# Processing of Ultrasonic Echo Envelopes for Object Location with Nearby Receivers

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***Abstract*— Ultrasonic sonar systems are commonly used for obstacle location in Robotics and Autonomous Navigation applications. When irregular objects have to be located, optimal algorithms for time-of-flight (TOF) estimation, like cross correlation, might be unreliable since complex reflecting surfaces can destroy phase coherence during the duration of the echo. Direct threshold methods acting on the envelope are equally inaccurate. This paper proposes a simple digital processing technique, called selective normalization, that works with the signal envelope and determines robustly the differential time-of-flight (DTOF) of the ultrasonic echoes received by two or more nearby transducers. It is demonstrated empirically that this method improves the positioning accuracy of non pointlike objects.**

***Index Terms*— Ultrasonic technology, Time-of-flight estimation, signal processing, sonar systems, autonomous navigation, personal mobility aids**

## I. Introduction

ULTRASONIC sonar systems are of widespread use for exploration of the environment and obstacle detection in many autonomous systems and robotic applications [1]. With the pulse-echo technique, an obstacle is positioned relative to the transducer unit by its range, computed from the time-of-flight (TOF) of the ultrasonic signals [2], and its angle of bearing, found from the difference of times-of-flight (DTOF) to two or more receivers [3]. This situation is shown in the left part of figure 1, where the range $D$ to the object is found from the mean TOF of both receivers, while the bearing angle $\beta$, in the plane defined by the emitter and receiver transducers, is computed as:

$$\sin\beta = c \cdot t_{12} / d\,, \qquad (1)$$

where $c$ is the velocity of sound in air, $d$ is the separation between receivers and $t_{12}$ is the DTOF of the two received signals.

Many methods exist for computation of both TOF and DTOF. The simplest is the threshold detection of the rising edge of the signals, which estimates the TOF at the time when the ultrasonic echo signal goes over a certain threshold value, set at a sufficiently high level over the ultrasonic noise [4]. This method is simple to implement but does not produce particularly good estimations of the TOF. If the signal can be digitized, curve-fitting algorithms can be used on the rising part of the echo to improve the precision [5], [6]. The correlation, or matched filter, detector correlates the received echo with the emitted signal (for TOF estimation), or the two received echoes between them (for DTOF estimation). Under certain circumstances, this method offers optimum performance, in the sense that it is not biased and exhibits minimum variance, according to the Crámer-Rao criterion [7]. Because signal correlation at ultrasonic frequencies is computationally demanding, many alternatives have been proposed to achieve TOF estimation in systems operating in real time. For example, a technique which combines envelope and phase information for precise ultrasonic ranging is described in [8]; the signal processing takes place in a Motorola MC68HC16 microprocessor. If the TOF is known without ambiguity within a period of the ultrasonic signal, pure phase methods like quadrature estimation [9] can be used, with very low processing requirements.

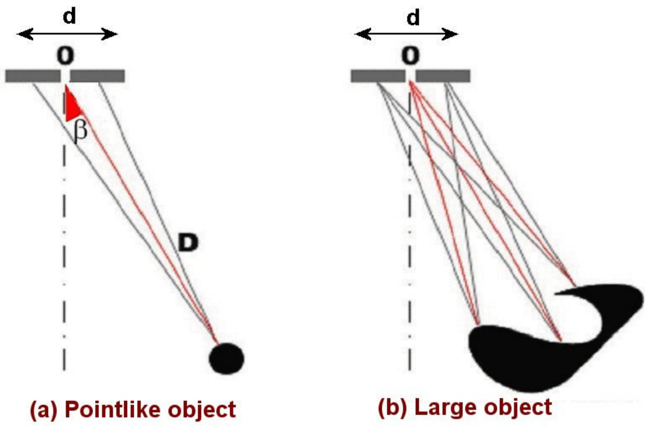


Fig. 1: Positioning of pointlike and non pointlike objects with an ultrasonic system formed by two receivers and a single emitter placed between them.

