IEEE Instrumentation and Measurement
Technology Conference
Brussels, Belgium, June 4-6, 1996

# Accurate Distance Measurement by an Autonomous Ultrasonic System Combining Time-of-Flight and Phase-Shift Methods

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***Abstract*** ***- Ultrasonic sensor distance measurements are based on the evaluation of the time-of-flight or on the determination of the phase difference between a transmitted and a received signal. Digital signal processing methods are developed in order to extract the useful information from the samples acquired from the received wave. This paper presents an efficient algorithm for distance measurement, combining both the propagation time method and the phase difference method and relying on a low rate sampling technique allowed by the limited bandwidth of the ultrasonic transducers. The measuring system was implemented and tested on a compact Motorola MC68HC16 based platform, with a minimum of attached hardware. Experimental results show an accuracy better than 1 mm.***

## I. INTRODUCTION

In industrial applications, distance in air is often measured by using ultrasonic sensors. The main measuring principle is based on the Time-of-Flight (ToF) estimation, that is the time needed for an ultrasonic wave to travel from the transmitter to a target and then, after reflection, back to the receiver located near the transmitter. The distance between the target and the transducers is d = (c × ToF)/2, where c is the sound velocity. Most often, in this *pulse echo method*, the same transducer is used as transmitter and receiver. A short burst is generated by the transducer and then is detected back. Frequently, the ToF is computed with the threshold method (the echo signal is evaluated versus a given amplitude level). This technique offers a low cost and a simple solution, but suffers from poor resolution measurements. More complex methods (e.g. cross correlation function) can improve the evaluation, because the detection does not rely on the signal magnitude but on its shape [1].

Another principle is the *phase shift method*, which relies on continuous waves. Here the echoes are detected with a separate receiver. In this case the distance is evaluated, within a wavelength, by computing the phase shift between the transmitted and the received wave. Although more accurate, this technique is more expensive due to complex hardware needed to measure the phase. Different frequencies often need to be used in order to determine the number of integer wavelengths [2].

The measurement repeatability for both methods is reported to attain some tenths of the ultrasonic wavelength.

Our paper presents an algorithm using sampled signals and combining the two exposed methods. It is based on a particular signal processing which firstly determines the ToF by computing the cross correlation between the *envelope* of the transmitted and received signals. The time index of the peak of the correlation function measures the delay between the two signals i.e. the ToF. Secondly, the carrier phase shift between transmission and reception is computed in order to refine the final result.

The technique is the result of a study searching suitable methods framing the potentialities of general purpose microcontrollers. The final goal is to correctly evaluate distances by an autonomous ultrasonic system using simple, non-continuous signals. The method allows accurate measurements (better than 1 mm) even at low sample rates and poor computing capacities. Moreover, the hardware attached to the microcontroller can be drastically reduced (two amplifiers, a gate, and a divider).

An analysis of the proposed method will be developed together with explanations of the used algorithms. A special attention will also be given to the implementation of this technique on the microcontroller based platform. Finally, experimental results will be presented.



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## II. ANALYSIS OF THE PROBLEM

The *pulse echo method* is based on the estimation of the delay between the emission moment and the arrival of the reflected wave. The ultrasonic signal is affected by the propagating medium, the attenuation of which increases with the frequency. Moreover, the signal to noise ratio is altered by external vibrations, air turbulence and quantization noise due to the A/D conversion. In these conditions, a robust algorithm has to be used in order to correctly evaluate the ToF [3]. A good choice is the method based on the cross-correlation function. Computing the cross-correlation between the transmitted and the received signals, one can find, by detection of the position of its maximum, the moment when the noisy received signal looks at best like the transmitted one. The time elapsed between this moment and the emission instant represents the ToF.

Assuming that e(t) is the signal driving the ultrasonic transmitter, the expression of the signal r(t) leaving the receiver will be [4]:

$$r(t) = e(t)*h(t) + n(t) \qquad (1)$$

where h(t) is the impulse response of the whole system (transducers plus propagating medium) and n(t) the noise. Using the notation y(t) for the convolution product, the cross correlation function between e(t) and r(t) becomes:

$$Cer(\tau) = Cey(\tau) + Cen(\tau) \qquad (2)$$

Assuming that the noise and the emission signals are uncorrelated ($Cen(\tau) = 0$), equation (2) transposed in the frequency domain via the Fourier Transform (FT) becomes:

$$FT(Cer(\tau)) = Rer(f) = k \cdot E^{*}(f) \cdot H_1(f) \cdot E(f) \cdot e^{-jfToF} \qquad (3)$$

where E(f) is the Fourier transform of the e(t) signal, $H_1(f)$ the transfer function of the transducers and k the constant taking into account the attenuation and dispersion of the wave (the target and the medium are considered as non selective in the system bandwidth). This equation can be rewritten as:

$$FT(Cer(\tau)) = k \cdot Ree(f) \cdot H_1(f) \cdot e^{-jfToF} \qquad (4)$$

where Ree(f) is the e(t) spectral density of energy. Equation (4) interpreted in the time domain means the auto-correlation function of the transmitted signal filtered by the transfer function of the transducers and delayed with the ToF.

