Proceedings of the 1998 IEEE
International Conference on Robotics & Automation
Leuven, Belgium • May 1998

Wall Following Using Angle Information Measured by a Single Ultrasonic Transducer

Teruko YATA* Lindsay KLEEMAN** Shin'ichi YUTA*

*Intelligent Robot Laboratory
University of Tsukuba
Tsukuba 305-8573 Japan

**Dept. ECSEng
Monash University
Clayton Vic. 3168 Australia

Abstract

Conventional wall following with an ultrasonic sensor uses only range data to the nearest reflecting point. However, the bearing angle information to the wall is more useful for a wall following motion. In this paper, we propose a simple wall following algorithm, where the robot moves perpendicular to the direction to the nearest reflecting point.

Also, in conventional ultrasonic pulse-echo sensing, an accurate target bearing measurement is often regarded as difficult due to the wide directivity of ultrasonic transducers. However, by assuming that the ultrasonic echo returns from a single direction, the bearing angle can be measured. A new sensing method is also proposed to determine accurately the bearing angle to the reflecting point by a single ultrasonic transducer.

This paper also presents experimental results from mobile robot wall following experiments using only bearing information measured by a single ultrasonic transducer. These experiments illustrate the effectiveness of proposed method.

1 Introduction

For a mobile robot, wall following is a useful motion in structured environments and can be employed for obstacle avoidance. In many mobile robots, ultrasonic range sensors are used for wall following. With these robots, the range from robot to wall is commonly measured by an ultrasonic sensor and used for motion control. However, from the point of view of vehicle motion control, the direction angle to the wall is more useful and suitable information to realize wall following. In this paper, we propose a new strategy for wall following by a robot, ie. "move in a perpendicular direction to the nearest point of an object".

To realize the above mentioned motion, the angle information to the nearest wall is required. Conventional ultrasonic sensors cannot measure accurately the direction of reflecting point. However ultrasonic sensing is naturally suitable for detecting this angle information. This paper therefore also proposes a simple bearing angle measurement method for use in a mobile robot wall following motion. The method exploits the frequency dependency of the echo signal on the echo arrival direction.

Experimental results from real mobile robot wall following using the proposed method are presented to illustrate the effectiveness of this new approach.

2 Wall following with angle information measured by an ultrasonic sensor

2.1 Wall following

2.1.1 Previous work

Wall following is a popular and useful technique for mobile robot navigation in structured or known environments. Mobile robot path planning or navigation often assumes that robots have the ability to perform wall following. For example, [1] gives a path planning method that depends on wall following. Many research approaches on sensor-based path planning of mobile robots in the unknown and complicated environment [4] [16] [19], assumed that robots are able to follow a wall in a given environment. However in practice on a real robot, wall following using real sensor data is not always straightforward to implement.

Research has been reported on mobile robot wall following navigation using real ultrasonic sensors where the ultrasonic sensors have been used for measuring range information. Because of the uncertainty of direction measurement inherent in range only ultrasonic sensors, some researchers assume that the wall is planar. Such assumptions help to estimate the orientation angle of the wall by continuous range measurement [21] [5]. For the case of complicated or curved environments, [2] a sonar ring is used and assumptions are made concerning the direction of the wall from sensor readings. Several other researchers attempt to extract information from the environment from a scan series of range measurements each of which has wide uncertainty in bearing angle [8] [11] [14].

2.1.2 New strategy for wall following

The principal idea of conventional wall following algorithms is to maintain a set distance to a wall using a series of range measurements. **When the bearing to the nearest point on an obstacle is measured, it becomes possible to follow the surface by just moving in a perpendicular direction to that bearing.**

It is possible to track around a convex corner (Fig.1) and a concave corner (Fig.2), not to mention the plane surface. Curved surfaces (Fig.3), can be followed with the same simple strategy.

