A Sonar Sensor for Accurate 3D Target Localisation and Classification

Huzefa AKBARALLY and Lindsay KLEEMAN

Intelligent Robotics Research Centre
Department of Electrical & Computer Systems Engineering
Monash University, Australia

ABSTRACT

This paper presents a novel sonar sensor consisting of three transmitters and three receivers that can localise and classify 3D targets into 16 different naturally occurring indoor classes. The sensor produces sub-millimeter range and sub-degree bearing accuracies using an optimal matched filter time of flight estimator up to a range of 6 meters. The sensor configuration, hardware and processing are described. Experimental results from the sensor are presented.

1. Introduction

Ultrasound is an active, yet unobtrusive, technique for robot sensing. Most research on sonar sensing has concentrated on two dimensional representation and sensing of the environment [1-11]. While important information is present in a 2D view of the world, it is useful to investigate 3D sensing for the following reasons:

- an accurate representation of the environment requires 3D primitives. For example, 3D reflectors not in the same horizontal plane as a 2D sensor can cause measurement errors due to the assumption that all reflectors are in the same horizontal plane.
- less opportunity exists in 3D sensing for incorrect measurement association with a map and incorrect measurement fusion with other sensors
- robust permanent 3D natural beacons can be selected more easily. Examples are the ceiling wall intersections of a room.

Three dimensional sonar target classification based on pulse amplitude measurements [12] and threshold based time of flight [13] have been developed. Other approaches to 3D sonar sensing are reported in [14-16]. We present a new more accurate and robust device based on extending a 2D sonar system proposed in [5], to perform three dimensional sonar target localisation and classification. The accuracy is derived from the use of wide bandwidth transducers and optimal arrival time estimation with match filtering and pulse shape modelling. The sensor is intended for mobile robots operating in indoor environments and can classify targets into 16 distinct classes. Accurate range, azimuth and elevation angles are estimated by the sensor.

The paper is organised as follows: In section 2, we review the approach of classifying 2D targets that forms the basis of the sensor presented here. In section 3, 3D target classifications are discussed and the 3D sensor is described in section 4. In section 5, experimental results obtained from the sensor are presented and section 6 concludes by highlighting applications of the sensor and future work.

2. Sonar Sensing in 2D

A sonar sensor that localises and classifies targets in 2D was introduced in [5, 17]. As our 3D sensor is an extension of the 2D work, a brief outline of the 2D sonar sensor is presented here.

The principle measurement used by this system is the Time of Flight (**TOF**) of a transmitted ultrasonic pulse to return to a receiver after reflecting off a target. The TOF estimation is performed by finding the maximum correlation between the received ultrasonic pulse and a set of stored templates - also called a matched filter. This TOF estimator is the minimum variance estimator when noise is white and Gaussian [18]. The templates are generated by carefully modelling the effects that change the pulse shape from the time of its transmission to its reception - such as angle of transmission and reception and frequency dependent absorption losses in air. By using a matched filter, TOF estimation can be performed to a sub sample precision. The Distance of Flight (**DOF**) is calculated by simply multiplying the TOF by the speed of sound.

2.1. Vector Receiver

Figure 1 shows two receivers R1 and R2 separated by a distance d. The DOF from the transmitter T to the two receivers is r_1 and r_2. Using one receiver and thus one DOF we can ascertain the distance to the transmitter.

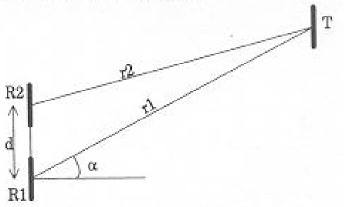

Figure 1: Vector Receiver

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

With both receivers and thus two DOFs r_1 and r_2 we can determine the bearing angle α to the transmitter using

$$\alpha = \frac{\pi}{2} - \cos^{-1}\left(\frac{r_1^2 - r_2^2 + d^2}{2 r_1 d}\right) \qquad (1)$$

With both distance and bearing estimation, the two receiver configuration is said to be a vector receiver.

