Principles for echo position determination using airborne ultrasound

Georg Kaniak, Herbert Schweinzer

Vienna University of Technology
Institute of Electrical Measurements and Circuit Design
Gusshausstrasse 25/354, A-1040, Vienna, Austria
Phone: +43-1-58801-35444 Fax: +43-1-58801-35499 E-mail: georg.kaniak@tuwien.ac.at

Abstract

Different approaches for determining the position of the reflection point of a transmitted ultrasound signal are investigated assuming a specular environment. Two different principles are outlined: one based on the evaluation of time of flight (TOF) differences at multiple receivers, the second on the evaluation of the directional characteristics of the ultrasound transducer itself. Experimental results are discussed as well as advantages that are gained by combining both methods.

Keywords: Ultrasound, angle determination, scene analysis

1. Introduction

The focus of our work lies on scene analysis using airborne ultrasound for applications like the collision avoidance of industrial robots or the navigation of mobile robots. For this purpose the position determination of reflecting objects is essential, assuming a specular environment. Due to the restrictions of ultrasound in air, especially the relatively slow speed of sound, we consider the use of only one sender together with the evaluation of all returning echoes preferably in a broad angle range as important, thus maximizing the measurement rate.

Different approaches are known from literature to determine the position of an object via echolocation in air [1-5], ranging from beam forming known especially from medical or sonar systems to bionic designs inspired from the impressive abilities of bats. Many of them are suffering from reduced accuracy, spacious design or high effort. We consider the determination of positions and orientations of differently shaped objects from only one sensor position as impractical in terms of reaching an adequate accuracy and therefore prefer compact sensor designs that enable determining reflection points with high accuracy but neglecting influence of object shape. The full three dimensional information about the scene can be gained by combining the measured reflection points from different sensor positions.

One key element for the accuracy of echolocation systems is the echo detection. An overview about echo detection methods can be found in [6]. For high precision TOF estimation, broadband signals linearly modulated in the frequency (chirps) are used in combination with correlation techniques. To reduce the computational effort and also to gain independence of the echo amplitude, we use one bit quantization of the received signals.

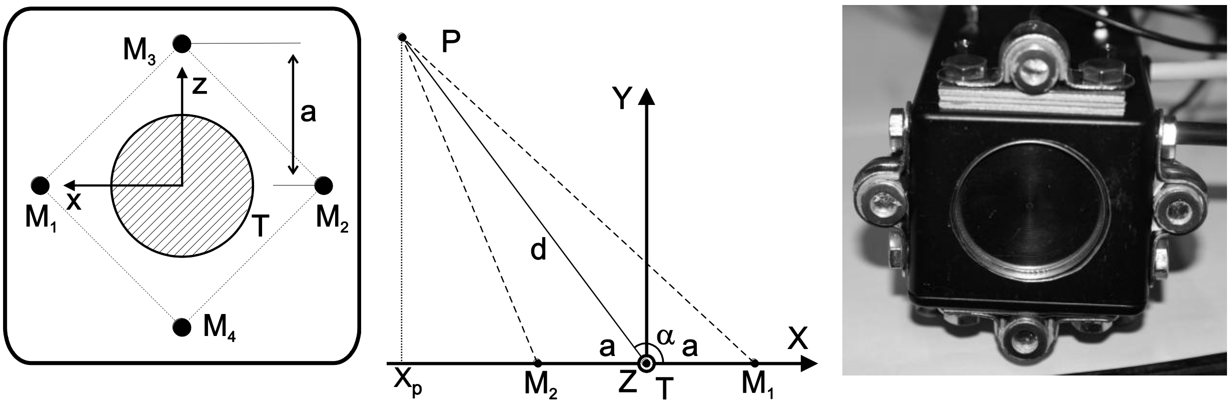
As the TOF of an ultrasound signal can be estimated with high precision using correlation, an approach based on multiple TOF measurements delivers the best results in terms of determining the direction of the reflected signal. However, there remain problems caused by the use of several receivers that can lead to misinterpretation of the collected data and result in object recognition in wrong positions (artifacts). A well known problem is multipath propagation, but also reflection points that partially lie on different objects can be erroneously interpreted as one object. The combination of two different methods for localizing reflection points enables to deal with these challenges.