From an energetical point of view, the peak detection of the cross-correlation function works best when the energy transferred between emission and reception is high. Moreover, equation (4) shows that, for a robust estimation of the ToF, the transmitted wave has to be slightly affected by the system transfer function. Therefore, the emission signal spectrum has to be inferior to the system's bandwidth. The latter is strongly limited by the ultrasonic piezoelectric transducers which are high quality factor, second order transfer function devices. A good solution is to modulate the amplitude of a carrier centered on the system's bandwidth, with a baseband pulse. This modulation signal, which will be used in the peak detection of the cross correlation function after demodulation, can be chosen such as the emission spectrum fits the system's bandwidth.

The power spectrum of a pulse is modulated by $\mathrm{sinc}^2(\pi fT)$, where T is the duration of the burst. The amplitude modulation produces a translation of this spectrum inside the system's bandwidth. The energetical transfer is satisfactory if the system transfer function does not affect the power spectrum's main lobe of the pulse. The pulse duration T and the system's bandwidth B are linked by the relation:

$$B_{3\,dB} \geq 2/T \qquad (5)$$

In our case, the evaluation of the ToF will be done by computing the cross correlation between the transmitted and received *envelopes*. As any real signal, a pulse has an auto-correlation function exhibiting a maximum in the origin and the longer the burst the higher the value of this maximum. Moreover, the width of the correlation peak equals 2T at the base (fig. 1). Thus, a secondary echo can dramatically affect the main echo if the time between the two maxima is less than T. This represents a limitation of the method. Therefore, the distance $d = c \times T/2$ can be considered as a "dead zone" around the target. Without additional processing, this correlation method gives a distance accuracy of one sampling wavelength.

*The phase shift method*, in addition to the correlation method, enhances the accuracy. It relies on the property that, for a sampled cosine signal, one can determine its phase shift from the origin by computing

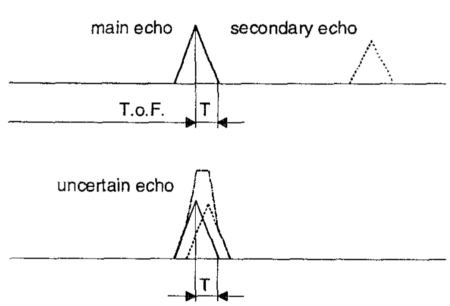


*Fig.1 Correlation figure of multiple echoes*

the coefficient of the Discrete Fourier Transform (DFT) corresponding to the frequency of this cosine wave. The arc-tangent of the ratio between the imaginary part and the real part of this complex coefficient gives the value of this phase shift. This calculus is more or less complex, depending mainly on the relation between the cosine frequency and the sampling rate.

This mechanism is exploited in our case. Indeed, if the sampling time is strictly synchronized with the transmission signal, one can evaluate the *phase shift* between transmission and reception *carriers* by computing the phase shift of the received signal from the sampling reference. A good choice of the sampling rate can simplify the calculus of the corresponding DFT coefficient.

The final time of flight resulting from both methods is:

$$ToF = (N + \alpha/2\pi)/fc \quad (6)$$

where N is the integer number of carrier wavelengths.

## III. THE MEASUREMENT ALGORITHM

This method is the result of a study focused on the optimal use of the Motorola MC68HC16 microcontroller in ultrasonic applications. The purpose of the present algorithm (fig.2) was to achieve a good measurement resolution with a relatively low sample rate. In our application, the useful information is concentrated in the envelope (cross-correlation computation) and in the carrier (phase shift measurement) of the received signal. For an envelope spectrum slightly affected by the ultrasonic transducers transfer function, this information can be recovered even when the sampling rate is lower than the Nyquist frequency. Indeed, for narrow band signals, the sampling rate must be at least twice the pass-band of the signal. For convenience with regard to phase shift detection, we choose a sampling rate of the echo pulse fs = 4fc/3 where fc is the carrier frequency. Consequently, the envelope spectrum was limited at less than fc/3.