This is very simple algorithm, but the following constraints are required for the robot to achieve wall following wall :

- An accurate direction measurement to the nearest point on a target.
- A sufficiently fast measurement cycle compared to the velocity of the robot. In Figures 1 - 3, the circles show the distance to the nearest point on the object. When the direction to the nearest point is measured fast enough compared to the forward speed of the robot, it is possible to keep the same distance to the object even by only using angle information.
- The robot is controllable to move in any direction.

When the motion of the robot is controlled using only the measured direction in this strategy, the difference between desired and real distance to the wall will be accumulated. So, to reduce such difference and to keep the desired value of distance to the wall, the difference between desired and measured distance may be used to slightly modify the direction of robot motion.

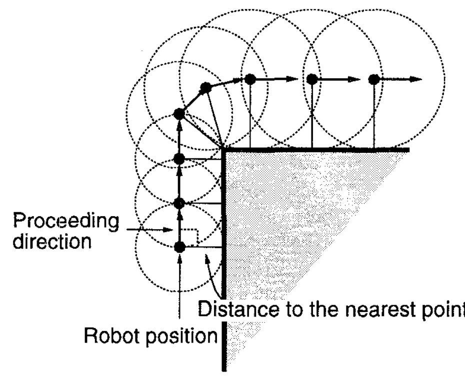

Figure 1: Following the convex corner.

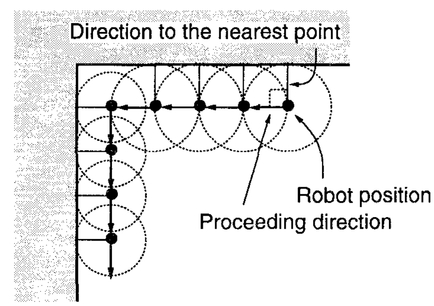

Figure 2: Following the concave corner.

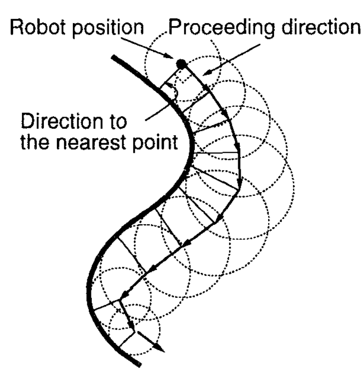

Figure 3: Following the carve surface.

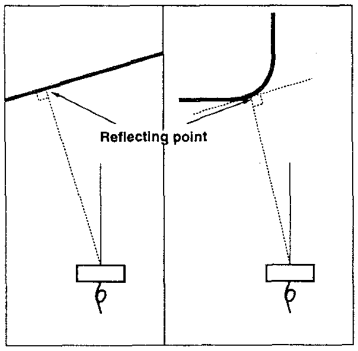

Figure 4: The bearing angle to the reflecting point is showing the perpendicular direction of the nearest point.

2.2 An ultrasonic sensor

2.2.1 Background – Specular reflection of ultrasound

A pulse-echo ultrasonic sensor is well known for its simplicity and low expense for robotics applications. It can detect easily the range to a suitable reflecting object. However the accurate direction to the reflecting object is not easy to measure in the conventional ultrasonic sensing since the direction of the object is estimated based on the heading direction of the transducer and its directivity. However the directivity is not sufficiently sharp in actual transducers.

The conventional method 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 the surface of the wall which is perpendicular to the incident direction or curved surface of a convex corner (Fig.4). That is, geometrically, the ultrasonic wave reflects from the locally minimum point in a direction - distance map. 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. So, if the direction in which the leading edge of reflected echo propagated from is accurately detected, it will be the most suitable information for the wall following approach proposed above.

2.2.2 Bearing angle sensing by a single transducer

Several papers have reported different approaches to measuring accurate direction to the reflecting point using multiple receivers, template matching, etc. under the assumption that the echo comes from a single or discrete reflecting point [3] [6] [10] [13] [15] [17] [20]. Use of multiple receivers requires more hardware and the template matching method requires a significant amount of signal processing. The received echo pulse shape is strongly related to the bearing angle to arrival direction [9]. It is well known that the amplitude of the echo is largest perpendicular to the transducer face and also depends on the distance of flight. It is not as well known that the peak frequency component of the echo also depends on the bearing angle and is not greatly effected by range [22]. Here we propose a new method of bearing measurement expoiting this frequency dependency of the echo.

