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# A NEW METHOD FOR HIGH RESOLUTION ULTRASONIC RANGING IN AIR

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**Abstract:** This paper presents a new method for ultrasonic ranging. It consists on continuously transmitting a signal composed by multiple sine wave segments, each containing an integer number of periods. The frequency of each segment is different from the adjacent segments, but close to the transducer resonant frequency, to minimise the filtering effects of the system. The transmitted and received signals are cross-correlated to determine the time-of-flight (TOF). Parabolic interpolation on the cross-correlation's magnitude is used to increase the accuracy of TOF estimation. High measurement resolutions and good noise immunity is achieved.

**Keywords:** Ultrasonic ranging, cross-correlation, time-of-flight

## 1. INTRODUCTION

Ultrasonic ranging is frequently required for localisation, map-building, identification, medical imaging, camera lens-focusing, fluid level measurement, non-destructive testing, parking aids, car's intelligent suspensions, and in many industrial applications.

Basically, there are two common principles to determine distance using ultrasonic waves: 1) phase-shift and 2) time-of-flight (TOF) [1],[2].

The first principle consists in measuring the phase-shift between continuously transmitted and received signals. The measured phase-shift $\theta$ is proportional to distance $d$, and these quantities are related by $360 \cdot d = \theta \cdot \lambda$, where $\lambda$ is the wavelength. The limitation in this principle is that the measurable distance range, without ambiguity, is only from 0 to one wavelength. For instance, at 20 ºC, a system operating at 40 kHz would only measure, without ambiguity, distances up to 8.6 mm, which is quite small for most applications. The ambiguity occurs because a given phase-shift does not correspond to a unique distance. To solve this problem one needs to know the integer number of wavelengths within the distance to be measured.

The second principle is mainly used for distances greater than a wavelength. In a transmitter-receiver configuration, the TOF is the time that an ultrasonic wave takes to arrive at the receiver. It is related to the distance $d$ between transmitter and receiver by $d = c \cdot TOF$, where $c$ is the speed of sound. Although the speed of sound in air depends on temperature, humidity and air turbulence, it depends mainly on temperature. Its value in m/s is approximated [3] by $c \approx 20.06\sqrt{T + 273.15}$, where $T$ is the temperature in degrees Celsius. For example, at 20 ºC the speed of sound is approximately equal to 343.5 m/s.

There are many techniques [4] for TOF estimation. The most common ones are the threshold and the cross-correlation. The threshold method [5] is simple and fast. After transmission of a train of pulses, the TOF is determined when the received signal exceeds, for the first time, a given threshold level. Figure 1 shows an example of how TOF estimation is obtained by the threshold technique.

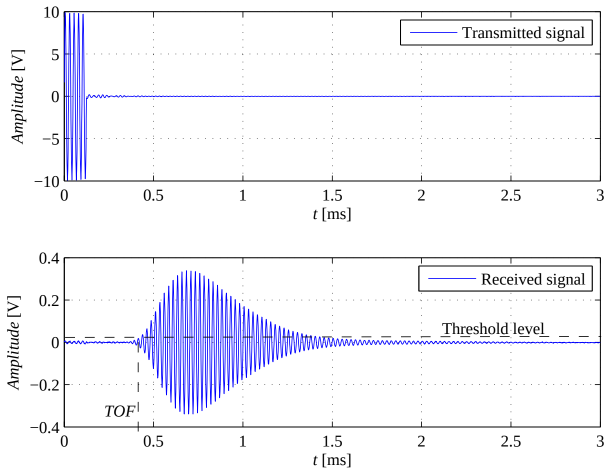


**Figure 1: TOF estimation by the threshold technique**

The problem here is that on the average, it estimates a larger TOF compared with the actual one. This happens because of the long rise time of the received signal caused by the current commercially available airborne ultrasonic transducers (narrow bandwidth). This error could be corrected if the shape of the received signal was constant. In practice, this is not the case as the error depends on many factors, for instance, on the signal-to-noise ratio (SNR) and on the defined threshold level.

A more suitable TOF estimation technique is the cross-correlation [4]. Here, the transmitted and received signals are cross-correlated. The time at which the correlation result reaches its maximum is an estimation of the TOF. Comparatively this technique works well with low SNR signals and it is less affected by low sampling rate problems.

It uses all the information contained in the signals. Therefore, it is considered an optimum TOF estimator technique. The accuracy depends mainly on the sampling rate. Figure 2 shows an example of TOF estimation by cross-correlation.