However in this application, the transmitter does not directly transmit to the two receivers. The ultrasonic pulses reach the two receivers after reflecting off targets. In this case, the distance and bearing estimates made by the vector receiver is to the virtual image of the transmitter rather than the transmitter itself. This is shown in Figure 2.

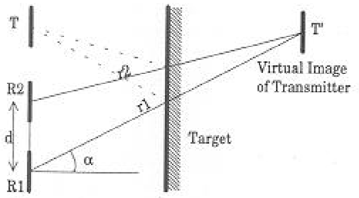

Figure 2: Vector Receiver With Target

When there are many targets, each receiver may have a multitude of DOF estimates for each pulse that is transmitted. The problem arises of pairing the many DOF estimates from the two receivers such that they correspond to the same target. By reducing the receiver separation (***d***) this problem is greatly reduced because both DOFs that form a pair will have similar values. The increased accuracy of DOF estimation, which is obtained by the correlation technique, provides sufficiently accurate bearing estimation with the spacing reduced to 35 mm.

2.2. Target Classification

Two transmitters and two receivers are required to classify targets into planes, corners and edges. Figure 3 shows the 2D sensor array where TR0 is a transceiver, R1 is a receiver and T1 is a transmitter. The receiver of transceiver TR0 and the receiver R1 form a vector receiver. The transmitter of transceiver TR0 and the transmitter T1 are spread apart to enable better performance in target classification.

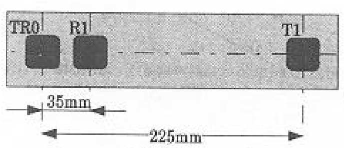

Figure 3: 2D Sensor Array

2.2.1. Detecting Planes, Corners and Edges

Figure 4 shows the 2D sensor array encountering a plane. The label T/V represent the transceiver TR0 and the receiver R1 while T1 is the second transmitter. The r_1 is the distance from TR0 to the virtual image of TR0. The DOF from R1 to the virtual image of TR0 is not shown for simplicity. Using equation (1), the bearing α_1 from the vector receiver to the virtual image of the T1/V' can be determined. Using α_1 and r_1, an estimate for the angles β, α'_2 and the distance r'_2 can be made from the equations below.

$$\beta_{plane} = \tan^{-1}\left(\frac{b\cos\alpha_1}{r1 - b\sin\alpha_1}\right)$$

$$\alpha'_{2plane} = \alpha_1 + \beta$$

$$r'_{2plane} = \sqrt{(r_1 + b\sin\alpha_1)^2 + (b\cos\alpha_1)^2} \qquad (2)$$

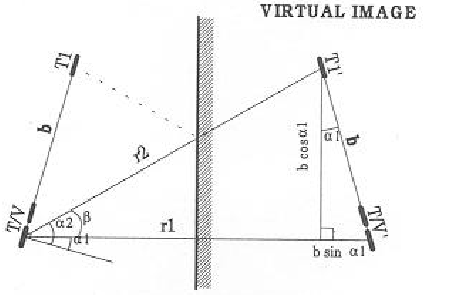

Figure 4: Geometry For Plane Reflector

For each r_2, where r_2 is the DOF from the virtual image of T1 to TR0, an estimate of α_2 can be obtained. If there exists an (r_2, α_2) within a certain error bounds to estimates $(r'_{2plane}, \alpha'_{2plane})$ then the target is classified as plane.

A corner can be analysed in a similar fashion except the virtual image is reversed and the angle $\beta_{corner} = -\beta_{plane}$. For an edge $\beta_{edge} = 0$. The angle β and ranges from each transmitters can be used to discriminate target types. Note that in the case of corners and edges, we have no way of determining their orientation since the virtual image is invariant under a rotation about the corner and edge.

3. Nomenclature of 3D Targets

There are three basic target categories: **planes**, **lines** and **points**. Line targets are formed by the intersection of two planes. Point targets are formed by the intersection of three planes. Line and point targets can be subdivided into **corners** and **edges**. When viewed from the sensor, a corner is a concave orthogonal intersection of planes whilst an edge is the convex intersection of planes.