The echo pulse shape is dependent on the propagation distance due to the dispersive effects of air absorption [9]. However, over short distances of flight, less than one or two meters, this does not have a significant effect on the peak frequency of the echo spectrum. Thus the relationship between this peak frequency and the direction of the reflecting object can be exploited practically for determining the bearing over short ranges [22], without resorting to multiple transducer schemes.

With respect to the pulse-echo method, the direction to the reflecting point can be measured by examining the spectrum of the echo as in [22]. However, calculating the power spectrum for each echo is computationally expensive and not suitable for fast measurement. A faster and simpler approach, conceptually similar to examining changes in peak echo frequency, is to measure the time difference between the zero-crossing points of the echo. By selecting consecutive zero crossings after the leading edge of the echo, a half cycle period of the echo can be measured as shown in Fig.5. This approach has also the important advantage that it would be possible to implement the algorithm with simple hardware.

The relationship between the half cycle period and the angle to the reflecting point from the transducer is difficult to derive theoretically. A more pragmatic approach is taken here, that also serves as a calibration function. A look-up table can be easily constructed experimentally [23]. For example, the relationship between the half cycle period and the direction to the reflecting point was measured using a plane reflector at a range of 370 mm from the transducer as shown in Fig.6 (See Section 3.1 for the experimental setup). The zero crossing times are measured by using linear interpolation between samples of differing signs above a noise threshold.

Due to the symmetrical shape of the transducer, there is no way of determining the sign of the echo arrival angle with respect to the transducer normal. However, during repetitive measurements, the direction of the reflecting point does not change abruptly when tracking a single target. Therefore, by choosing a suitable bias point away from the point of symmetry and by careful steering operation of the transducer, the echo arrival direction can be restricted to lie on only one side of the symmetric function shown in Fig.6, and it is possible to measure the change of the angle in a signed sense.

The construction of the look-up table before the experiment is achieved by placing a wide plane in front of the transducer and rotating the transducer. The half cycle period data (Fig.5) was collected at intervals of 0.5 degrees, and a polynomial least squares fit applied. The middle of the useful data set is defined as the bias angle.

In the measurement process, the half cycle period is measured by a single transmit/receive cycle. The angle is obtained from this measured half cycle period and the look-up table.

When the look-up table is used during measurements, values outside the range of the look-up table are ignored.

As an example, the measured angle data using a planar board at 50 cm is shown in Fig.7 (See Section 3.1 for the experimental setup). In this measurement the look-up table was prepared with the data at 42 cm, and zero degrees corresponds to the bias angle of 10 degrees in the look-up table. The results show that this method is possible to measure the angle ± 1 degree in accuracy 10 degrees in range.

2.3 Proposal of wall following method with ultrasonic sensor

In Section 1, we have proposed a wall following motion strategy using the direction to the nearest point in wall. Also we have presented a simple and fast method to measure the direction in Section 2. By combining the motion strategy and the sensing method, a simple and robust method for wall following behavior of the mobile robots can be realized.

3 Experiment

Using the proposed algorithm and the new sensing method, wall following experiments with a nonholo-

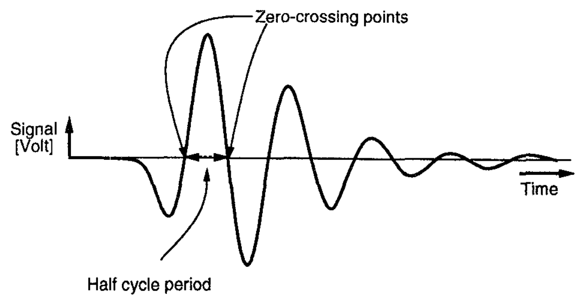

Figure 5: Zero-crossing points and measured half cycle period.