Inside the microcontroller, the signal processing of the acquired samples r(n) follows two independent

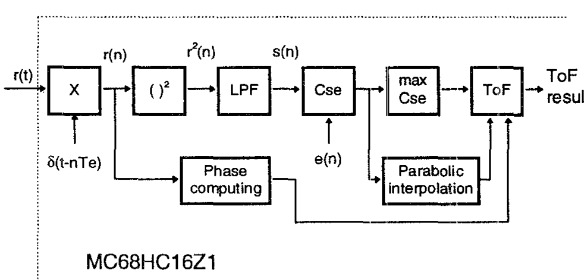


*Fig.2 Computing algorithm*

paths. The first one is intended to roughly estimate the time-of-flight. The samples are firstly squared and further filtered with a linear phase, second order, digital low-pass filter:

$$s(n+1) = r^2(n) + 2r^2(n+1) + r^2(n+2) \quad (7)$$

where s is the filtered signal (i.e. the squared envelope) and $r^2$ are the squared samples. The role of the filter is to eliminate the spectral components situated around half of the sampling frequency. These components are a consequence of squaring. The digital cross-correlation between the transmitted envelope e(n) and the recovered (squared) envelope is then performed. The cross-correlation peak detection, which is not affected by this squaring, gives a first estimation of ToF.

As the resolution of the ToF is limited to the sampling period, an amelioration is required in order to obtain an accuracy better than half the carrier wavelength, needed for the phase shift method. This can be achieved by a parabolic interpolation on 3 points of the sampled cross-correlation function, i.e. the maximum, the point before and the point after it [1]. The abscissa shift of the parabola maximum versus the correlation maximum is:

$$\Delta t=(C(n-1)-C(n+1))/(2\cdot(C(n-1)-2\cdot C(n)+C(n+1))) \quad (8)$$

where C(n) is the value of the cross-correlation function for the sample number n (fig. 3).

The second path calculates the phase difference between the transmitted and received waves. This value can be computed by using the DFT coefficient of r(n) corresponding to the carrier frequency. The proper choice of the sampling rate (fs = 4fc/3 as above mentioned) simplifies the calculus of the phase difference:

$$\begin{aligned} Re\left(f_{\frac{3N}{4}}\right) &= \sum_{k=0}^{N/4} x_{4k} - \sum_{k=0}^{N/4} x_{4k+2} \\ Im\left(f_{\frac{3N}{4}}\right) &= \sum_{k=0}^{N/4} x_{4k+1} - \sum_{k=0}^{N/4} x_{4k+3} \\ \alpha &= \arctan\frac{Im}{Re} \end{aligned} \quad (9)$$

where $f_{3N/4}$ is the carrier's discrete Fourier transform coefficient, $x_i$ is the sample number i of the acquired signal and α the phase shift, in radians, between the transmitted and received waves.

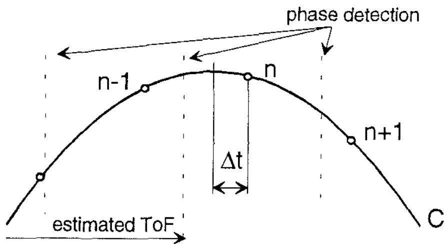


*Fig.3 ToF estimation*

Although accurate, the phase determination is insufficient for the evaluation of the ToF because the result has a periodicity of one carrier wavelength. Among the positions determined by phase computation the one which is nearest the maximum of the cross-correlation parabolic approximation is the final value of the measured ToF (fig. 3).

It is obvious that this approach requires a determination of the correlation peak with an accuracy better than half the carrier wavelength. This explains now the necessity of the parabolic approximation of the correlation function: the correlation function itself has an accuracy (imposed by the sample rate) of only ¾ of the carrier wavelength.

The presented method (correlation plus phase shift) allows highly accurate results (better than a tenth of the carrier wavelength). Moreover, simulations show that the phase evaluation is significantly less affected by the additive white noise than the cross correlation peak determination. This path is used in order to improve the accuracy of the result obtained in the first branch. The experimental results confirm this comment.

## IV. EXPERIMENTAL SETUP

The hardware is presented in figure 4. A square wave, generated by a Motorola MC68HC16 microcontroller, is modulated by an on/off type amplitude modulator and driver. The carrier frequency (30 kHz) is very close to the central frequency of the ultrasonic transducers. The received signal is amplified and digitized by the microcontroller's 8 bits A/D converter at a sample frequency of 40 kHz.

