

A LabVIEW Based Experimental Platform for Ultrasonic Range Measurements

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Abstract

Ranging using ultrasonic waves is applied in several areas such as robotics, industry and medicine. Great efforts have been taken in research to improve the precision of this system. These efforts developed different techniques to attain more accurate result. To evaluate the performance of these techniques a flexible platform is needed to implement them and then to analyze and compare their performances. In this framework a novel design and implementation of a general purpose ultrasonic ranging system is presented. This system is employed to implement three different methods they are; simple threshold, double threshold, and correlation detection. Then we analyze statistically their experimental results. The performance of these techniques is compared in terms of the change of bias, standard deviation, and total error as a function of range. The experimental results exhibit the flexibility and simplicity of the proposed system by which it can be easily adapted to support other similar applications.¹

Keywords: LabVIEW- time of flight - ultrasonic ranging - DSP

1. Introduction

Measuring the distance between a known base location and the surface of an object by using ultrasound signal is referred to as ultrasonic ranging which is very important in wide range of applications, including Sonar Mapping [1], robotic ranging and positioning [2], as well as ultrasonic based navigation [3]. One of most dominant ranging systems is the Time-of-flight (TOF) based system, which measure the round trip time between an energy pulse emission and the return of the pulse echo resulting from its reflection from an object at distance R from the ultrasonic sensor. In this case R can be computed using the following equation:

$$R = C \times \frac{T_f}{2} \tag{1}$$

C is the propagation speed of the ultrasonic waves in the medium, and T_f is the TOF.

The range measurement uncertainty depends on the quality of estimation of both C and T_f . The first quantity depends dominantly on the temperature according to equation (2)

$$C = 331.4\sqrt{T / 273} \text{ m/s} \tag{2}$$

T is the absolute temperature in Kelvin

This dependency can be relatively easily compensated for [4], so the critical point of the whole measurement procedure is the TOF estimation.

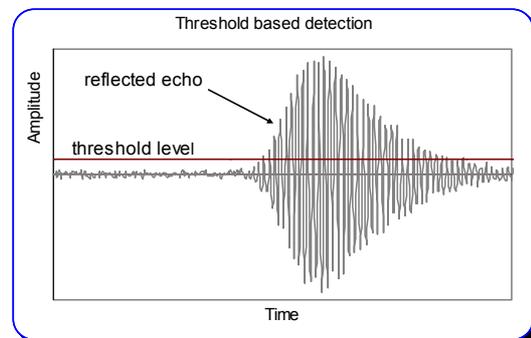


Figure (1) Threshold based detection

The basic method is to transmit several cycles at least five, preferably ten or more [5] of high-frequency ultrasound and to use a simple hardware or software counter to measure the time it takes for the sound to return. The counter is started when the sound is transmitted and stopped when the reflected echo is received. Threshold based detection [6] is the most widely used method for TOF estimation, and applies to any type of short duration signal. By this method, the received signal is compared with a preset threshold level, such that the arrival of the wave is acknowledged when the signal reaches this level as shown in figure (1). The threshold level should be set sufficiently high to eliminate false detection due to ground level noise.

¹ This study has been implemented on LabVIEW platform at electronics lab. Faculty of engineering Shobra. Benha University

Applying threshold based detection to ultrasonic ranging is shown in figure (2). The detection of the reflected echo occurs at t_2 , however the signal actually started at TOF so there is a bias error T_{error} defined by:

$$T_{error} = t_2 - T_f \quad (3)$$

Even at t_2 there can be an uncertainty of half the wavelength.

One way to reduce this error is to find the envelope and comparing it with the threshold as shown in figure (2), this gives the detected time t_1 .

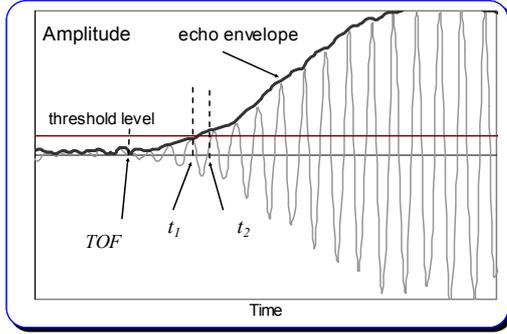


Figure 2 Threshold based detection error

The bias error in this case is given by:

$$T_{error} = t_1 - T_f \quad (4)$$

The main problem with the threshold method is that, the TOF measurement obtained is larger than the actual TOF , which corresponds to the starting point (onset) of the echo signal. This is a consequence of the relatively long rise-time of the echoes produced by low-bandwidth ultrasonic transducers for operation in air. Then, the range information obtained by threshold is biased, making the target appear slightly farther than it actually is. The resulting bias error, which is in the range of several millimetres to centimetres is not constant then it can not be avoided and it is difficult to be modelled analytically [7].