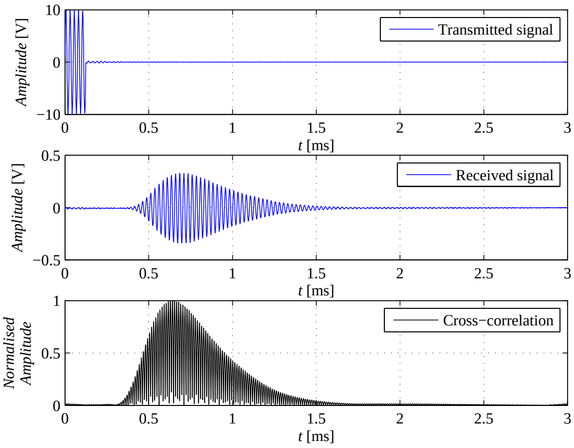


**Figure 2: TOF estimation by cross-correlation technique**

Many benefits can be gained by proper selection of the signal to be transmitted and an adequate signal processing technique. The selection of the signal to be transmitted is limited by the bandwidth of current ultrasonic transducers.

It would be advantageous to apply a signal to the transmitter with both high energy and low bandwidth (for ex: a quasi-continuous sine wave) which does not have the ambiguity problem. Amplitude modulation (AM) has been used [6] to achieve this end. Here, the carrier signal, at the resonant frequency of the transducer, is modulated by different low frequency modulating signals. The phase-shift, for each modulating frequency, between the transmitted and received envelopes is measured. The maximum range and resolution depends on the number and value of the modulating frequencies. One limitation is that the signals are transmitted sequentially, increasing the net time to obtain a distance measurement. Also, calibration for each modulating frequency, at a specific distance, must be performed to compensate the randomness of initial phase-shifts among the number of modulating frequencies.

## 2. PROPOSED METHOD

We propose a method that consists on continuously transmitting a signal whose time domain representation is a sequence of $N$ sine wave segments, as shown in Figure 3. Each sine wave segment is composed by an integer number $n$ of periods. The frequency of each segment is different from the adjacent segments, but it is close to the transducer resonant frequency. Thus, the bandwidth of this signal is narrower than the system's bandwidth, enabling its use in current low-cost commercially available transducers (narrow bandwidth).

The amplitude of the segments is equal and the transition between them occurs at equal phases of the sine waves. Increasing the number of sine wave segments increases the maximum range and the SNR, increasing also the measurement time.

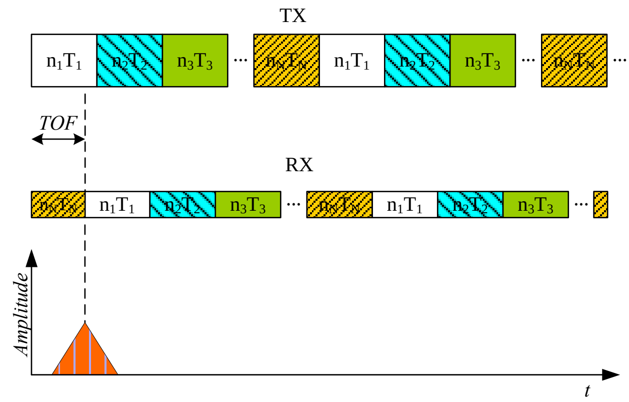


**Figure 3: Diagram showing the idea of the proposed method**

The received signal is approximately an amplitude-scaled and a time-shifted version of the transmitted signal. Thus, by cross-correlating the transmitted and received signals, the TOF can be estimated with high accuracy. Note that this is not the case if the applied signal is highly affected by the filtering characteristics of the transducers. An example of this situation is shown in Figure 2. One can observe that there is a large difference in shape, between transmitted and received signals.

### 2.1. *Increasing the Accuracy of TOF Estimation*

As mentioned before, the TOF is estimated from the maximum of the cross-correlation's magnitude. The amplitudes of the peaks, around the maximum of the cross-correlation's magnitude, are very close to one another, as shown in Figure 4. Therefore, due to noise, the TOF estimated may be incorrect by $\pm T/2$ seconds (time interval between two peaks), where $T$ is approximately equal to the inverse of the transducer resonant frequency. To minimise this problem we have used parabolic interpolation around the maximum of the cross-correlation's magnitude.