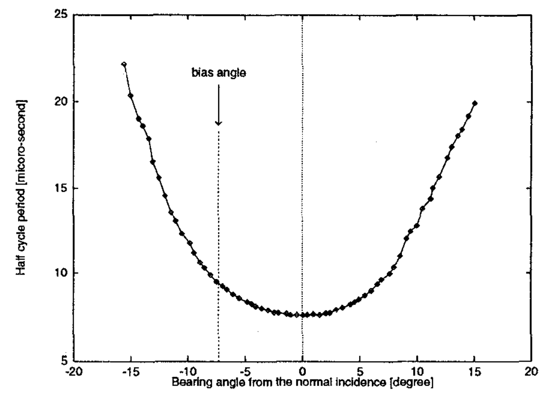

Figure 6: Relationship between angle and the half cycle period. The bias angle is used for overcoming symmetry.

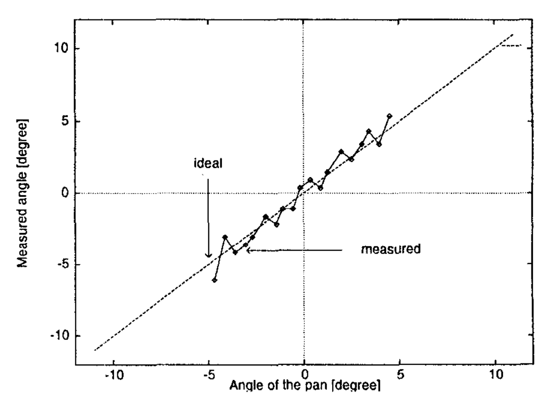

Figure 7: Measured angle by the zero-crossing method using a plane reflector at distance 50 cm. Zero degrees in angle corresponds to a bias angle of 10 degrees.

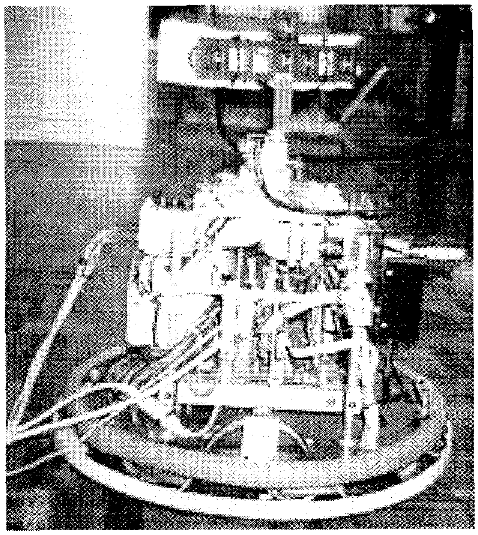

Figure 8: The robot Werrimbi used in the experiment. Werrimbi is 560mm in diameter and 650mm in height. The distance between odometry wheels is 371 mm and the maximum velocity is 0.3 m /sec.

nomic mobile robot have been performed.

3.1 Robot and sensor hardware

The mobile robot, named Werrimbi, used in this experiment is shown in Fig.8. The size of Werrimbi is 560 mm in diameter and 650 mm in height. It has the PWS (Powered Wheel Steering) mechanism, and each powered wheel has independent odometry wheels. The distance between odometry wheels is 371 mm and the maximum speed is 0.3 m/sec.

The communication backbone of the robot is an ISA AT Bus. Through it, a 486DX2-66MHz processor board controls a custom made sonar sensor card and a motion control card. The motion control card provides PID control of pan/tilt motors and locomotive motors. For every motor, an encoder provides feedback information. The servo period of the PID control is 400 μsec for each loop. The software control of the robot is performed with a real-time multitasking operating system called RTKernel.

