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

Francis E. Gueuning, Mihai Varlan, *Associate Member, IEEE*, Christian E. Eugène, and Pascal Dupuis

***Abstract*— This paper presents an efficient algorithm for distance measurement, combining both the pulse time-of-flight method and the CW phase-shift method. It copes with a low-rate sampling technique allowed by the limited bandwidth of two ultrasonic transducers working in air at 30 kHz and with modest software resources of autonomous devices. 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 for a poor reflecting target at a distance of about 1 m.**

***Index Terms*—Acoustic correlator, acoustic distance measurement, acoustic signal processing, algorithm, delay estimation, phase detection.**

I. Introduction

In industrial applications, distance in air is often measured by using ultrasonic sensors. The main measuring principle is based on a pulse time-of-flight (ToF) estimation (*pulse echo method*). The distance between the reflecting target and the transducer site (typically, a pair of sensors acting as transmitter and receiver, respectively) is $d = (c \times \text{ToF})/2$, where c is the sound velocity [1].

Another principle is the *phase shift method*. Here, the distance is evaluated to within a wavelength by computing the phase shift between the transmitted and the received continuous waves. Although more accurate, this technique is more expensive due to often complex hardware needed to measure the phase and due to the difficulty in determining the number of integer wavelengths, requiring, for instance, the use of different frequencies [2].

The originality of our paper is to combine both methods in order to achieve accurate distance measurement (better than 1 mm) despite a low sampling rate and limited computing capabilities. The algorithm developed is based on a particular signal processing technique which first determines the ToF by computing the cross-correlation between the *envelopes* of the transmitted and received signals. Secondly, the *carrier phase shift* between transmission and reception is computed in order to refine the final result.

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II. Analysis of the Problem

The *pulse echo method* is based on the estimation of the delay between the moment of emission 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 (SNR) is altered by the absorption of the target, external vibrations, and air turbulence. Under these conditions, conventional threshold-detecting techniques are not suitable, and a robust algorithm has to be used in order to correctly evaluate the ToF. Among the numerous proposed solutions, one of the best choices for low SNR and low-sampling rate is the method based on the cross correlation function [3]. 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.

The method is more efficient when the energy transferred between emission and reception is high, requiring therefore an emission signal spectrum limited to the system's bandwidth. The latter is strongly limited by the ultrasonic piezoelectric transducers we used, which are of rather 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 can be chosen so that the emission spectrum fits the system's bandwidth. In our case, the evaluation of the ToF will be done by computing the cross correlation between the transmitted and received *envelopes*. This technique allows a low sample rate and eliminates difficult side-lobes problems in the correlation function when this function is computed on the modulated signals themselves.

Other digital processing techniques have been proposed in the literature which optimize the shape of the transmitting signal in order to enhance the correlation peak. Use is often made of pseudorandom codes [4]. Their efficacy is proportional to their duration which poses problem for short distances.

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 the phase shift from the origin by computing the coefficient of the discrete Fourier transform (DFT) corresponding to the frequency of this cosine wave. This calculation is more or

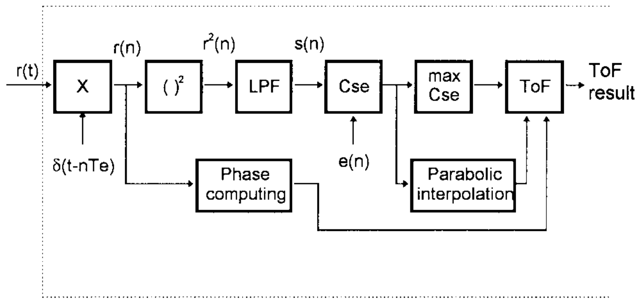

Fig. 1. Computing algorithm.

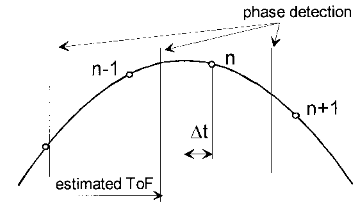

Fig. 2. ToF estimation.

less complex, depending mainly on the relation between the cosine frequency and the sampling rate.