2. Localization by evaluation of TOF measurements at multiple receivers

Measuring the TOF from one sender to several receivers reduces the localization of a reflection point to a geometric problem, as the TOF values are interpreted as length measurements from the sender to the reflecting object and back to the receiver. A high resolution of the TOF measurement provided by using broadband signals in combination with correlation allows high resolutions in the determination of the spatial position of the reflection point. Restricting the system to only one sender is a good choice for a high measurement rate that is only limited by the TOF of the largest distance. For reliable length measurements the air temperature has to be known, as it has a strong influence on the speed of sound. This can be done by a temperature sensor or a reference reflector with known distance.

A basic system for object localization using one sender and four receivers was presented in [7]. This sensor (Fig. 1) is better suited for 3D localization tasks than more from biology inspired ‘bat-heads’ [5] that are equipped with only two receivers and one sender in the center. The second pair of receivers allows 3D position estimation of reflection points which is a central demand of generic use.

A new sensor system was built based on the same principle, however using self built receivers assembled from ferroelectret-foil to maximize the usable bandwidth (Fig. 1b). A large bandwidth of the signal is not only useful to get a good correlation result for echo detection, but also to evaluate the directional characteristic of the sender as described in chapter 3.



a) b)

Fig. 1. Sensor configuration and schematic of reflection point determination (a), design of the new sensor (b).

For the configuration in Fig. 1a the Cartesian coordinates of a reflection point can be calculated by equations (1-3) with l_1 through l_4 as the distances corresponding to the TOF measurements at the four receivers.

$$d_{12} = \frac{(l_1^2 + l_2^2)/2 - a^2}{l_1 + l_2} \qquad d_{34} = \frac{(l_3^2 + l_4^2)/2 - a^2}{l_3 + l_4} \tag{1}$$

$$x_p = (l_1 - l_2)\frac{l_1 \cdot l_2 + a^2}{2 \cdot a \cdot (l_1 + l_2)} \qquad z_p = (l_3 - l_4)\frac{l_3 \cdot l_4 + a^2}{2 \cdot a \cdot (l_3 + l_4)} \tag{2}$$

$$y_p = \sqrt{d^2 - x_p{}^2 - z_p{}^2} \qquad d_{12} = d_{34} = d \tag{3}$$

The distances d_{12} and d_{34} are equal for a point reflector. As shown in [7], the differences for different object types can be neglected if the sensor is built compactly, respectively the base distance *a* between transmitter and the microphones is small enough, e.g. 40 mm.

3. Utilizing the directional characteristics of the transducer

For numerous ultrasound sensor applications a narrow beam is desired for scanning the region of interest line by line, i.e. in medical systems. If airborne ultrasound is used for object detection in the range of several meters scanning is impractical as it would be too time consuming considering the relatively slow speed of sound in air. Another point is, that in a specular environment only a few discrete reflections occur and from this it follows that scanning would be inefficient. In contrast, we wish to cover a broad angle range with the transducer and to evaluate all returning echoes resulting from one transmitted signal to maximize the measurement rate.

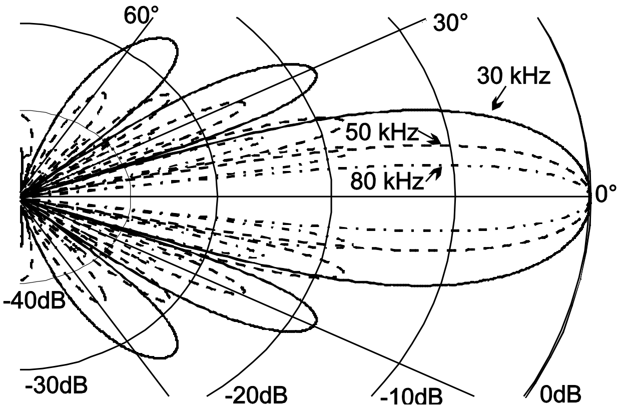


Fig. 2. Radiation pattern of an ultrasound transducer (40mm diameter) according to piston membrane model.