The robot has five Polaroid 7000 series electrostatic transducers [18] with their front grills removed. The beamwidth of the transducer driven with a 300 V wide band pulse is approximately 50 degrees depending on the range and signal to noise ratio of the receiver [7]. Just one central transducer was used in this experiment. The panning angle was set at first, and after

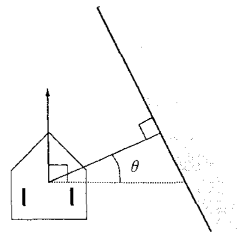

Figure 9: The perpendicular direction to the proceeding direction of the robot is set as zero degree. The measured bearing angle to the nearest point is θ.

that pan-tilt motors were not used in this experiment. An ADC samples the reflected echo signal at a rate of 1 MHz. The proposed method requires only the zero-crossing times from the receiver wave form, and these are extracted from the entire echo waveform in software instead of designing special purpose hardware.

3.2 Control of the PWS vehicle

For controlling the nonholonomic mobile robot with PWS (Powered Wheel Steering) mechanism, a simple direction control feedback loop was installed as follows

The reference velocity of right ω_r and left ω_l wheels are given as

$$\omega_r = \omega_s - k\theta \tag{1}$$

$$\omega_l = \omega_s + k\theta \tag{2}$$

where ω_s is the wheel angular velocity for the desired translational velocity of the robot (ie. 0.1 m/second), θ is the bearing angle to the nearest points measured by proposed ultrasonic sensing, and k is the feedback gain suitably chosen at the experiment (Fig.9).

Since, the translational velocity and angle velocity of the robot are expressed as

$$\begin{bmatrix} V \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{R}{2} & \frac{R}{2} \\ \frac{R}{T} & -\frac{R}{T} \end{bmatrix} \begin{bmatrix} \omega_r \\ \omega_l \end{bmatrix} \tag{3}$$

where, R is the diameter of wheels and T denotes the distance between wheels.

The resultant velocity of the robot are as

$$\omega = k\frac{R}{T}\theta \tag{4}$$

$$V = 2R\omega_s = 0.1m/sec \tag{5}$$

Giving the feedback as shown, the robot is supposed to move with constant forward speed keeping the same distance to the object, when sufficient accuracy of angle data and sufficiently fast sampling rates are guaranteed in the measurement.

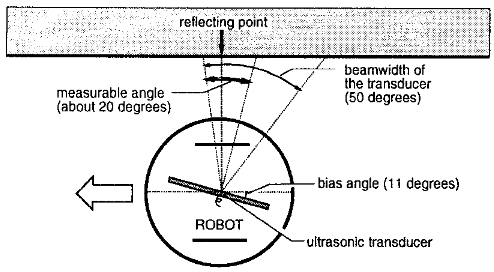

Figure 10: The relationship between the robot and the pan angles.

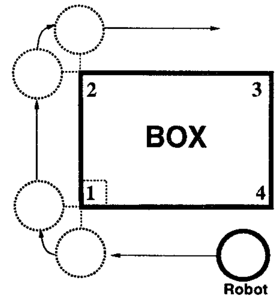

Figure 11: The robot follows a box with right angled corners.

3.3 Experimental environment

Experiments using boxes which have different corner angles were performed. The size of the box was 610 × 410 × 820 mm. The angle of the corner were changed 70, 75, 90, 105, 110 degrees.

At first, the robot is set in front of the box and the transducer is pointed at the bias angle to the box (Fig.10). The robot commences moving with continuous ultrasonic measurement.

3.4 Experimental result

The robot successfully followed the boxes with different corner angles. These experiments show the effectiveness of the proposed angle-measuring method on a real robot. In these results, the distance is kept almost constant. Even during turning around corners with different angles by just controlling motion using only bearing information. And it indicates that keeping the same angle to the reflecting point is an effective way to follow the surface of the object.

The measured angle and distance in the experiment for the right angle corner box (Fig.11) are shown in Fig. 12. In Fig.12 the top plots are the measured angle when the robot is following the box. The bottom plots show the distance to the box from the robot. In these results, the distance is kept almost constant, even whilst turning corners with different angles by just controlling motion using only bearing information.