However, when ultrasonic signals are reflected from large objects present in the environment (as shown in the right part of figure 1), the composition of echoes received from multiple points from the surface alters the phase coherence and distorts the received waveforms [10]. In this case, estimation of the DTOF can be so biased that it is preferable to dispense with phase information altogether. Methods that utilize the correlation to produce robust estimations of the TOF in spite of the deformation suffered by the ultrasonic waveforms do exist [11], [12], but are complex and not feasible to implement in a low-resources system, like a microprocessor or a DSP operating in real time.

By working with the envelope (or baseband) ultrasonic signal, instead of the phase, the maximum attainable precision in the estimation of the TOF, according to the Cramér-Rao criterion, decreases by a factor $f_0/B$, where $f_0$ and $B$ are the central frequency and bandwidth of the ultrasonic signals [3]. However, even in those situations where the phase information is practically irrelevant, an estimation of the location of the obstacle is still desirable, even if it is computed with limited precision. This paper presents a simple but robust algorithm based on the envelope of the ultrasonic signals to achieve this goal.

The next section gives an analysis of the problem encountered when positioning large (non pointlike) objects. In section III, a processing technique, which has been named algorithm of selective normalization, is presented. An experimental setup and empirical results with this algorithm are described in section IV. Finally, the paper offers some conclusions about the new technique.

## II. Analysis of the Problem

Consider the envelope of the ultrasonic echo signals received by two transducers closely placed, as shown in figure 2. As described in the last section, the bearing angle of the reflecting object can be computed from the DTOF, or time lag, between them. However, from the figure it can be ascertained that this time lag depends on the threshold selected for the process. For example, $Lag_2 - Lag_1$ is smaller for threshold 2 than for threshold 1, and close to zero for threshold 3.

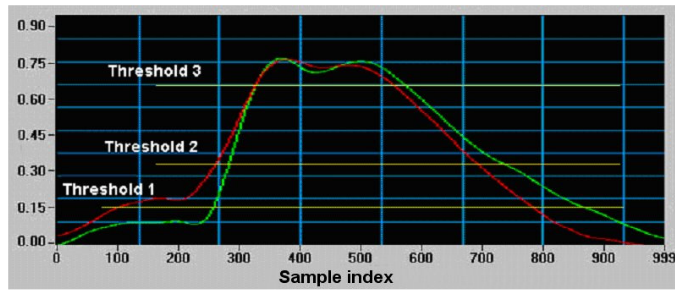


Fig. 2: Experimental signals from the same object and different thresholds for the detection of time of flight.

Even though both signal echoes come from the same object, it is a very common situation that the signal amplitudes might be different, due to different transducer gains, or caused by oblique incidence of the ultrasonic signal on the object. In most of the cases, a standard normalization of both signals is applied by means of the ratio of maximum amplitude values. However, since the value of the maximum of the waveform is a complicated function of the physical shape and orientation of the object as viewed from that individual transducer, this simple method is not very reliable when the object is not pointlike, and might bias the DTOF information contained in the rising part of the echo signal. This fact has been exploited by other researchers to classify objects by their ultrasonic reflections, by using receiver units with more transducers that in our case [13,14]. For example, in figure 3, we present empirical results showing how normalization of the ultrasonic echo envelopes with respect to the absolute maximum of the waveforms does not guarantee good performance of DTOF, since the rising edges of the signals are not parallel (parallelism is an indication that the DTOF can be reliably estimated).

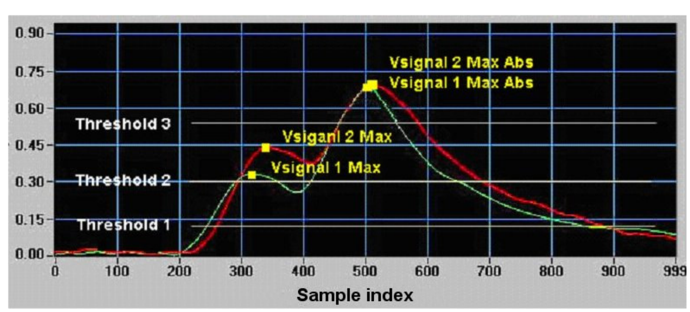

Fig 3: Envelope of two experimental signals from the same object, after normalization.