Two alternative methods double threshold and correlation detection method are used to reduce the bias error [7].

The paper is organized as follows: an introduction to ultrasonic signal modeling is proposed in section 2. The different ranging techniques using ultrasonic is analyzed in section 3. In section 4 the experimental work and performance comparison discussions is illustrated. Section 5 and 6 presents the conclusion and future work respectively

2. Ultrasonic signal modelling

Since the signal fed to the ultrasonic transducer is a short train of ultrasonic waves, and the electrical equivalent of the transducer is a high quality resonant circuit [8], therefore the signal generated in response to the transmit command can be represented in the form:

$$S_i(t) = a(t) \cdot \sin(2\pi f_o t) \quad (5)$$

Where f_o is the resonant frequency of the transducer, and $a(t)$ represents the envelope with a finite duration.

The shape of the echo detected by the receiver can be approximated by the following model [9]

$$S_r(t) = a(t - T_f) \sin[2\pi f_o(t - T_f)] + w(t) \quad (6)$$

Where the signal $w(t)$ is a white Gaussian noise having zero mean and variance σ_w^2 .

The transmitted signal is a noise free signal, while the received echo signal is an attenuated and delayed version of $S_i(t)$ plus additive white noise.

The envelope $a(t - T_f)$ of the reflected echo is given by

$$a(t - T_f) = a_o e^{-a_1(t - T_f)^2} u(t - T_f) \quad (7)$$

Where $u(t - T_f)$ is a unit step function delayed by T_f and a_o is the amplitude parameter, and a_1 is shape parameters of the signal.

After envelope detection equation (6) becomes:

$$S(t) = a(t - T_f) + n(t) \quad (8)$$

the form of $a(t - T_f)$, given by equation (7) is capable of modelling observed echo envelopes for a wide variety of obstacle types located at different locations within the active region of the ultrasonic receiver. The exponential term in equation (7) can be neglected at the start of the envelope where $t > T_f$ and $(t - T_f)$ is small. A parabola is a good approximation for the onset of $a(t - T_f)$ in the time interval $t \in [T_f, T_f + 2/a_1]$, therefore the signal observation model becomes:

$$S(t) \cong a_o (t - T_f)^2 + n(t) \quad (9)$$

$$\text{for } t \in [T_f, T_f + 2/a_1]$$

Uniform sampling in time produces the sequence

$$S_k \cong a_o (t_k - T_f)^2 + n_k \quad (10)$$

$$\text{for } t_k \in [T_f, T_f + 2/a_1]$$

Where t_k are the sample times, and s_k and n_k are the corresponding signal and noise samples that can be processed by a computer.

In the next section, three different methods of TOF estimation are discussed namely simple threshold method, double threshold and optimal correlation detection.

3. Ultrasonic ranging techniques

3.1. Simple threshold method

The simplest way of measuring TOF is the threshold method. In which the TOF is the time at which the echo amplitude waveform first exceeds a preset threshold level (L). This level is set according to the noise level. Assuming Gaussian noise, L is usually set equal to 3–5 times the noise standard deviation σ_n [7]. Neglecting noise, the time at which the noiseless



signal envelope first crosses the threshold L is denoted by t_x^* .

By equating the noiseless $s(t)$ in (9) to L gives:

$$t_x^* = T_f + \sqrt{L/a_o} \quad (11)$$

However, the time t_x , when the signal plus noise exceeds the threshold for the first time, is not equal t_x^* . Further, the observed TOF is also affected by the sampling frequency. If the sampling interval T_s , then the estimated TOF \tilde{T}_f can take on values that are only discrete multiples of the sampling time T_s

$$\tilde{T}_f = kT_s = t_x + \Delta \quad (12)$$

Where k is an integer, Δ is a random delay uniformly distributed in the interval $[0, T_s]$. The variable Δ is added to continuous-valued t_x to produce the clock reading kT_s . The statistics for this estimator have been driven by Kuc [9] to evaluate its bias and variance which are defined by equations (13), (14) respectively:

$$B[\tilde{T}_f] = E[\tilde{T}_f] - T_f \quad (13)$$

$$Var[\tilde{T}_f] = E[\tilde{T}_f^2] - E^2[\tilde{T}_f] \quad (14)$$

E is the expectation operator. The results reported in [7] for the above two equations as L/σ_n increase yields:

