri-aural sensor system achieves more accuracy between the real world and the sonar map. However, there are still some problems such as failure of discrimination at long distances, the error caused by multiple reflection, and so on, as shown in global map, Fig. 14. Further researches are necessary for the analysis of combining frequency[10] and time domain information, or including the process of multiple reflections[11] for better recognition about environments. The suggested system can make two dimensional map horizontally, but, if the transducers is added vertically, then three dimensional one can be obtained.

References

[1] M. Beckerman and E. M. Oblow, "Treatment of Systematic Errors in the Processing of WIde-Angle Sonar Sensor Data for Robotic Navigation", *IEEE Transactions on Robotics and Automation*, pp 137-145, April, 1990

[2] H. P. Moravec and A. Elfes, "High resolution maps from wide angle sonar", *Proc. IEEE Int. Conf. Robotics and Automation*, pp 116-121, 1985

[3] J. H. Lim and D. W. Cho, "Physically Based Sensor Modeling for a Sonar Map in a Specular Environment", *Proc. of the IEEE Int. Conf. on Robotics and Automation*, pp 1714-1719, May, 1992

[4] Ö. Bozma and R. Kuc, "Building a Sonar Map in a Specular Environment Using a Single Mobile Sensor", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, pp 1260-1269, December, 1991

[5] R. Kuc, "Physically Based Simulation Model for Acoustic Sensor Robot Navigation", *IEEE Transactions Pattern Analysis and Machine Intelligence*, pp766-778, November, 1987

[6] B. Barshan and R. Kuc, "Differentiating Sonar Reflections from Corners and Planes by Employing an Intelligent Sensor", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, pp 560-569, June, 1990

[7] H. Peremans and J. Van Campenhout, "Tri-aural perception on a mobile robot", *IEEE Int. Conference on Robotics and Automation*, pp 265-270, May, 1993

[8] Y. Nagashima and S. Yuta, "Ultrasonic sensing for a mobile robot to recognize an environment", *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp 805-812, July, 1992

[9] Polariod Corporation, "Ultrasonic Ranging System",

[10] K. Sasaki and M. Takano, "Classification of Object's Surface by Acoustic Transfer Function", *Proc. of the IEEE/RSJ Int. Conference on Intelligent Robots and Systems*, pp 821-828, July, 1992

[11] D. Wilkes and G. Dudek and M. Jenkin and E. Milios, "Multi-transducer sonar interpretation", *IEEE Int. Conference on Robotics and Automation*, pp 392-397, May, 1993