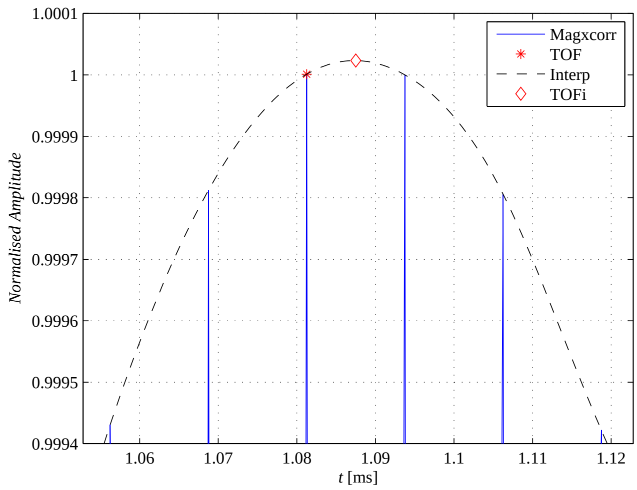


**Figure 4: Parabolic interpolation around the maximum of the cross-correlation's magnitude to increase the TOF estimation accuracy**

We can observe that the TOF estimated after interpolation (TOFi) has less error than the one estimated just from the maximum (TOF) of cross-correlation's magnitude (Magxcorr).

## 3. EXPERIMENTAL PROCEDURE

The steps followed to validate the previously described method are shown in Figure 5.

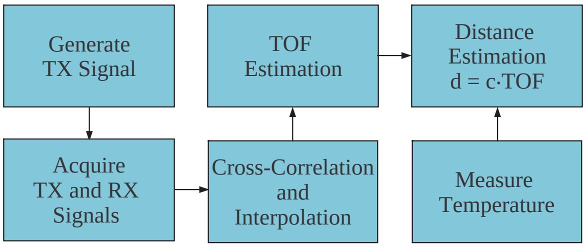


**Figure 5: Experimental procedure for TOF estimation**

## 4. EXPERIMENTAL SETUP

A schematic diagram representing the experimental setup used to validate our method is shown in Figure 6.

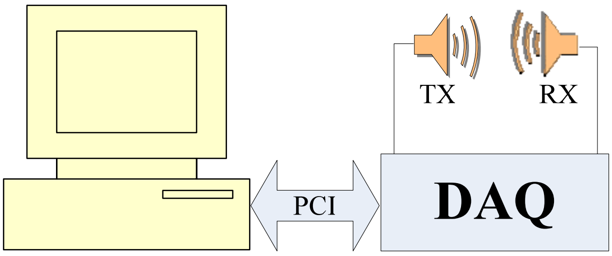


**Figure 6: Diagram showing the experimental setup**

The fact that we are continuously transmitting, implies the use of two transducers, one transmitter and one receiver. We have used ultrasonic transducers (refer to Figure 7) manufactured by SensComp having the following specifications: model 40L16, operating frequency of 40±1 kHz, 2 kHz bandwidth (-6 dB), and 55º of total beam angle (-6 dB).

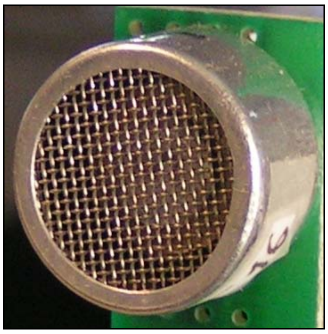

**Figure 7: Typical ultrasonic transducer for air applications. This is the 40L16 model from Senscomp**

The transmitted signal is generated by the analog output of the data acquisition (DAQ) card from National Instruments (NI6111). The analog inputs of the same card are used to acquire the transmitted and received signals. This card simultaneously samples both analog inputs and it has the following main specifications: 12 bits ADC, 16 bits DAC, and sampling rate of 5 MS/s. The data acquisition and the signal processing are performed in Matlab.

Figure 8 shows a specially built mechanical structure to displace the ultrasonic transducers. It enables movement in the x and y-direction, as well as relative angle adjustment. It can move from 0 to 690 mm in x-direction and from 0 to 1500 mm in y-direction, with 0.125 mm resolution. The relative angle between transmitter and receiver can vary from 0 to ± 90º with 1º resolution All movements are manual and the transducers are 1100 mm above the ground to avoid interference with the floor.

**Figure 8: Photograph of the transducers' positioner. The transducers are in the transmit-receive configuration**

The temperature is measured before each distance calculation to compensate its influence on the speed of sound. It is measured with an integrated circuit temperature transducer from National Semiconductor, the LM35. The output of it is linearly proportional to the temperature in degrees Celsius and it does not require external calibration, providing a typical accuracy of 0.5 ºC.

## 5. EXPERIMENTAL RESULTS

Figure 9 shows an example of the cross-correlation between the transmitted and received signals. In this case, the transmitted signal is composed by three segments. The frequency of the sine wave in each segment is 39.9, 40 and 40.1 kHz, respectively. The number of sine wave periods is equal to 400 in each segment. Thus, the duration of the transmitted signal is 30 ms. The maximum of the interpolated cross-correlation's magnitude (TOFi) can easily be identified. The number of cross-correlation's peaks and the relation between its maximum and its root-mean-square (RMS) value (crest factor) increases with the number of segments.