$$B[\tilde{T}_f] = \sqrt{\frac{L}{a_o}} + \frac{T_s}{2} \quad (15)$$

$$var[\tilde{T}_f] = \frac{T_s^2}{12} \quad (16)$$

Equation (15) illustrates the problem inherent to threshold method. For $L > 0$, this estimator is biased since the actual echo arrival time occurs before the time t_x where the echo exceeds the threshold. Since a_o changes along with the echo amplitude it is clear that the bias will be amplitude dependent, this will be verified in the experimental work.

(3-2) Double threshold method

A second method for estimation the TOF and reduce the bias obtained in the simple threshold is the double threshold method. In which a two-points are fit to the rising edge of the ultrasonic echo envelope to an appropriate power law [11]. It was found that the rising edge was very well approximated by a parabola. The conventional electronics used to detect and process the signal had near negligible additional effect on pulse shape, since the signal $s(t)$ rises parabolically in the form $a_o(t - T_f)^2$. The time of flight T_f can be determined directly from double threshold measurements

$$L_1 = a_o(t_1 - T_f)^2 \quad (17)$$

$$L_2 = a_o(t_2 - T_f)^2 \quad (18)$$

Eliminating a_o then

$$T_f = \frac{\sqrt{V}t_1 - t_2}{\sqrt{V} - 1} \quad (19)$$

This is independent of the signal amplitude. Here $V = L_2/L_1$ is the ratio of upper to lower threshold. The accuracy of this estimate will depend on the SNR of the received signal and the setting of these two levels in order to cover the widest possible range of probable signal levels with the least amount of error is examined. It has been reported in [11] that a threshold ratio V of 2 represents a suitable choice.

The double-threshold technique is applicable to any waveform whose rising edge is of the form $a_o(t - t_f)^x$, and it can be seen from equations (17), and (18) that it is straightforward to generalize from the $x=2$ case to an arbitrary x . The appropriate power law, and whether or not the initial t^r rise is of sufficient duration for the approximation to remain useful, can be readily determined experimentally for a given system by measurement of the pulse shape. While our work deals with applying and characterizing the parabolic case, it is also valid for general power laws.

3.3. Correlation detection for time of flight estimation

Digital Signal Processing (DSP) is one of the most powerful technologies that have been widely used in a broad range of fields. It provides high performance and high precision of signal processing ability, which is impossible to achieve in the conventional Analog signal processing.

There are many different DSP algorithms used to deal with the range finding signal processing where the main task of DSP is the time of flight estimation sometimes refers as time delay estimation TDE. In order to obtain TOF accurately, DSP has the ability to suppress various kinds of noise, detect and extract the desired echo signal. Those DSP algorithms include correlation [12], adaptive filter, wavelet analysis and more [13]. This work deals with the study of the correlation application in range finding systems.

The digitized versions of the transmitted and received echo signal presented in (5), and (6) that being stored for digital signal processing are expressed as $X_T(nT)$, and $X_E(nT)$ respectively:

$$X_T(nT) = s_t(nT) \quad (20)$$

$$X_E(nT) = \alpha s_t(nT - T_f) + w(nT) \quad (21)$$

Where T is the sampling interval, α is the attenuation coefficient, $w(nT)$ is the additive Gaussian white noise, and T_f is the time delay between the transmitted and received signal (TOF), the transmitted digital sequence $X_T(nT)$ is also known as a template signal.

Correlation is used to reveal the degree of similarity between one sequence of data and the other as a function of time shift between them, the Cross-correlation processing is to take the sum of the



products of the corresponding data pairs. The Cross-correlation function between the transmitted and received sequences is defined as [14]:

$$C(kT) = \sum_{n=0}^{N-1} x_T(nT)x_E(nT - kT) \quad (22)$$

$k = 0, 1, 2, 3 \dots$, and kT is the shifted sampling points in respect to the $X_T(nT)$,

In practice, the delay can be estimated by finding the peak of the cross-correlation function in equation (22), since the amplitude of each sample in the cross-correlation signal is a measure of how much the received signal resembles the template, at that location. In other words, the value of the cross-correlation is maximized when the target signal is aligned with the same features in the received signal.

It reported in [15] that it is possible to estimate the delay from the cross-correlation of signal envelopes rather than ultrasonic signals with the advantage improved resolution can be expected. Since of the transmitted signal is narrow band signal, the envelope of cross correlation decreases slowly, while the correlation function itself is highly oscillatory.