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 time reference. A good choice of the sampling rate can simplify the calculation of the corresponding DFT coefficient.

The final ToF resulting from using both methods simultaneously is

$$\text{ToF} = (N + \alpha/2\pi)/fc \tag{1}$$

where N is the integer number of carrier wavelengths inferred from the correlation result, α the phase shift, and fc the carrier frequency.

III. The Measurement Algorithm

Our study has been focused on the practical implementation of our method in an autonomous hardware environment around the Motorola MC68HC16 microcontroller. The purpose of the algorithm developed (Fig. 1) 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 $r(t)$. For an envelope spectrum slightly affected by the ultrasonic transducer transfer function, this information can be recovered if the sampling rate is at least twice the passband of the signal. For convenience with regard to phase shift detection, we chose a sampling rate of the echo pulse $fs = 4fc/3$, where fc is the carrier frequency. Consequently, the envelope spectrum had to be limited at less than $fc/3$ to avoid aliasing.

Inside the microcontroller signal processing of the acquired samples $r(n)$ follows two independent paths. The first one, which computes the cross-correlation between the envelopes, is intended to roughly estimate the time-of-flight. The samples are first squared and further filtered with a linear phase, second-order, digital low-pass filter

$$s(n+1) = r^2(n) + 2r^2(n+1) + r^2(n+2) \tag{2}$$

where s is the filtered signal (i.e., the squared envelope) and r^2 is the squared sample. The role of the filter is to eliminate the spectral components situated around one half of the sampling frequency. These components are a consequence of squaring. The digital cross-correlation Cse 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 estimate of the ToF.

As the resolution of the ToF is limited to the sampling period, an improvement is required to obtain an accuracy better than half the carrier wavelength. This is needed for the phase shift method. It can be achieved by a parabolic interpolation on three points of the sampled cross-correlation function, i.e., the point of maximum amplitude and the two points surrounding it [1]. The abscissa shift (the axis being the sample number) of the parabola maximum versus the correlation maximum is $(-1 \leq \Delta t \leq +1)$

$$\begin{aligned}\Delta t = {} & [C(n-1) - C(n+1)]/\{2 \cdot [C(n-1) \\ & - 2 \cdot C(n) + C(n+1)]\}\end{aligned} \tag{3}$$

where $C(n)$ is the value of the cross-correlation function for the sample number n, giving the maximum amplitude (Fig. 2).

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 transmitted signal is replaced by the synchronous sampling clock). The proper choice of the sampling rate ($fs = 4fc/3$ as previously mentioned) simplifies the calculation of the phase difference

$$\begin{aligned}\text{Re}(f_{3n/4}) &= \sum_{K=0}^{N/4} x_{4k} - \sum_{k=0}^{N/4} x_{4k+2} \\ \text{Im}(f_{3n/4}) &= \sum_{k=0}^{N/4} x_{4k+1} - \sum_{k=0}^{N/4} x_{4k+3} \\ \alpha &= \arctan \frac{\text{Im}}{\text{Re}}\end{aligned} \tag{4}$$

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

This computed phase-shift has an accuracy mainly limited by the amplitude accuracy of the samples and thus the resolution of the A/D converter. Moreover, simulations show that the phase evaluation is significantly less affected by the additive white noise than the cross-correlation peak determination.

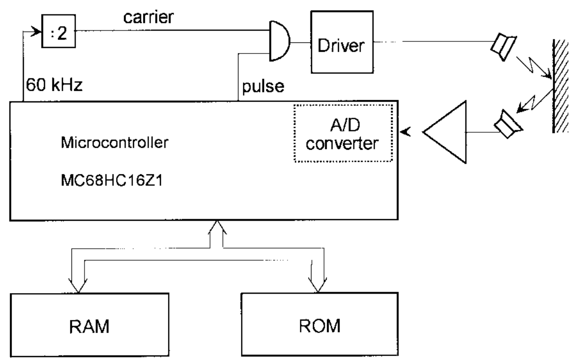

Fig. 3. Hardware implementation.

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 to the maximum of the cross-correlation parabolic approximation previously determined, is the final value of the measured ToF (Fig. 2).