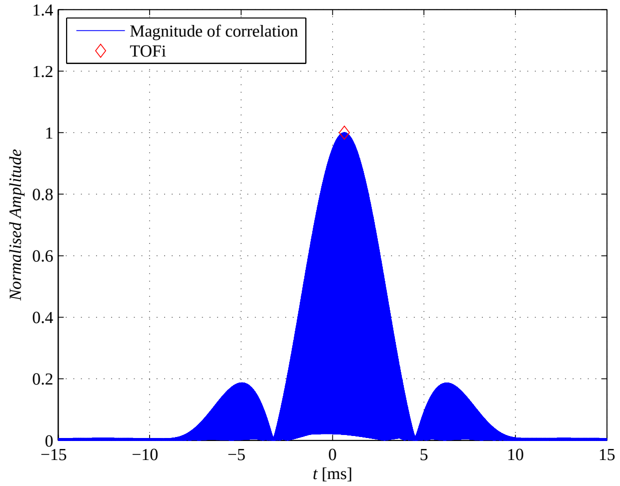


**Figure 9: TOF estimation by cross-correlating transmitted and received signals for the 3 segments example described in the text**

Figure 10 shows preliminary experimental results obtained with the proposed method for 3, 5 and 7 segments. The frequencies in each case are 39.9, 40 and 40.1 kHz for 3 segments, 39.8, 39.9, 40, 40.1 and 40.2 kHz for 5 segments, and 39.7, 39.8, 39.9, 40, 40.1, 40.2 and 40.3 kHz for 7 segments. The number of periods was 400 for each sine wave segment. For each distance between the transmitter and the receiver, the same measurement was repeated 100 times in order to evaluate the standard deviations.

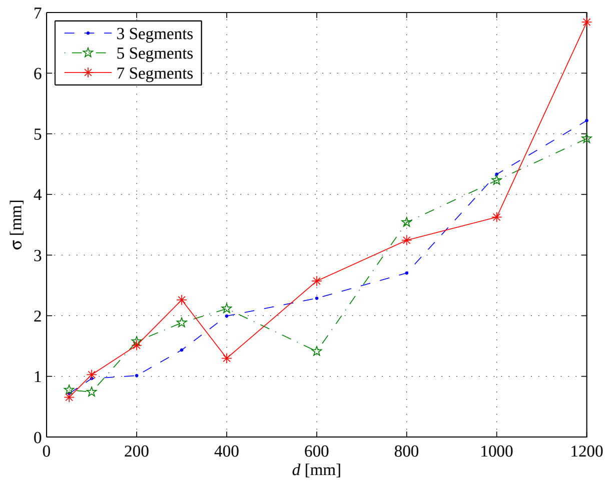


**Figure 10: Standard deviation as a function of the distance between transmitter and receiver**

From Figure 10 one can observe that the standard deviation for the presented cases increases with the distance. We can also see that the standard deviation is less than a wavelength (8.7 mm in this example) for the presented full range. Also note that for small distances, the standard deviation is less than 1 mm.

Observing Figure 11, we note that the case of 7 segments gives the lowest error of the cases presented. It is within -5 and +5 mm in the presented full range.

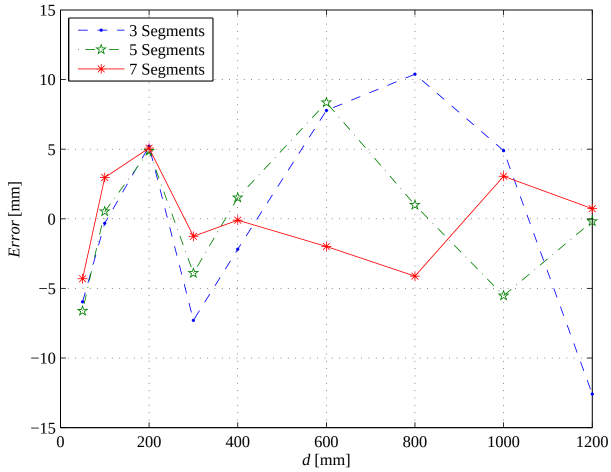


**Figure 11: Error as a function of the distance between transmitter and receiver**

## 6. CONCLUSION

This paper presents an innovative method for ultrasonic ranging. The main contribution of the proposed method is the continuous transmission of a signal composed by a number of sine wave segments, whose frequencies are different but close to the transducer's resonant frequency. Thus, it permits the use of current low-cost, commercially available, ultrasonic transducers, which have narrow bandwidth. The cross-correlation is then used to estimate the time-of-flight. High resolution ultrasonic ranging in noisy environments, without ambiguity, is achieved.

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