The amplitude spectrum of the transmitted signal is shown in Figure (3).

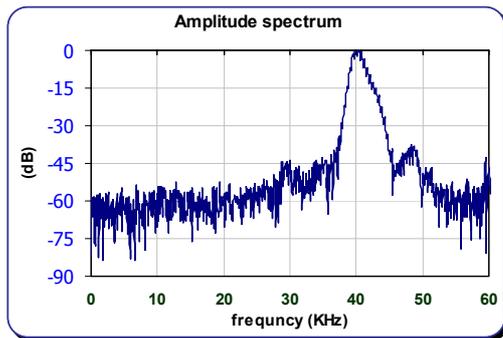


Figure (3) the amplitude spectrum of the transmitted ultrasonic waves

The envelopes of the transmitted and received ultrasonic echo are extracted by digital technique, where the envelopes are the magnitude of the analytic signal obtained via Hilbert transformation (HT) of the transmitted and received echo sequences [16].

The complex-valued analytic signal $\varphi(t)$ is defined as

$$\varphi(t) = s(t) + j\hat{s}(t) = \mu(t)\exp[2\pi f_o t] \quad (23)$$

Where the imaginary part of the analytic signal is the Hilbert transform of the ultrasonic signal $s(t)$

The algorithm that is presented in this work has been implemented with the aim of achieving a resolution of the same order of magnitude as the sampling interval T for the estimation of the delay T_f .

4. Experimental works and results

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) [17] developed by National Instrument, is a graphical programming environment suited for high-level or system level design. The

advantage of this approach is given mostly by the flexibility and very rapid development time offered by this graphical programming software. Figure (4) depicts the block diagram of the LabVIEW based data acquisition system. The major hardware components include the data acquisition board (DAQ board- National Instruments PCI-6036E), transmitting unit, receiving unit, ultrasonic transmitter and receiver transducers, and temperature measurement circuit.

The system requires three analog inputs (AI) channels. The first one is used to receive the temperature information, the second one is used to acquire the exciting pulses on the ultrasonic transducer, and the last one is to acquire the reflected ultrasonic echo signal.

The DAQ device has the capability to sample any signal up to a rate of 200 KHz, so we can not sample the three Analog channels at the maximum rate (200 KS/s) but at rate equal to 66.6 KS/s (since all Analog channels are multiplexed) this frequency does not satisfies Shannon criteria which indicates that a continuous signal can be properly sampled, if its highest frequency content does not exceed half the sampling rate. In this case minimum the sampling frequency must be greater than 80 KS/s (twice ultrasonic frequency). To solve this problem we first use one channel to measure the temperature (AI ch3) before the experiment. Then we use the other two channels for the transmitted and the received signal. In this case we can sample each of the two channels at 100 KS/s ($T_s = 10 \mu s$), this sampling frequency gives a poor resolution since the period of the ultrasonic pulses is $25 \mu s$ then every complete cycle will be sampled about 2 samples. But experimental work leads to that the DAQ device can sample each of the two channels at maximum sampling frequency of 190KS/s

The main program starts with measure of the temperature. The temperature data is acquired by means of AD 590 which is a two-terminal integrated circuit temperature transducer that produces an output current proportional to absolute temperature. The interface of temperature circuit with the data acquisition card is the most basic circuit used for interfacing the AD590, the circuit acts as current to voltage converter, and the output voltage of this circuit is proportional to temperature. A voltage of 1 mV/K can be adjusted. The output voltage of the interface circuit is measured and is converted to temperature. This temperature is used to calculate the speed of ultrasonic waves in air according to equation (2). The second step in the program is to determine the noise statistics of the background noise.



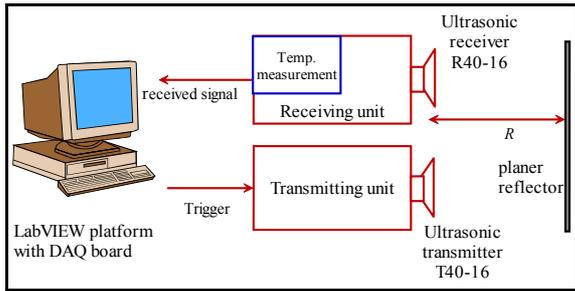


Figure (4) Experimental system

A signal is received from the receiver unit output in the absence of any received echo; this signal represents the noise. (In our system, the sources of noise include thermal noise in the electronic components and acoustic noise from sound sources in the environment). This noise signal is analyzed statistically to determine its standard deviation. This value is passed to the program, to set the threshold level or double threshold levels.