As the predominant planes that exist in rooms are vertical and horizontal, we constrain ourselves to these two target types and their intersections. Figure 5 depicts an instance of each target type. A **Vertical Line Corner** is a concave intersection of two vertical planes. A **Horizontal Line Corner** is concave intersection of a vertical and a horizontal plane. A **Horizontal Line Edge** and a **Vertical Line Edge** are the same as their Line Corner counter parts but the intersections are convex. A **Point Corner** is a concave intersection of two Vertical and one Horizontal plane. A **Point Edge** is the same as Point Corner but the intersections are convex. Finally, **Complex Point** is a point that has a mixture of concave and convex intersections of planes.

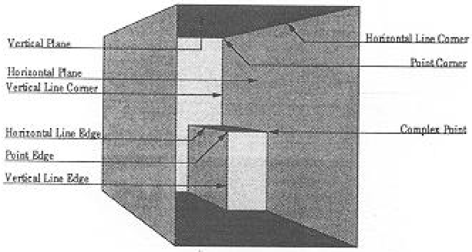

Figure 5: Simplified Room Scenario

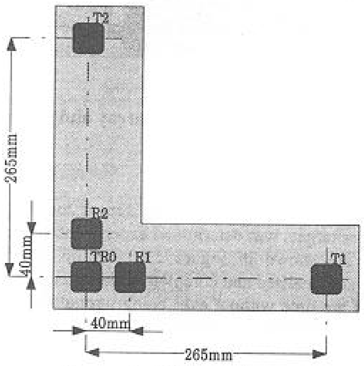

Figure 6: 3D Sensor Array

4. 3D Sensor Configuration.

The sensor configuration that we use for 3D target localisation and classification is shown in Figure 6. This consists of two 2D sonar arrays with one mounted in the horizontal direction and the other mounted in the vertical direction. The transceiver TR0, the receiver R1 and the transmitter T1 form the horizontal sensor array while TR0, R2 and T2 form the vertical sensor array.

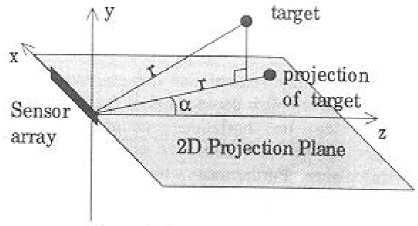

Figure 7: 2D Projection Plane

4.1. 3D Target Localisation

Figure 7 shows the 2D sensor array with its associated projection plane. It projects the target from the 3D space onto a horizontal plane.

Figure 8 shows the 3D coordinate system. The 3D sensor uses the receivers R0, R1 and R2 to form a 3D vector receiver. The receivers R0 and R1 estimate the horizontal bearing angle α whilst the receivers R0 and R2 give the vertical bearing angle β.

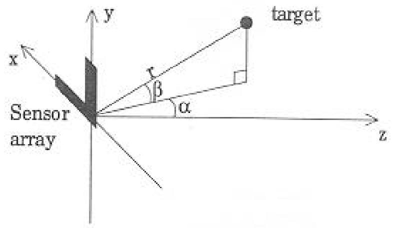

Figure 8: 3D Coordinate System

4.2. Target Classification in 3D

Using the 3D sensor configuration, we are able to make a 2D classification of both the horizontal and vertical sonar views of the target. Each target is classified as one of either a plane, corner, edge or unknown for both its vertical and horizontal views. As a result, there can be sixteen different target types of which nine are positively classified in both views, six are semi classified, while one is totally unclassified. Table 1 shows the nine positively classified target types and the appropriate classifications made by the vertical and horizontal sensor arrays.

When the sensor locates a 3D plane, it determines the normal and a point on the 3D plane. As a result of the sensor array orientation relative to the room, no reflection of ultrasonic pulses can reach it from horizontal planes. It follows that vertical planes are predominantly seen by the sensor.