The transducers are Massa model TR89 - Type 31. Their bandwidth was adjusted at a value of 10 kHz which represents a third of the carrier frequency. This allows a minimum possible value for the parameter T (pulse duration) of 200 μs (see equation (5)), which gives a minimum "dead zone" of 34 mm. For our measurements we choose a 800 μs pulse.

The measured ToF contains both the time needed by the wave to cover the two ways between the target and the transducers and the delay of the electronic circuits which is constant and can be eliminated by calibration.

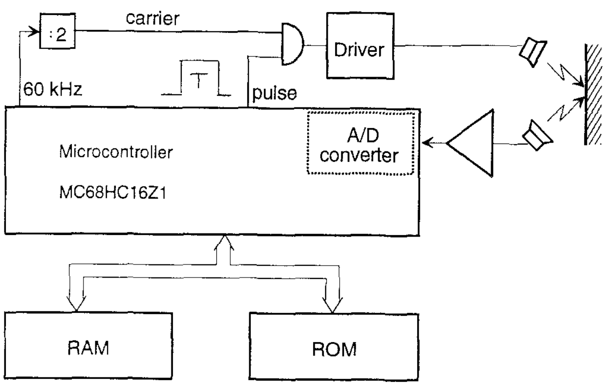


*Fig. 4 Hardware implementation*

In order to correctly determine the distance, the air temperature must be measured since the sound velocity is dependent on it (about 1% variation every 6°C around 20 °C).

## V. DATA ANALYSIS

In the frame of another research program in progress [5], preliminary series of measurements were performed on a poor reflecting target materialized by a piece of tree (25 cm diameter) presenting an heavy corrugated and crackled bark. Starting from a distance of about 42 cm between the target and the ultrasonic transducers pair, this latter was progressively moved away from the target, mm by mm, on a total shift of 31 mm, with a mechanical precision of about 0.1 mm. For each position, the same measurement has been repeated 100 times in order to evaluate the dispersion inherent to the measuring method. The measuring time for each measurement (for a distance range of 2.5 m) was 120 ms. Figure 5 gives an illustration of a sampled echo r(n) and its corresponding correlation figure Cse. The pulse transmission starts at the origin. The abcisa is the sample numbering.

Figure 6 gives, for each trial reported in abscissa, the distance (expressed in number of carrier wavelengths) computed successively by the correlation-only method (fig. 6a) and the combined (correlation plus phase) method (fig. 6b). The progress introduced by the phase shift computation is obvious at first glance. Note that a few negative peaks appear in fig 6b for situations corresponding to such bad correlation results that the computed integer number of wavelengths is shifted by one point. These false results were rejected for the statistic processing which follows.

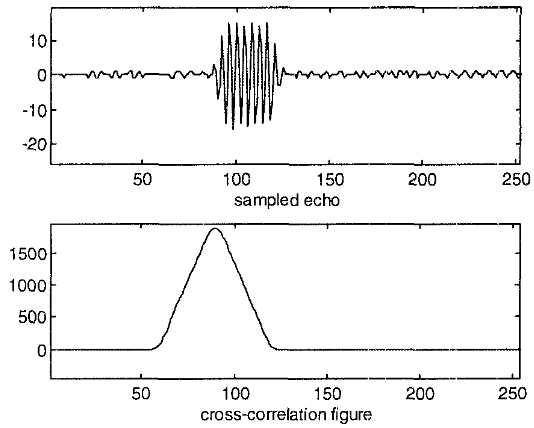


*Fig.5 Example of echo and correlation figures*

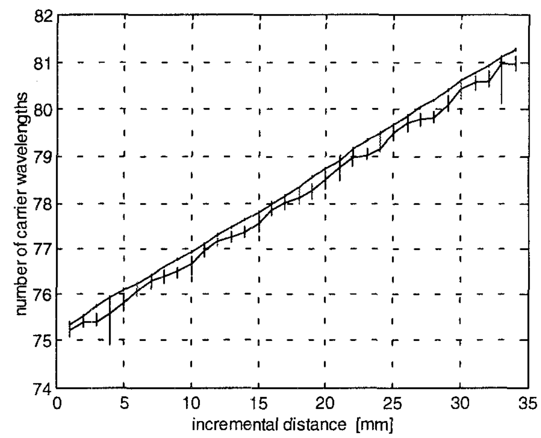


*Fig.7 Means of the measured values*

Figure 7 shows the means of the measured values (in wavelength units) in function of the incremental displacement for each series of 100 results. The upper line is the combined method, the under line the correlation-only method ; the vertical segments define the total excursion of the results at each position.