For this case an *algorithm of selective normalization* has been developed. The objective of this method is to correct the error introduced by the standard normalization in a robust way, and permit a meaningful computation of the DTOF.

## III. Algorithm of Selective Normalization

The start of the echo signal represents the closest point of the object with respect to the receivers, since the remaining of the signal is the sum of the contributions from successive points of the reflecting surface. Therefore, measuring the delay between the starting points of both echoes provides a reliable estimation of the position of a pointlike object or the closest point of a large object, as long as this is point is common for both receivers.

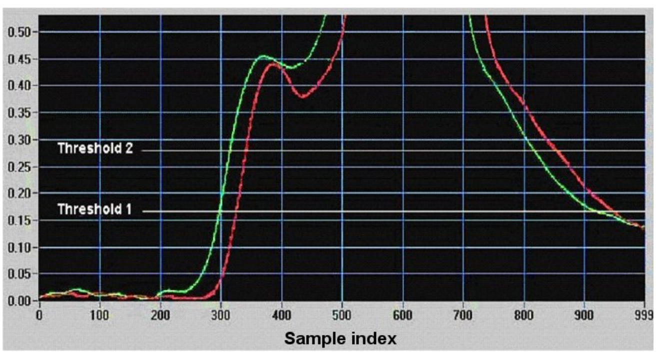


Fig. 4: The signals of figure 3 after applying the algorithm of selective normalization.

One direct solution consists in detecting the beginning of the echoes with a very low threshold; however, this idea is not practical since it is prone to outlier errors caused by signal noise peaks.

The algorithm presented in this paper is based, in a first stage, on normalization at the initial part of the signals by the relation of the amplitude factors at the first maximum or inflection point of the envelope, which might not be the absolute maximum of the complete signal. To determine this point, a search is performed in the acquired signal to detect the point where the signal amplitude drops by a small amount (empirically, we have found good results using a value of 4%) with respect to the previous point. In this way the ideal points to define the ratio amplitudes for the selective normalization are selected as:

$$V_1[n] \geq 0{,}96 \cdot V_1[n+1] \Rightarrow V_{1Max} \qquad (2)$$

$$V_2[n] \geq 0{,}96 \cdot V_2[n+1] \Rightarrow V_{2Max} \ , \qquad (3)$$

where $V_1[n]$ and $V_2[n]$ are the digitized ultrasonic echoes, $n$ is the sample index, and $V_{1Max}$ and $V_{2Max}$ are the values selected for the process of selective amplitude normalization.

At this point, the following selective normalization is applied to the second signal:

$$V_2^{norm}[n] = (V_{1Max}/V_{2Max}) \cdot V_2[n], \qquad (5)$$

and the first signal is not altered: $V_1^{norm}[n] = V_1[n]$.

After application of this normalization (figure 4), the rising edges of both envelopes are now parallel, meaning that the object presents a unique 'close' point which is common for both receivers. Then a robust estimation of time delay, DTOF, can be now produced, regardless of the selected threshold. In the same way, this procedure can be used to detect complex objects for which no meaningful DTOF can be found, if this parallelism is not maintained for a substantial part of the rising edge of the normalized signals.

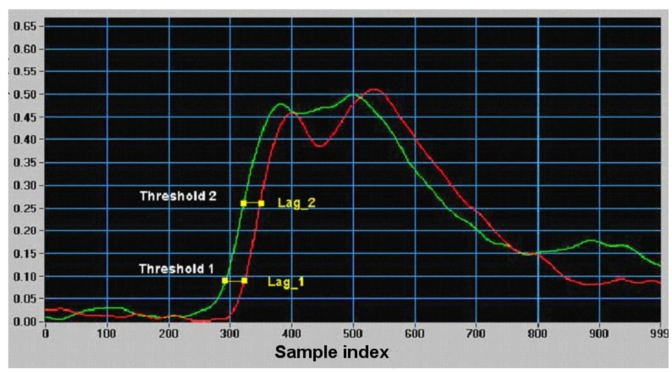


Fig. 5. Verification of the degree of parallelism between the envelopes by the equivalence of signal lag times for two different thresholds.