It is obvious that this approach requires a determination of the correlation peak with an accuracy better than half the carrier wavelength. This now explains the necessity of the parabolic approximation of the correlation function, as the correlation function itself has an accuracy (imposed by the sample rate) of only 3/4 of the carrier wavelength.

The presented method (correlation plus phase shift) allows highly accurate results (better than a tenth of the carrier wavelength) as it is hereafter experimentally confirmed.

IV. Experimental Setup

The hardware is presented in Fig. 3. 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 (4/3 the carrier).

The transducers are Massa Products Corporation model TR89-Type 31. Their bandwidth was adjusted to a value of 10 kHz which was a third of the carrier frequency as needed. For all measurements, a 800-μs pulse was used.

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

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 order to evaluate the efficacy of our method, preliminary series of measurements were performed on a deliberately poorly reflecting target embodied by a log from tree (25 cm in diameter) presenting a heavily corrugated and crackled bark. Starting from a distance of about 40 cm between the target and the ultrasonic pair of transducers, the latter was progressively moved away from the target, millimeter by millimeter, to a total shift of about 30 mm, with a mechanical precision of about 0.1 mm. For each position, the same measurement was repeated 100 times in order to evaluate the dispersion inherent to the measuring method. The measuring time for each measurement (for a full scale range of 2.5 m) was 120 ms. Fig. 4 gives an illustration of a sampled echo $r(n)$ and its corresponding correlation figure Cse. The pulse transmission starts at the origin. The abscissa is the sample numbering.

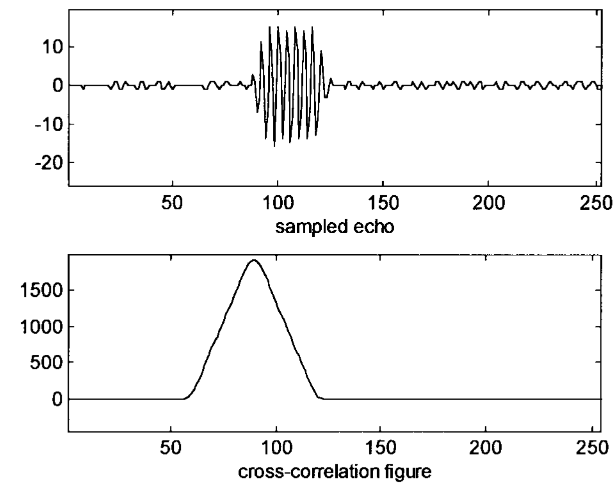

Fig. 4. Example of echo and correlation figures.

Fig. 5, for each trial reported in abscissa, gives the distance (expressed in number of carrier wavelengths) computed successively by the correlation-only method [Fig. 5(a)] and the combined (correlation plus phase; $\lambda \cong 9$ mm) method [Fig. 5(b)]. The improvement introduced by the phase shift computation is obvious at first glance. Note that a few negative peaks appear in Fig. 5(b) for situations corresponding to bad correlation results where the computed integer number of wavelengths is shifted by one point. These false results were rejected for the statistical processing which follows.

Fig. 6 shows the averages of the measured values (in wavelength units) as function of the incremental displacement for each series of 100 results. The upper line is the combined method, the lower line the correlation-only method; the vertical segments define the total excursion of the results at each position (barely perceptible for the upper line).

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 in Kelvin.

Fig. 7 shows the difference in distance versus the position, of each result for both methods, with reference to the linear regression of the mean results obtained by the combined method ("phase results"). The continuous curves (combined method is the upper curve) are the fluctuations of the mean,

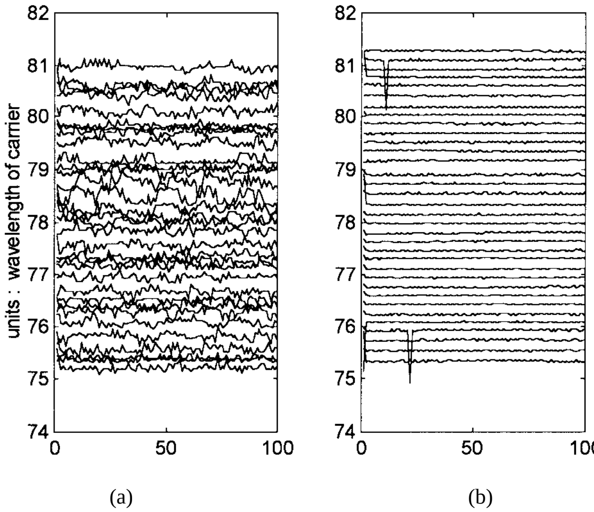

Fig. 5. Measurement results (a) from correlation method and (b) from correlation plus phase method.