When the device detects a horizontal line corner or edge, it is able to completely establish the 3D location of the line which is created by the intersection of the two planes. However it cannot ascertain the orientation of these intersecting planes. Assuming that the room consists of predominantly horizontal and vertical planes, we can determine the orientation for the intersecting planes. However, this strategy will fail when planes are not always horizontal or vertical.

When locating vertical line corners and edges, we can similarly establish the location of the line in 3D, however unlike its horizontal counterparts, no assumptions can be made about the orientation of the intersecting planes. Furthermore with these two vertical line target types, the sensor is able to detect any off-vertical slant in the line target as long as the line is contained in a vertical plane that includes the y-axis. A slanted vertical line that meets the above constraint is shown in Figure 9. This localisation property is position dependent. A slanted vertical line may be detected with the sensor in one position while it may be missed if the sensor observed it from a different position. Although the detection of slanted vertical lines is position dependent, the detection of absolutely vertical lines which is a subset of slanted vertical lines is independent of position. These absolutely vertical lines are the more commonly observed target type in indoor scenarios

Table 1: Target Classification

Horizontal Sensor Classification	Vertical Sensor Classification	3D Target Classification
Plane	Plane	3D Plane
Plane	Corner	Horizontal Line Corner
Plane	Edge	Horizontal Line Edge
Corner	Plane	Vertical Line Corner
Corner	Corner	Corner Point
Corner	Edge	Complex Point
Edge	Plane	Vertical Line Edge
Edge	Corner	Complex Point
Edge	Edge	Edge Point

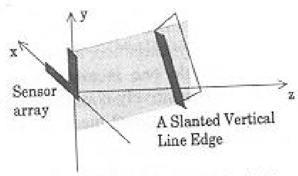

Figure 9: A Slanted Vertical Line

In detecting point corners and point edges, the device returns the 3D position of the point. It does not fix the orientation of the three planes whose intersection created the point. It may be generally assumed that one of the planes is horizontal and the other two a vertical.

5. Experimental Results

Polaroid 7000 series ultrasonic transducers were used in the sensor array. A photo of the sensor array and the analogue interface electronics is given in Figure 10. A custom designed data capture card was built to acquire the complete ultrasonic echoes. The data capture card consists of three 800 kHz 12 bit analogue to digital converters. A computer based on the Intel 486DX/66 was used to perform all computation. The results were taken with the room temperature varying between 20°C to 22°C while the relative humidity varied from 34% to 40%.

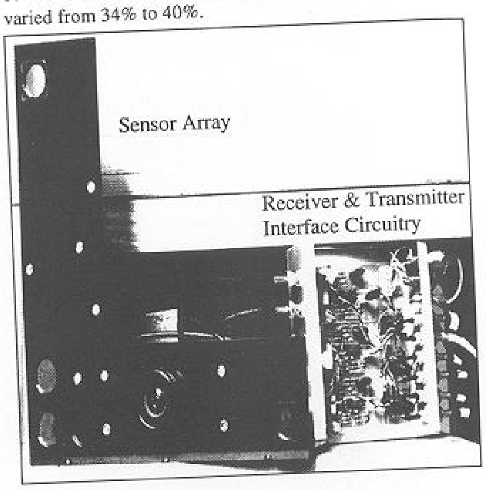

Figure 10: Photo of the sensor array and analogue electronics

5.1. Field of View

The regions in which the sensor localises and classifies targets was determined experimentally and the results are shown in Figure 11. Within the region targets are localised and completely classified more than 50% of the time without ever being wrongly classified. The axis labelling convention is shown in Figure 8. Figures 11(a) and (b) show that both vertical planes and vertical line corners can be detected to approximately 6 meters. The closest that these targets can be detected is limited by the saturation of the receiver amplifiers which occurs at 0.5 m. Figure 11(c) shows the region of detection for a corner point. The corner point was located 380 mm below the xz-plane to model a sensor mounted on a robot. This results in reduced echo energy and consequently the region of view is less than that of a vertical plane. The region of view for a vertical line edge shown in Figure 11(c) was obtained using a cylinder with a diameter of 35 mm. The edge type targets have a smaller region of detection as they return little energy.

