Comparison of Two Methods for Determining the Position of Reflection Points Using Ultrasound Echolocation in a Specular Environment

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Abstract

With the final goal of three dimensional scene analysis by ultrasound echolocation, two approaches are discussed for determining the position of reflection points on specular objects. The first approach uses time-of-flight information at four receivers for the estimation of distance and direction. The second one is based on determining the angle of transmission by evaluating the directional characteristic of the signal pattern. Finally both methods are compared.

1. Introduction

Our work is aimed at scene analysis using ultrasound echolocation in an industrial indoor environment. As the air damping of ultrasound signals increases with the frequency, echolocation in air is restricted to lower frequencies, in our case below 100kHz, if distances up to 10 meters are to be measured reflectively. These low frequencies correspond with wavelengths in the range of millimeters. Therefore if we consider the roughness of most surfaces in the mentioned industrial environment to be far below the wavelength the assumption of a specular environment is justified.

Due to the nature of the specular environment approaches different from known methods in medical systems or sonar applications are favoured. Especially scanning line by line with a narrow beam is not appropriate for two reasons. First, the slow speed of sound in air represents an important restriction to the measurement rate that would make scanning in the described way too time consuming. Second, because the surfaces are expected to act as mirrors only a few discrete reflections return to the sensor in opposition to i.e. medical systems where echos are expected from every spatial direction and can be combined to images.

Under the mentioned conditions we consider the evaluation of a maximum of information for a single transmitted signal in a wide angle range as vital to maximize the measurement rate of the sensor system. So the task is to detect all returning echoes resulting from one transmitted signal. However, the determination of reflection points from one sensor position is not sufficient for scene analysis in a specular environment. A plane or an edge that behaves as a mirror delivers only one discrete reflection or might even be invisible if the signal is reflected away from the sensor. For this reason, sensor movement is an inevitable condition for getting full 3D information of the scene. Only the trace of reflection points on a specific object gained from different sensor positions allows to determine the object type, its orientation, and spatial position.

2. Echo detection

A critical point for the performance of echolocation systems is the detection of received echo signals. Different detection methods are described in [6]. A method delivering high acurracy is correlative echo detection in combination with broadband signals, although it implicates an increased computational effort. For the systems described in this paper linear chirps are used.

A special form of correlation is used as all signals are one-bit quantized (sign of samples). This one-bit-correlation reduces the computational effort dramatically and brings the benefit to be independent from the amplitude of the received signal over a wide range. This is of importance because the reflected amplitude differs extensively for different object types like planes or edges.

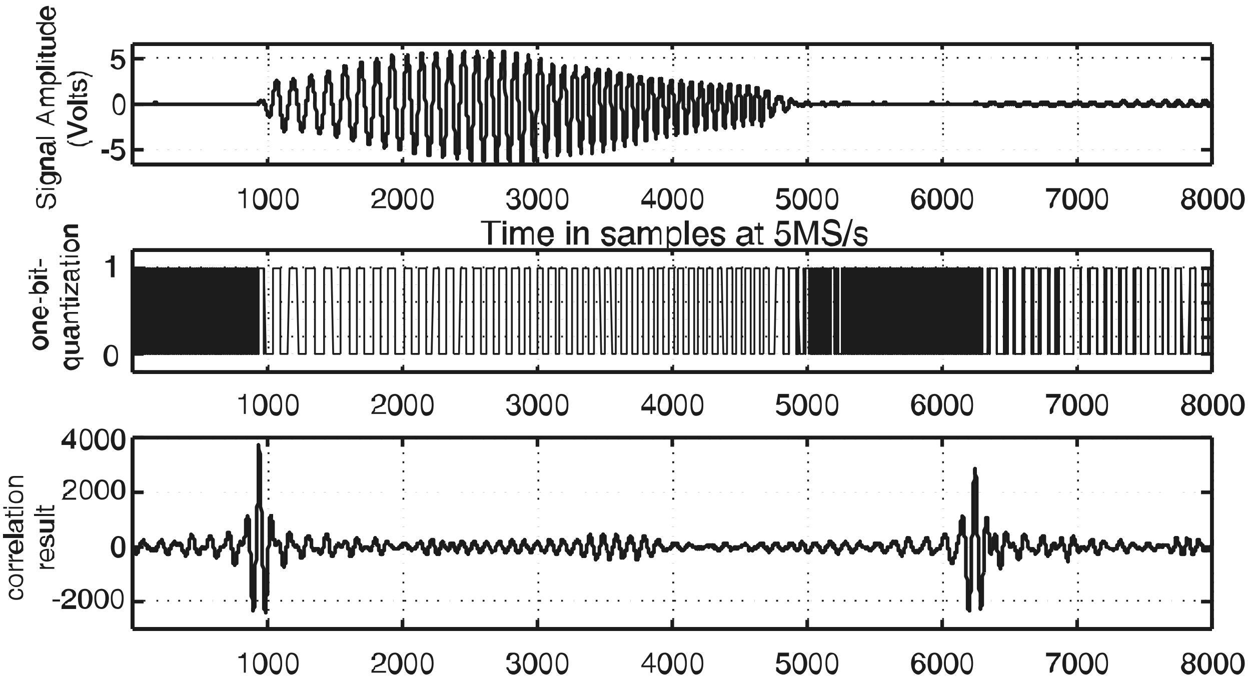


Figure 1: Correlative echo detection incorporating one bit quantization of signals