Sometimes, especially at corners, the angle measurement fails because no echo is detected. For the case that the measured half cycle period was out of the range of the table, it was ignored.

To avoiding any failures in the experiments, it is necessary to make the measurement cycle faster, and keep the reflecting point within the directivity that has sufficient amplitude. This can be achieved by de-

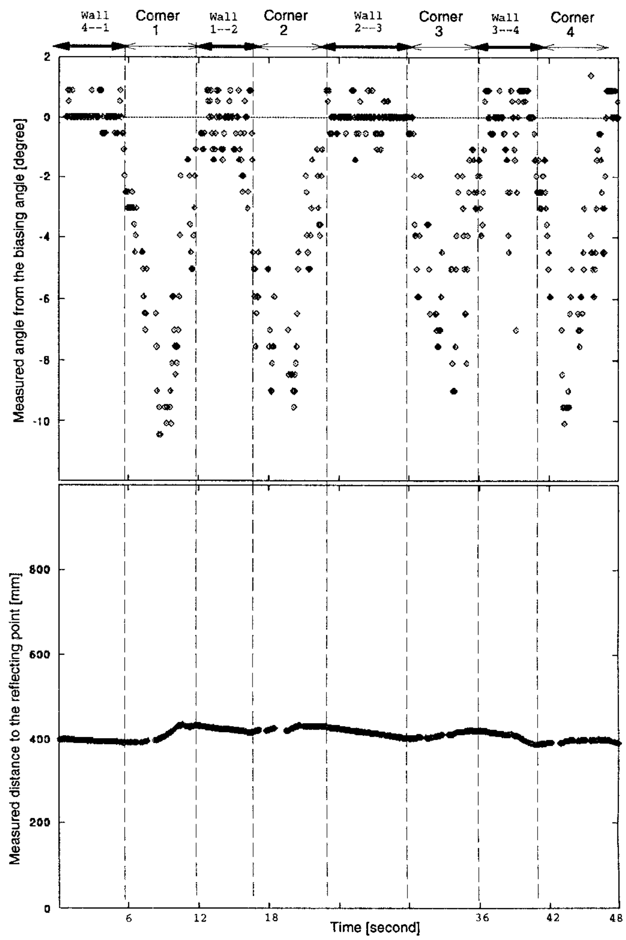

Figure 12: Measured angle and distance to the reflecting point when following the box with right angled corners.

tecting the zero-crossing points directly in a hardware implementation.

4 Conclusion

In this paper, we have presented a simple wall following method using an accurate angle measurement approach, and a new ultrasonic sensing method to measure accurate bearing angle of the reflecting point. For showing the potential of the method, only the angle information was used in the experiments. The experimental results show that the approach is effective.

Acknowledgments

We thank Prof.Jarvis and Mr.Curmi for their support and assistance. The exchange study between Tsukuba and Monash Universities has fostered this research which is partially supported by the scholarship from the Dept. of Japanese Studies, Faculty of Arts at Monash University and an Australian Research Council large grant.

References

[1] Alami,R., and Simeon,T. 1994. Planning robust motion strategies for a mobile robot. *Proceedings of IEEE International Conference on RA.* San Diego CA, pp.1312 - 1318.

[2] Ando,Y., and Yuta,S. 1995. Following a Wall by an Autonomous Mobile Robot with a Sonar-Ring. *Proceedings of IEEE International Conference on RA.* Nagoya,Japan. pp.2599 - 2606.

[3] Barshan,B., and Kuc,R. 1990. Differentiating Sonar Reflections from Corners and Planes by Employing an Intelligent Sensor. *IEEE Transactions on Pattern Analysis and Machine Intelligence* Vol.12, No.6, pp.560 - 569.

[4] Budenske,J., and Gini,M. 1994. Why is it so difficult for a robot to pass through a door way using ultrasonic sensors ? *Proceedings of IEEE International Conference on RA.* San Diego CA, pp.3124 - 3129.