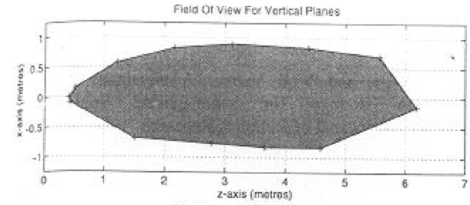

Figure 11 (a)

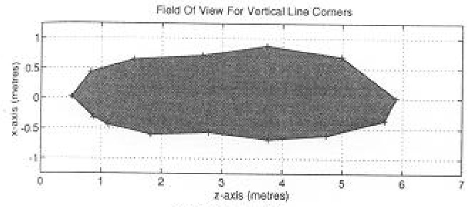

Figure 11 (b)

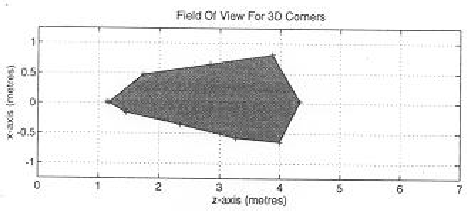

Figure 11 (c)

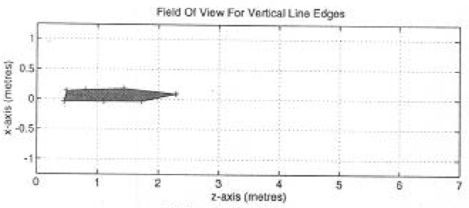

Figure 11 (d)

Figure 11: Field of View Results

5.2. Standard Deviation of Range and Bearings

The absolute accuracy of the 2D sensor configuration was investigated in [5, 17] and we will not reproduce similar results for this system. The standard deviation in parameters for consecutive measurements is investigated. The results are tabulated below in Table 2. They show the standard deviation in both distance and bearing estimates for 20 consecutive measurements of a vertical plane that is directly in front of the sensor array. The standard deviation of the range estimate is less than a millimeter while the standard deviation in bearing estimation is less a few tenths of a degree.

Standard Deviation	Vertical Plane 1.01m away	Vertical Plane 3.22m away
Range (mm)	0.23	0.51
Angle α(degrees)	0.0823	0.1928
Angle β (degrees)	0.1626	0.2285

5.3. Speed of Operation

The dominant factor in the speed of operation of the sensor is the time taken in estimating the time of flight via correlation and increases with the number of targets. A single plane at 3 meters takes 4 seconds to localise and classify. This will be reduced significantly when the computation is optimised.

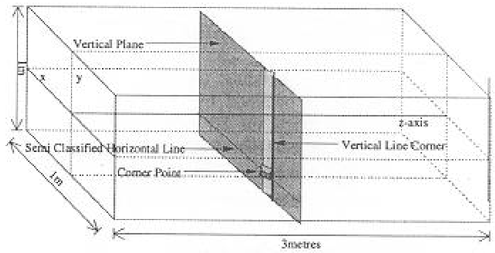

Figure 12: Sensor screen dump showing 4 different 3D objects localised and classified simultaneously.

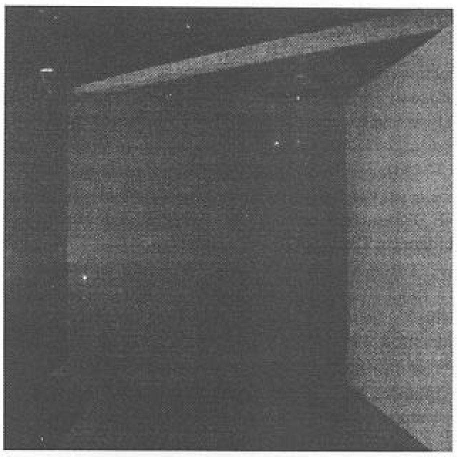
Figure 13: A camera view of the scene in Fig 12.

5.3. Multiple Target Demonstration

The sensor has the capability of simultaneously localising and classifying multiple targets with one measurement cycle. Figure 12 shows the sonar view of the multiple target scene and Figure 13 shows the more conventional visual view of the same scene from a camera mounted on the sensor.