The correlation function of a linear chirp is a sinc function (sin(x)/x) and the characteristic spike of the function determines the time position of the received echo with high precision. Figure 1 shows the one-bit quantization of received signals and the resulting correlation function. Note that even the weak second echo ist detected without any difficulty. For the experiments described in this paper a high sample rate of 5MS/s was used. With this information the time-of-flight (TOF) of the signal can be calculated. Under laboratory conditions a repeat accuracy in the distance measurements based on the TOF information of about ±0.3mm in a medium range of one to two meters can be reached.

3. Echo position determination by TOF evaluation at four receivers

Due to the high accuracy in distance measurement based on correlative echo detection, a sensor system that estimates the direction of a returning echo by evaluation of TOF-differences at several receivers has a good potential for accurate determination of reflection points. Many different approaches are known from literature, ranging from bionic designs inspired by bats to spacious designs for determining the shape of spherical objects [1-5].

Determining the shape of objects from only one sensor position with sufficient acurracy is hardly possible especially if a compact sensor design suitable for industry applications is desired. For this reason our approach is targeted at determining the reflection points of specular reflections with high acurracy from one sensor position. The full three-dimensional information about the scene can then be gained by evaluating the trace of reflection points on different objects.

A first sensor system consisting of one sender and four receivers was presented in [7]. The use of only one sender is best suited for reaching a high measurement rate of the sensor that is only limited by the TOF of the longest distance. The use of four receivers arranged as a cross (figure 2a) with the sender in the center has many advantages for three dimensional reflection point estimation compared to more bionic designs where for simulating bat ears even movement of the receiver ‘ears’ had to be incorporated.

Each pair of receivers delivers the distance from the sender to the reflection point and one cartesian coordinate of the reflection point (figure 2b). The third cartesian coordinate can then be calculated from the known distance. For a point reflector the two estimated distances are equal. For other object types they differ. However, for a compact sensor design the differences may be neglected as shown in [7].

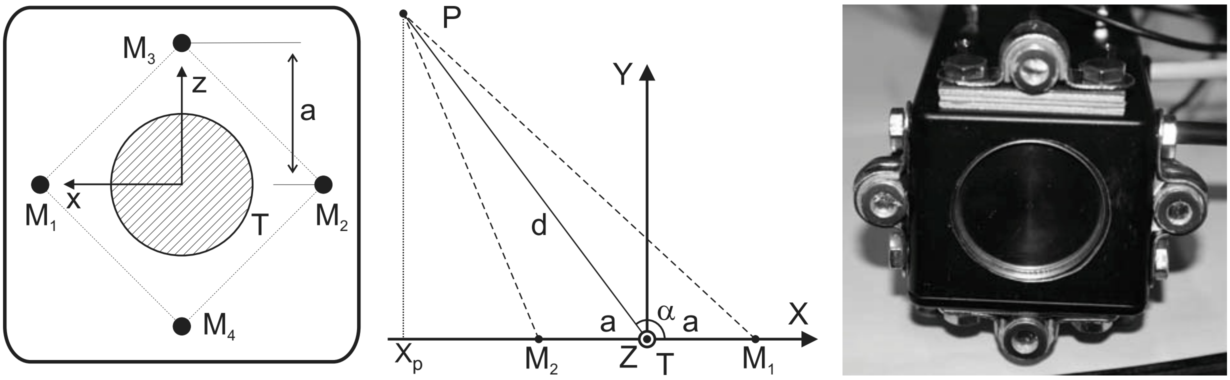
With l1 to l4 representing the distances corresponding to the measured TOF at the four reveivers the position of the reflection point can be calculated according to equations (1-3).