The threshold levels used to check the parallelism of both rising edges are based on the amplitude of normalized signals and the time difference comparations of *Lag_1* and and *Lag_2* (see figure 5):

$$Threshold \quad 1 = 0.2 \cdot V_{1\,\max} \qquad (6)$$

$$Threshold \quad 2 = 0.5 \cdot V_{1\,\max} \qquad (7)$$

$$Lag\_1 = n_1[Threshold\_1] - n_2[Threshold\_1] \qquad (8)$$

$$Lag\_2 = n_1[Threshold\_2] - n_2[Threshold\_2] \qquad (9)$$

$$Lag\_1 \cong Lag\_2 \qquad (10)$$

If the slopes are not parallel, *Lag_1*≠*Lag_2*, and it is considered that the object does not have a shared physical point that maintains a given range to both receivers, and it is not possible to indicate by means of a distance and an angle the position of the object or a part of it. For example, the procedure of selective normalization fails for the echo signals of figure 6.

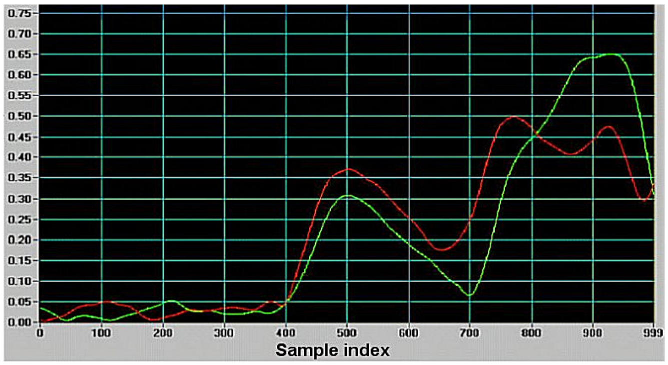


Fig 6: Echo signals from a complex object, for which the process of selective normalization does not return a reliable DTOF.

The degree to which an object is considered ‘pointlike’ or ‘large’ depends, indirectly, on the separation between the receivers, *d*. With the simple technique described in this section it is possible to verify if the estimation obtained in the measurement of the angle is reliable or not. It must be mentioned that the separation *d* between the ultrasonic receivers is a tradeoff between resolution in the determination of the bearing angle and the maximum dimension of an object to be considered pointlike. Higher values of the separation result in better angular resolutions but bring forward the issue of the correspondence of the echoes received by each transducer and clustering of different ultrasonic echoes into the same physical object, making interpretation of the scene perceived with ultrasound more complex [13], [14].

## IV. EXPERIMENTAL RESULTS

The algorithm of selective normalization was tested with an experimental ultrasonic sensor developed in our center for assistance to the displacement of blind people. This is a hard test for obstacle detection algorithms, since, in real environments, many large objects are presented to the user, with random orientations, and containing specular or diffuse reflecting surfaces (like clothing, curtains, etc). For this kind of application, there’s a great need for reliable ranging methods, which guarantee safety of the user and do not provoke many false detection alarms.

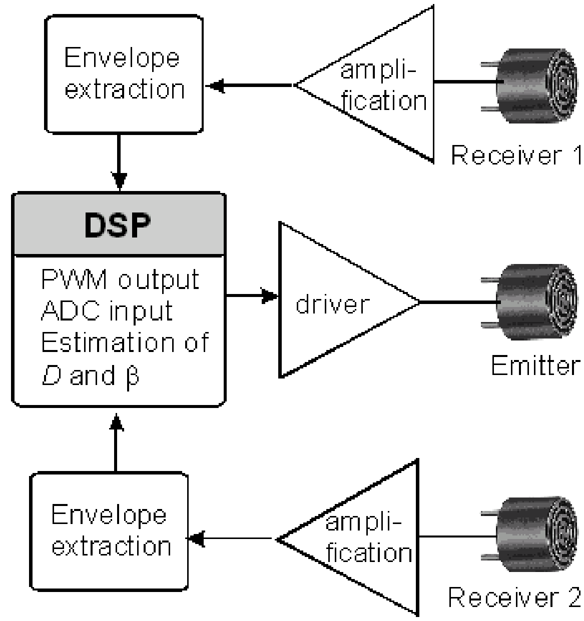


Fig. 7: Block diagram of the system used in the experimental tests.