[5] Everett,H.R. 1995. Sensors for Mobile Robots: Theory and Application. A K Peters.

[6] Kleeman,L., and Kuc,R. 1994. An Optimal Sonar Array for Target Localization and Classification. *Proceedings of IEEE International Conference on RA.* San Diego,USA. pp.3130 - 3135.

[7] Kleeman,L., and Kuc,R. 1995. Mobile Robot Sonar for Target Localization and Classification. *International Journal of Robotics Research.* Vol.14, No.4, pp.295 - 318.

[8] Kleeman,L. 1996. Scanned Monocular Sonar and the Doorway Problem. *Proceedings of IEEE/RSJ International Conference on IROS.* Osaka,Japan. pp.96 - 103.

[9] Kuc,R., and Siegel, M.W. 1987. Physically Based Simulation Model for Acoustic Sensor Robot Navigation. *IEEE Transactions on Pattern Analysis and Machine Intelligence.* Vol.9, No.6, pp.766 - 778.

[10] Kuc,R. 1996. Biologically Mobivated Adaptive Sonar System. *Journal of Acoustical Society of America.* Vol.100, No.3, pp.1849 - 1854.

[11] Leonard,J.J., and Durrant-Whyte,H.F. 1991. Mobile Robot Localization by Tracking Geometric Beasons. *IEEE Transactions on Robotics and Automation.* Vol.7, No.3, pp.376 - 382.

[12] McKerrow,P.J. 1993. Robotics. *Addison - Weslsy.*

[13] McKerrow,P.J., and Hallam,J.T.C. 1990. An Introduction to the Physics of Echolocation. *Proceedings of third national conference on robotics of the ARA.* Melbourne,Australia. pp.198 - 209.

[14] McKerrow,P.J. 1993. Echolocation - From range to ouline segments. *Robotics and Autonomous Systems* Elsevier. 11(1993) pp.205 - 211.

[15] Nagashima,Y., and Yuta,S. 1992. Ultrasonic Sensing for a Mobile Robot to Recognize an Environment – Measuring the Normal Direction of Walls. *Proceedings of IEEE/RSJ International Conference on IROS.* Raleigh,USA. pp.805 - 812.

[16] Noborio,H., Yoshioka,T., and Yominaga,S. 1997. On the sensor-based navigation by changing a directin to follow an encountered obstacle. *Proceedings of IEEE/RSJ International Conference on IROS.* Glnouble,France. pp.510 - 517.

[17] Peremans,H. 1994. A Maximum Likehood Algorithm for Solving the Correspondence Problem in Triaural Perception. *Proceedings of IEEE International Conference on MFI.* Las Vegas,USA. pp.485 - 492.

[18] Polaroid Corporation. 1993. Data Sheet for Series 7000 Transducer. *Polaroid OEM Components Group.*

[19] Rimon,E. 1997. Sensor Based Navigation of Mobile Robots. *International Symposium of Robotics Research.* Hayama,Japan.

[20] Sasaki,K., and Takano,M. 1992. Classification of Objects' Surface by Acoustic Transder Function. *Proceedings of IEEE/RSJ International Conference on IROS.* Raleigh,USA. pp.821 - 828.

[21] Turennout,P., and Honderd,G. 1992. Following a Wall with a Mobile Robot using Ultrasonic Sensors. *Proceedings of IEEE/RSJ International Conference on IROS.* Raleigh,USA. pp.1451 - 1456.

[22] Yata,T., and Yuta,S. 1997. Measurement of Reflecting Direction from the Center Frequency of the Echo in Ultrasonic Sensing. *Advanced Robotics: International Journal of Robotics Society of Japan.* Vol.11, No.3, pp.269 - 283.

[23] Yata,T., Kleeman,L., and Yuta,S. Fast Bearing Measurement with a Single Ultrasonic Transducer. *to appear: International Journal of Robotics Research*