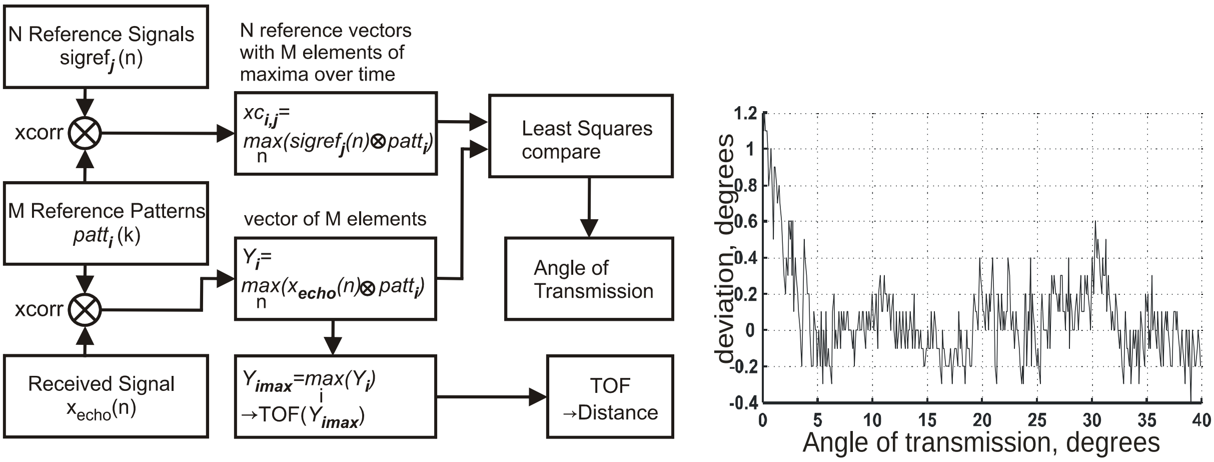
Most available ultrasound transducers behave more or less according to the piston membrane model. Depending on frequency and angle of radiation, this means that the radiation pattern possesses one main lobe followed by several side lobes with signal phase shifts changing from lobe to lobe. The challenge for using ultrasound transducers in a wider angle range is to deal with this directional characteristic.

Additionally, the use of broadband signals like linear chirps has a great advantage in combination with the directional characteristic because a chirp provokes a continuous change of the lobes of the radiation pattern within the signal progress. Thus, phase shifts occur at different frequencies depending on the angle of transmission. The positions of the phase shifts are characteristic for the angle of transmission which can be estimated from a returning echo.

A basic method to determine the angle of transmission of an echo signal is to correlate the signal with reference signals fitting for different angles and to choose the best correlation result. However for a high angle resolution an adequate number of reference signals would be needed resulting in a high computational effort. A more advanced method was presented in [8]. The correlation results of the signal patterns $patt_i(n)$ measured for known angles of transmission with reference signals $sigref_j(n)$ form reference vectors $xc_{i,j}$ that can be compared with the vector of an actual measurement Y_i. For the comparison, a simple algorithm minimizing the quadratic error (5) can be used. Figure 3a shows a block diagram of the algorithm according to equations (4, 5).

$$xc_{i,j} = \max_n(sigref_j(n) \otimes patt_i) \qquad Y_i = \max_n(x_{echo}(n) \otimes patt_i) \qquad (4)$$

$$errf_j = \sum_{i=1}^{m}(Y_i(x_{echo}) - xc_{i,j})^2 \qquad errf_{j,\min} = \min(errf_j) \rightarrow \alpha_{j\min} \qquad (5)$$



a) b)

Fig. 3. Algorithm for angle determination from phase signal patterns (a), measurement results of reachable accuracy (b).

The main lobe of the used transmitter SensComp 600 ranges from 0° to 11° at 75 kHz. However, Fig. 3b shows the accuracy of measuring the polar angle in a range from 0° to 40° sending a chirp ranging from 35 kHz to 75 kHz. Beginning from 4° the deviations of the polar angle remains within -0.4° and +0.6°.

4. A multi receiver system incorporating the transducer's directional characteristic

The first advantage in combining the two methods is the extended angle range of the measurement system. The correlation patterns deliver correct TOF information not only in the main lobe but also for higher angles of transmission. The method is only limited by the worsening of the SNR at higher angles. With the used SensComp 600 transducer polar angles up to about 40° can be measured.