A schematic view of the system is shown in figure 7. It consists in a Murata MA40B8S piezoelectric ultrasonic transmitter, and two Murata MA40B8R receivers, working at 40 kHz [15]. The separation between the receivers is *d*=6 cm. The transmitter is excited by an 8 cycles pulse train at 40 kHz from the PWM output of a Texas Instruments TMS320LF2401A DSP, and amplified by a driver in a differential configuration, producing a ±18 volts swing. The received ultrasonic signals are amplified by an instrumentation amplifier (Analog Devices AMP02), rectified with a complete wave rectifier with diode compensation, and then lowpass filtered with a fourth order Bessel filter in order to eliminate the $2 \cdot f_0$ frequency signal component. The signals are digitized by the ADC inputs of the DSP, and can be sampled at a relatively low rate, since the Nyquist frequency in this case is given by the bandwidth of the piezoelectric transducers (approximately 2 kHz). The sensibility of the system is adjusted so a cylindrical bar of diameter 2.4 mm is reliably detected at 1.2 m. Even for the designed maximum range in our application (1.8 m), the number of samples to be stored for the signal processing of the echoes does not overflow the capacity of the DSP. The signal conditioning electronics introduces a delay of 160 us (equivalent to 5 cm) which is compensated by the software.

Although this sensor for vision impaired people is designed to run on its own, a computer interface was also created in an ordinary PC, with the LabWindows/CVI software and an acquisition card, for visualization and debugging purposes. This software tool permits to capture the ultrasonic echo signals available for the DSP, and study the performance of the DTOF estimation algorithm for the objects detected within its range. For digitalization in the PC, the envelope signals are sampled at a relatively high rate of 500 kHz.

In figures 8 and 9 we show through the graphical interface the results of the application of the algorithm of selective normalization described in section III. An object with an irregular geometric shape was placed at a distance D = 0.86 meters from the transducer unit, and bearing angle β=0.15 radians from the frontal direction, and its relative orientation was allowed to change slightly, simulating the inherent motion of a person, even when standing static. From equation 1 and figure 8, the angular error $\Delta\beta$ caused by the estimation error of the ultrasonic signals DTOF is:

$$\Delta\beta = \frac{c}{d} \cdot \frac{\Delta t_{12}}{\cos\beta}, \qquad (12)$$

where β is the estimated angle from the mean of the TOFs from each receiver, and $\Delta t_{12}$ is the error in the estimation of the DTOF. Direct estimation of the DTOF from the received envelopes results in an error $\Delta t_{12}$ = 11 μs, with amounts to an angular error of $\Delta\beta$ = 0.063 radians, or an uncertainty of $D \cdot \Delta\beta$ = 54 mm in the lateral position of the object (figure 8). After application of the selective normalization algorithm, the error in the DTOF was reduced to $\Delta t_{12}$ = 1.2 μs, amounting to an angular error of $\Delta\beta$ = 0.0069 radians, or an uncertainty in the lateral position of 6 mm. We can see that a considerable improvement has been obtained in the accuracy of the object location.

The described algorithm has shown remarkable performance in two common problems encountered in ultrasonic guided navigation aids. The first is the ability to accurately locate people walking by the user, dressed in clothes which produce randomly changing echoes, and determine if the relative course of the user and these persons will result in a collision, without provoking a large amount of false alarms, something which distracts the user and produces a rejection of this kind of aids. The second is the problem posed by having to go through a door. It often happens that the echoes coming from both sides of the doorframe appear to be nearly in phase, resulting, for simple systems, in the wrong belief that there is an obstacle right in front of the user. Our algorithm permits to resolve the position of several objects with similar ranges (but different angles), and guides the user through the door reliably.