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

$$x_p = (l_1 - l_{2)} \frac{l_1 \cdot l_2 + a^2}{2 \cdot a \cdot (l_1 + l_2)} \qquad z_p = (l_3 - l_{4)} \frac{l_3 \cdot l_4 + a^2}{2 \cdot a \cdot (l_3 + l_4)} \tag{2}$$

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

As the bandwidth of the transmitted chirp signal is essential for the correlative echo detection, a sensor was built based on new self built microphones based on ferro-electret-foil, that allow to exploit the full bandwith of the used SensComp 600 open face transducer from about 30kHz to 75kHz (figure 2c).



a) b) c)

Figure 2: a) Sensor configuration, b) determination of reflection point, c) new sensor assembly

4. Estimating object positions by calculating the angle of transmission by means of the directional characteristic of the signal pattern

For industrial applications, scanning with a narrow beam is too time consuming for echolocation in air. Nevertheless, broadband signals can be used to conduct a limited sweep over the scene within one single signal. The key for doing so is the directional characteristic of the ultrasound transducer that depends on the angle of transmission as well as on the transmitted frequency. In most cases, planar ultrasound transducers can be modeled accoding to the piston membran model that implicates an in-phase vibration of the transducer's active surface.

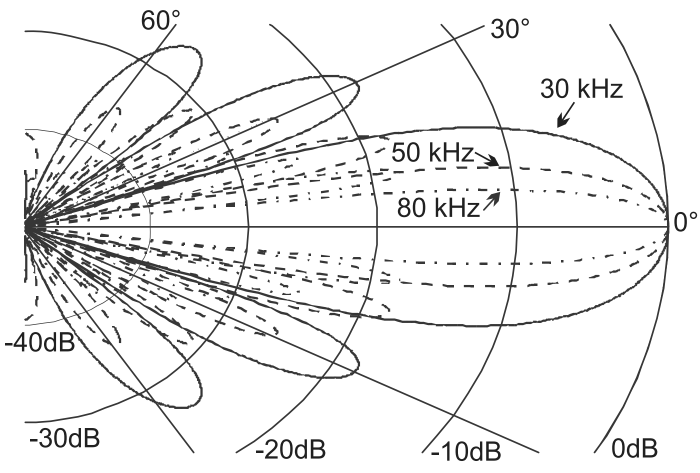
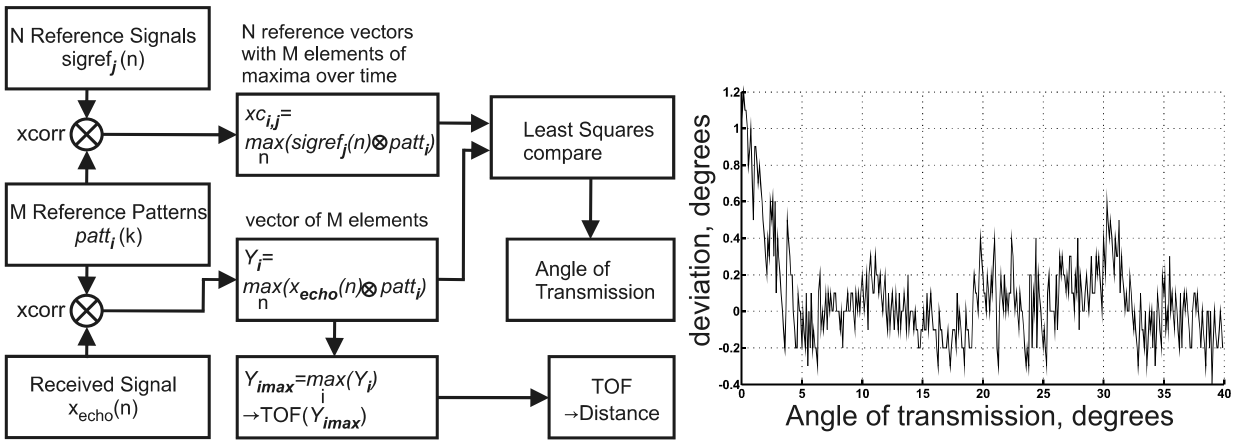


Figure 3: Directional characteristic of a 40mm diameter transducer according to pistone membrane model

The piston membrane model (figure 3) predicts a mainlobe followed by several side-lobes with increasing polar angle from the main axis of the transducer. From lobe to lobe the phase of the transmitted signal changes about 180°.

If a broadband signal like a linear chirp is used the lobes and therefore the phase shifts at a specific angle occur at certain frequencies and therefore time positions of the received chirp. These phase shifts can be used to determine the angle of transmission of the received chirp. To measure the directional characteristic of the transducer, a separate receiver with an omnidirectional characteristic has to be used. If the measurement of the distance and direction of the reflection point at the object is desired, the position of the receiver must be placed in the center of the transducer.