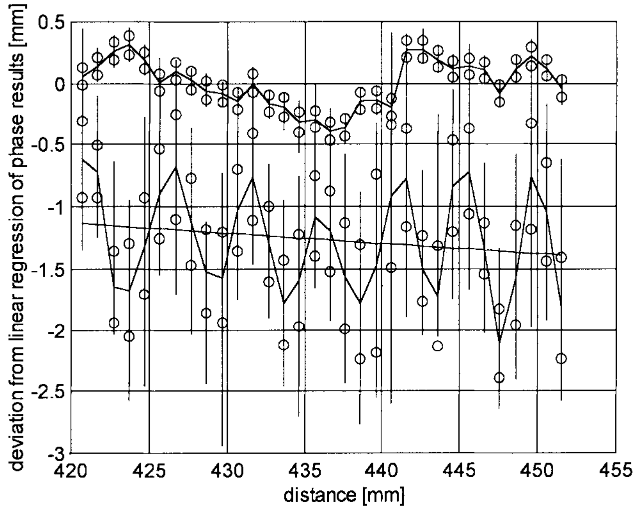

Fig. 7. Distance deviations from linear regression of the mean of results obtained by the combined ("phase") method.

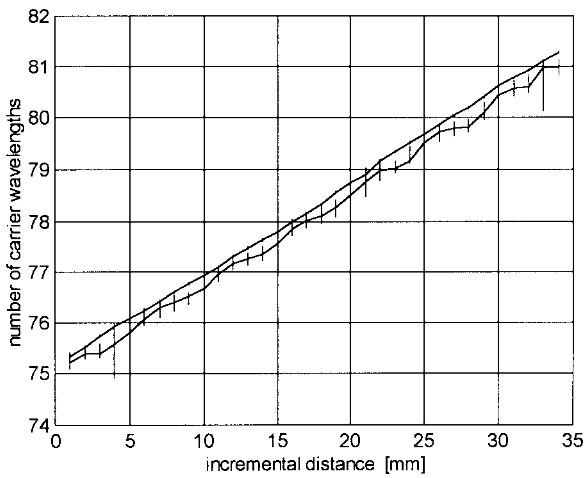

Fig. 6. Means of the measured values.

the vertical segments are the total excursion of the results at each position, and the dots represent the standard deviations. The pseudoperiodicity of about 4.8 mm, 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. 1) due to an imperfect filtering (see our comments of relation 2). We don't find these pseudoperiodic variations in the combined method, because the phase computing bypasses this squaring step. 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 have not been explained in the present state of our investigations.

The computation of the mean standard deviation averaged over all the positions gives

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

The reproducibility of the computed distances is thus five times better with the combined method! These results are comparable with those obtained in the literature with more sophisticated hardware and software resources.

VI. Conclusions

An original algorithm combining both the pulse-echo method and the continuous-wave phase-shift method was developed for ultrasonic distance-measurement applications, in order to optimize the resources utilization of a microcontroller of general purpose tasks. The technique is based on a particular signal processing method which determines the approximate ToF by computing the cross correlation between the envelope of the transmitted and received signals and time-indexing of the peak of this function after a parabolic interpolation. The carrier phase shift between emission and reception is then computed in order to drastically refine the final result.

Accurate measurements (typically better than 1 mm, even for poorly reflecting targets for a distance of about 1 m) can be achieved despite low sample rate and limited computing capabilities. The algorithm is simple and needs no complex associated hardware. Moreover, the method can be easily adapted for other microcontrollers or digital signal processor-based platforms.

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