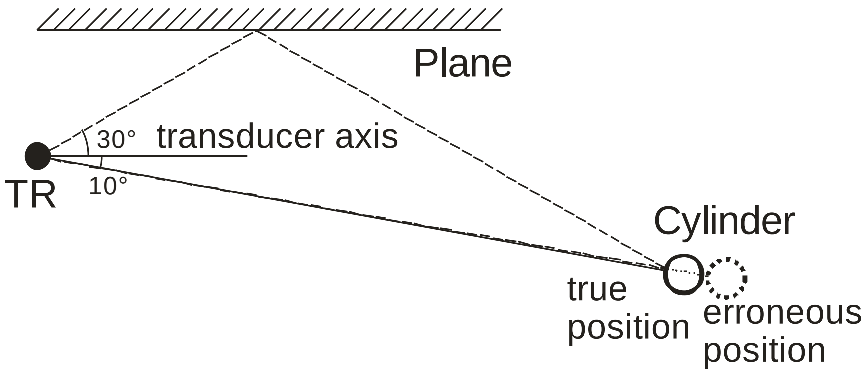


Fig. 4. Detection of multipath propagation.

The second advantage results from the fact that angle information gained independently can be compared to strengthen the reliability of the measurement result. A typical problem is multipath propagation of the signal that leads to misinterpretation of the measured data in systems that rely only on TOF information as shown in Fig. 4. A second echo occurs as the signal is reflected by a plane and returns from the cylindrical object a second time to the sensor (TR). For convenience a planar situation is showed, although the sensor is capable of gaining full 3D information of the reflection points. The TOF information of the second echo would suggest the second reflection point to be in a polar angle of 10° towards the main axis of the sensor. This would lead to the erroneous object position shown in Fig. 4. However, the evaluation of the phase information of the returning echo clearly shows that the signal was transmitted with a polar angle of 30° towards the plane. As this information does not match the four receiver TOF angle measurement, the second echo will be identified as effect of multipath propagation and therefore dropped in terms of estimating the 3D scene. However, if the second echo is assigned to the cylindrical object determined by the direct transmitted echo by plausibility analysis, even information about the position of the reflection point on the plane can be gained.

In this situation, also further echoes may occur which are not drawn in Fig. 4. This results from reflecting back from the object over the 30° path which delivers artifacts in 30° direction. These echoes can also be eliminated as the second one and enhances the plausibility assigning the echoes to a multipath situation.

5. Conclusion

In this paper, two methods for determining the reflection point of a broadband ultrasound signal in a specular environment were discussed. While TOF information at multiple receivers allows determining the reflection point with high precision, phase shifts of a chirp signal deliver information about the angle of transmission at the sender already using only one sender and one receiver. The advantages of combining both methods that lead to an extended angle range of the sensor and allow to avoid misinterpretation of measurement data were outlined. Even additional scene information can be gained from multipath propagations.

6. Acknowledgements

Authors would like to thank Prof. Siegfried Bauer and Petr Bartu from the Institute of Experimental Physics, Johannes Kepler University, Linz for their continued support in providing material for our receivers based on ferro-electret foil. We also would like to thank Geronimo Mitaroff for his contribution building the sensor shown in Fig. 1b.

References

1. L. Kleeman and R. Kuc. *Mobile Robot Sonar for Target Localization and Classification*. Journal of Robotics Research. 1995, vol. 14, issue 4.
2. B. Barshan. *Location and Curvature Estimation of "Spherical" Targets using a Flexible Sonar Configuration*. 1996 IEEE Conference on Robotics and Automation, Minneapolis, USA. 1996.
3. H. Peremans, K. Audenaert, J.M. Van Campenhout. *A High-Resolution Sensor Based on Tri-aural Perception*. IEEE Transactions on Robotics and Automation. 1993, vol. 9 (1).
4. B. Barshan, R. Kuc. *ROBAT: A Sonar-Based Mobile Robot for Bat-Like Prey Capture*. IEEE International Conference on Automation, Nice, France. 1992.
5. H. Peremans, A. Walker J.C.T. Hallam. *3D object localisation with a binaural sonarhead, inspirations from Biology*. IEEE International Conference on Robotics and Automation, Leuven, Belgium. 1998.
6. B. Barshan, B. Ayrulu. *Performance comparison of four time of flight estimation methods for sonar signals*. Electronics Letters. 1998, vol. 34, issue 16.
7. G. Kaniak, H. Schweinzer. *A 3D Airborne Ultrasound Sensor for High-Precision Location Data Estimation and Conjunction*. IEEE IMTC 2008, Victoria, Canada. 2008.
8. G. Kaniak, H. Schweinzer. *Advanced Ultrasound Object Detection in Air by Intensive Use of Sidelobes of Transducer Radiation Pattern*. IEEE Sensors, Lecce, Italy. 2008.