Fundamentally, correlative echo detection using a set of reference signals fittion for different angles is well suited for determining the angle of transmission. The easiest method would be to find out which reference signal results in the best correlation thus being a measure for the angle. For this method a large number of reference signals is needed, if a sufficient angle resolution should be reached. Each of the reference signals would have to be correlated with the echo signal, resulting in a high computational effort.
In [8] a more sophisticated method is presented increasing the angle resolution, while reducing the number of necessary correlations. The point is not only to look at the best fitting reference signal $sigref_j(n)$, but as each echo $x_{echo}(n)$ has to be correlated with all reference signals, to use the height of the correlation function of non-fitting reference signals as additional characteristic value. The vectors Y_i gained in this way can be compared to reference vectors $xc_{i,j}$ previously established. The full algorithm is described by equations (4-5) and shown in figure 4a.



a) b)

Figure 4: Algorithm for detrmining a) angle of transmission and b) measured acurracy

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

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

The algorithm allows an angle accuracy of 1° and below with typical N=10 reference patterns in a range of 0 to 40° (figure 4b).

As described in [9], the measured distances and angles from two sensor positions already allow to determine position and orientation of basic geometric objects like planes, edges and cylinders. Figure 5 illustrates this method for the determination of an edge. As distance and angle of transmission are measured the reflection point has to lie on a circle for each of the two measurement positions. Solutions for the edge that match the measurements are shown in Figure 5.

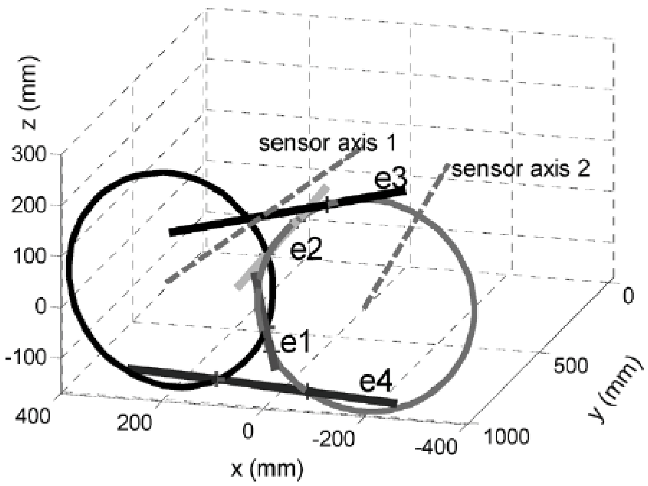


Figure 5: Edge determination with known distance and angle of transmission according to [9]

5. Comparison of position determination by a multireceiver system and by evaluation of signal pattern

Both methods allow the determination of position and orientation of basic geometric objects in combination with measurements from different sensor positions. Another common charcteristic is the use of brodband signals that allow accurate TOF estimation in combination with correlative echo detection. For both systems the repeat accuracy of range estimation based on TOF measurements is about ±0.3mm.

The angle accuracy of the multireceiver based system can reach ±0.05° due to the use of TOF differences that supress deviation caused by air turbulence. The evaluation of phase information with the algorith described in chapter 4 allows an an acurracy of about ±1°. The angle range of the multireceiver based system is typically limited by the main lob of the highest frequency of the transmitted signal. For the used SensComp600 transducer this are 11° (compare figure 3). The correlation patterns fitting for different angles allow distance and angle measurements also at higher angles of transmission which is only limited by the decreasing amplitude in the side lobes. For the SensComp600 transducer angles up to 40° can be measured, dependent of the SNR.

Table 1: comparison of multireceiver sensor system and sensor system evaluating the directional sender characteristic

Features	Multireceiver system	Directional characteristic
Basic precondition	used within main lobe	only one receiver
Receivers	4	1
Angle accuracy	± 0.05°	±1°
Angle range	typical 11°	Up to 40°
Distance accuracy	±0.3mm	±0.3mm
Distance range	reduced at higher angles	up to 30m
Computational effort	4 correlations per echo	Typical 10-20 correlations per echo
Analog hardware effort	4 input channels	1 input channels
Problems of application	Assigning echoes to objects	Centric receiver needs specialized sender

The hardware effort for the multi receiver system is definitely higher because analog amplifer and filter circuits have to be implemented for each channel. Also the echoes received by the four shifted microphones have to be assigned to the same object. This can lead to misinterpretation of data. On the other hand, for the evaluation of the signal pattern the computational effort is higher as more correlations are needed. The use of only one sender and one receiver allows a very compact sensor design. A bief summary comparing main features of both systems is shown in table 1.

6. Conclusion

Two methods for object detection in a specular environment were presented and the differences were outlined. The use of four receivers allows a very accurate estimation of the direction of a returning echo for the price of an increased hardware effort. Evaluating the directional characteristic of the transducer allows to extend the angle range of the measurement. However, the determination of the angle of transmission has a reduced accuracy compared to the four receiver system. Both systems use correlative echo detection to increase accuracy and depend on sensor movement to determine the spatial position and orientation of objects.

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. 2c.

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