6. Concluding Remarks

We developed a sonar sensor that can localise targets in 3D to sub-millimeter accuracy in range and less than 0.2° angle. The targets are classified into sixteen types of which nine types are classified without unknowns in either horizontal or vertical views. The region of detection is suitable for indoor mobile robots. The sensor can be used for robot localisation and map building. To fix position in a known floor plan, we need two {x,z} independent target observations. By allowing the sensor array to rotate about the y-axis, we increase the likelihood of observing these two required targets.

For 2D map building tasks, the sensor will improve the results obtained by its 2D predecessor. When creating 2D maps, the 2D sensor was not able to verify whether targets detected were in the same horizontal plane as the sensor.

With the increased accuracy and reliability that is afforded by the 3D sonar, sensor data fusion with other information sources is being considered. Future work will concentrate on fusing a camera view with the sonar measurements.

References

[1] B Barshan and R Kuc, "Differentiating sonar reflections from corners and planes employing an intelligent sensor", IEEE Transactions on Pattern Analysis and Machine Intelligence, 1990. **12**(6): p. 560-569.

[2] O 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, 1991. **13**(12): p. 1260-1269.

[3] J Budenske and M Gini. "Why is it so difficult for a robot to pass through a doorway using ultrasonic sensors?", in *IEEE Conference on Robotics and Automation*. 1994. San Diego CA:

[4] J Iijima and S Yuta, "Searching unknown 2-D environment by a mobile robot with a range sensor", Computers Elect. Engng, 1992. **18**(1): p. 83-98.

[5] L Kleeman and R Kuc. "An optimal sonar array for target localization and classification", in *IEEE International Conference on Robotics and Automation*. 1994 May. San Diego USA:

[6] R Kuc and V B Viard, "A physically based navigation strategy for sonar-guided vehicles", International Journal of Robotics Research, 1991. **10**(2): p. 75-85.

[7] J J Leonard and H F Durrant-Whyte, ***Directed Sonar Sensing for Mobile Robot Navigation***. 1992, Kluwer Academic Publishers.

[8] Y Nagashima and S Yuta. "Ultrasonic sensing for a mobile robot to recognize an environment - measuring the normal direction of walls", in *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 1992. Raleigh NC USA:

[9] H Peremans, *et al.*, "A high-resolution sensor based on tri-aural perception", IEEE Transactions on Robotics and Automation, 1993. **9**(1): p. 36-48.

[10] A M Sabatini and O D Benedetto. "Towards a robust methodology for mobile robot localisation using sonar", in *IEEE Conference on Robotics and Automation*. 1994. San Diego CA:

[11] M Yang, *et al.* "Design of ultrasonic linear array system for multi-object identification", in *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 1992 July. Raleigh NC USA:

[12] M L Hong and L Kleeman. "Analysis of ultrasonic differentiation of three dimensional corners, edges and planes", in *IEEE International Conference on Robotics and Automation*. 1992. Nice FRANCE:

[13] M L Hong and L Kleeman, *A low sample rate ultrasonic sensor system for the differentiation and location of common three-dimensional room features*. 1994, Monash University:

[14] A S Acampora and J H Winters, "Three-dimensional ultrasonic vision for robotic applications", IEEE Transactions on Pattern Analysis and Machine Intelligence, 1989. **11**(3): p. 291-303.

[15] R Kuc. "Three dimensional docking using qualitative sonar", in *International Conf Intell Autonomous Systems IAS-3*. 1993 Feb 15-19. Pittsburgh PA:

[16] S Watanabe and M Yoneyama, "An ultrasonic visual sensor for three dimensional object recognition using neural networks", IEEE Transactions on Robotics and Automation, 1992 April. **8**(2): p. 240-249.

[17] L Kleeman and R Kuc, "Mobile robot sonar for target localization and classification", to appear International Journal of Robotics Research, 1995. .

[18] P M Woodward, ***Probability and Information Theory with Applications to Radar***. 2nd ed. 1964, Oxford: Pergamon Press.