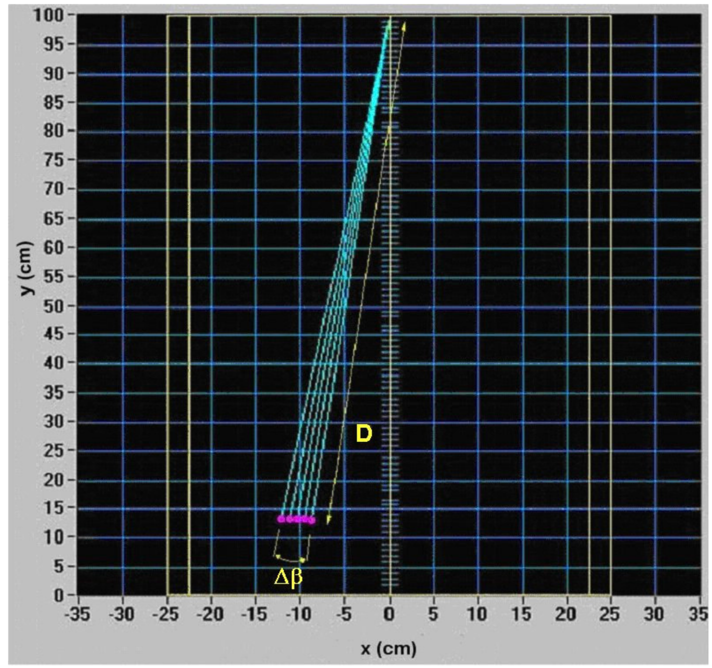


Fig. 8: Error in the estimation of the position of a complex object before application of the algorithm of selective normalization.

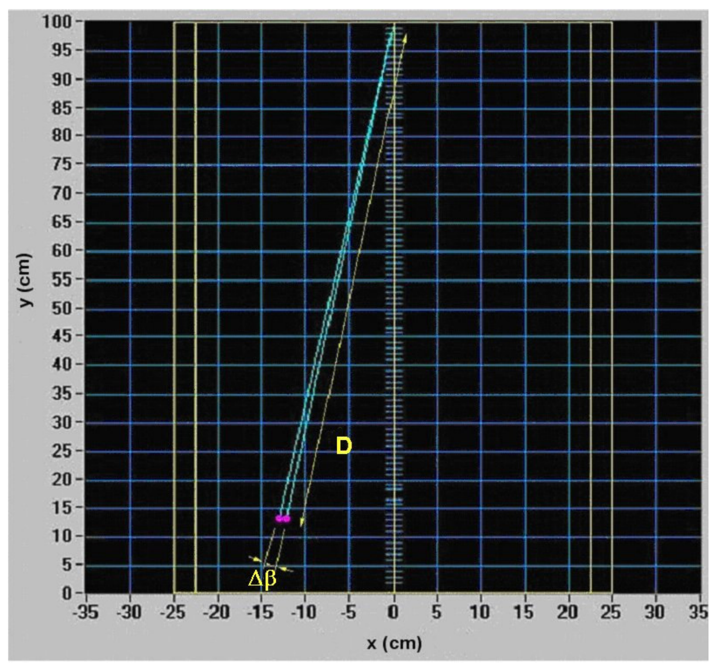


Fig. 9: Results of the application of the algorithm of selective normalization to the same ultrasonic waveforms used in figure 8.

## V. Conclusions

In this paper we have presented a simple algorithm that permits to accurately position objects by processing the ultrasonic signals returned by them with a pulse-echo procedure. This algorithm has been designed to work with the envelope of the ultrasonic signals, for increased robustness when the phase information is not reliable, and techniques like matched filter are subject to large errors. The algorithm applies a selective normalization at the rising edge of the envelope, and checks the parallelism between both waveforms to see if a reliable DOTF can be produced (i.e., the reflecting object presents a point common to both transducers). This technique requires low processing and storing resources, being well suited for implementation in simple processing systems. The algorithm is shown experimentally to improve the positioning of complex objects encountered in practical situations, as well as permitting to overcome some of the difficulties encountered in blind navigation application

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