In order to interpret the results in terms of distances, the wave velocity must be known ($c = f\lambda$). This latter depends on the temperature according to the relation (near the ambient temperature) : $c=20.1\sqrt{T}$, where T is the absolute temperature. Keeping for the moment the combined curve, and considering in a first step that the propagation medium temperature remained constant during the experiments (half an hour duration), the wave velocity is determined by the slope of the regression straight line. By this way, we obtained a temperature of 11°C which is from far below the measured temperature of the room. A model of linear temperature shift versus time has then been considered in a second step, which led to a total shift of 0.6°C which is quite plausible : this model was thus kept for the following.

Figure 8 shows the distance difference versus the position, of each result for both methods, by reference to the linear regression on the mean results obtained by the combined method (the best one). The curves in continuous line (combined method is the upper curve) are the fluctuations of the mean, the vertical segments are the total excursion of the results at each position and the dots represent the standard deviation. The pseudo-periodicity of about 4.8 mm, say about half of a wavelength at the sampling frequency, of the results obtained by the correlation-only method is explained by a residual effect of the squaring in the computing algorithm (fig. 2) due to an imperfect filtering (see our comments of relation 7). We don't find these pseudo-periodic variations in the combined method because the phase computing by-passes this squaring step.

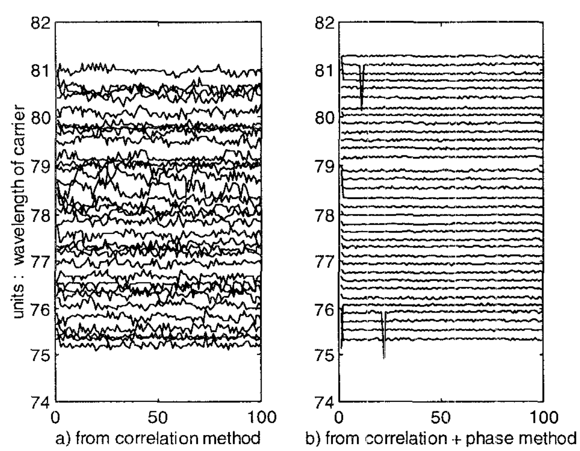


*Fig. 6 Measurement results*

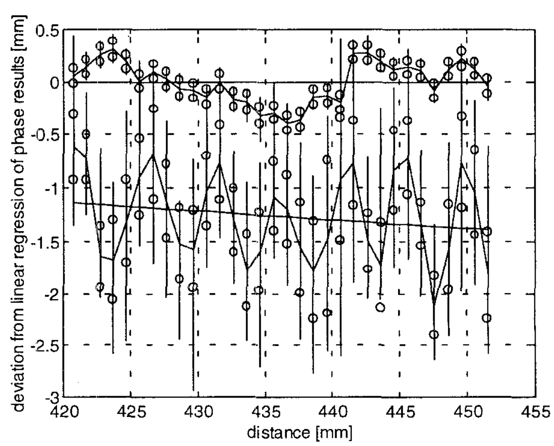


*Fig. 8 Distance differences versus linear regression on the best results*

Here, the residual fluctuations are probably due to air temperature fluctuations (the observed variation of 0.3 mm is, in this view, explained by 0.4°C temperature variation). The systematically lower results (about 1.3 mm) for the correlation-only method are not explained in the actual state of our investigations.

The computation of the mean standard deviation averaged on the whole positions gives :

- for the correlation-only method : $\sigma_{mean} = 0.37$ mm
- for the combined method : $\sigma_{mean} = 0.07$ mm

The reproducibility of the computed distances is thus five times better with the combined method !

## VI. CONCLUSIONS

An algorithm combining both the pulse echo method and the phase shift method was developed for ultrasonic distance measurement applications, in order to optimize the resources utilization of a microcontroller of general use. The technique is based on a particular signal processing which determines the ToF by computing the cross correlation between the envelope of the transmitted and received signals. The time index of the peak of the correlation function, through a further parabolic interpolation, measures the delay between the two signals i.e. ToF. The carrier phase shift between emission and reception is evaluated in order to refine the final result.

Accurate measurements (typically better than 1 mm, even for poor reflecting targets) can be achieved despite low sample rates and poor computing capabilities. The algorithm is simple and needs no complex associated hardware. Moreover, the method can be easily accommodated to other microcontoller or DSP based platforms.

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