A trigger signal is generated by the DAQ module that trigger the transmitter unit to generate 10 complete cycles of 40 KHz square wave (center frequency of the ultrasonic piezoelectric transducer), the transmitter unit consisting of a microcontroller followed by a driver circuit that is used to increase the voltage applied on the ultrasonic transmitter.

The system is then acquires both the driving pulses at ultrasonic transmitter end and the reflected echo signal after being amplified the two signals at rate 194 kS/s per each.

It was found a delay about 300 micro-second between the moment at which the DAQ module triggers the microcontroller and the moment at which the driving signal reaches the transmitter terminal. This delay time t_0 is mainly due to the execution time of the LabVIEW program. We define this delay time as initialization time (t_0) this time must be taken into consideration in the calculation of the time of flight.

The proposed system uses digital techniques for extracting the envelope of the received echo. This is done by using Hilbert transformation of the incoming signal, where the magnitude of the complex analytic signal is the envelope of the original time signal.

According to the selected method the time of flight will be calculated. For the case of simple threshold the program search the received echo envelope data array for array index at which its data exceeds the threshold level, and then multiply this index by sampling time which leads to the time t_1 . The initialization time t_0 must be subtracted to get the actual time of flight T_f . Consequently the range information is obtained by equation (1), 30 trials were stored and the statistical analysis is done obtaining the bias, standard deviation, total error, from a statistical point of view. It is more realistic to express the overall system accuracy as the root mean square (rms)

of the individual element accuracy then the total error ε is calculated using the equation (24):

$$\varepsilon = \sqrt{\sigma^2 + B^2} \tag{24}$$

Where: σ is the standard deviation of the collected 30 range information's and B is the bias of the estimated of the range.

For double threshold method, in a similar manner, the times t_1 , and t_2 are first determined. Equation (19) is used to obtain the TOF and then the range can be calculated.

For the correlation detection method it has chosen to digitize the transmitted signal $x_T(nT)$ according to the arrangement shown in fig (5).

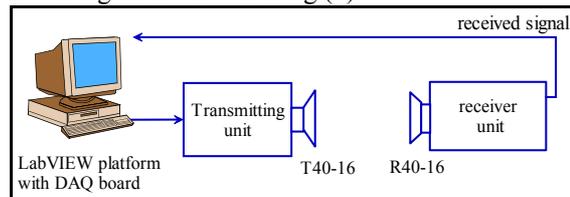


Figure (5) Acquisition of the template signal

In this scheme the receiver is put to face the transmitter, both transducers have 40 kHz resonant frequency. The transmitted signal from the transducer is picked up by the ultrasonic receiver R40-16. After amplification the acquired data is stored.

The resulting sequence $x_T(nT)$ is delayed by the time of flight between the transmitter, and the receiver, however the difference can be corrected as a result of calibration procedures.

The cross correlation virtual instrument tool built in LabVIEW software has been used to compute the cross correlation between the template envelope, and received echo envelope, the index at which the value of the cross correlation output array is maximum is then multiplied by the sampling time, this will be the time delay between the two waveforms.

Figure (6) presents the flow-chart that demonstrates the major functions of our system.

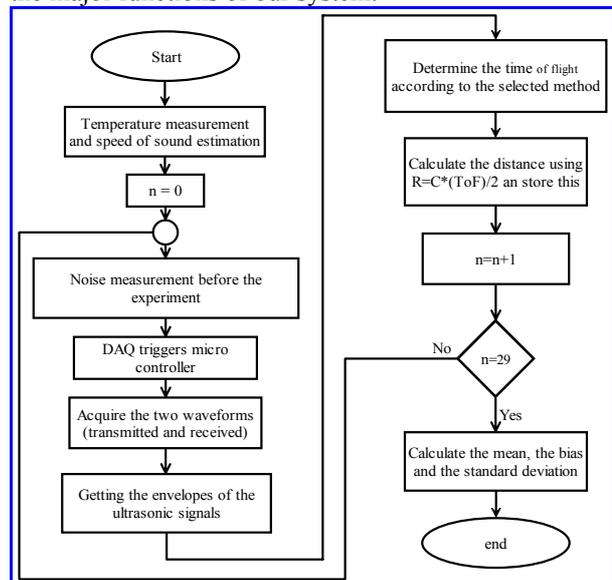


Figure (6) flowchart of the system program



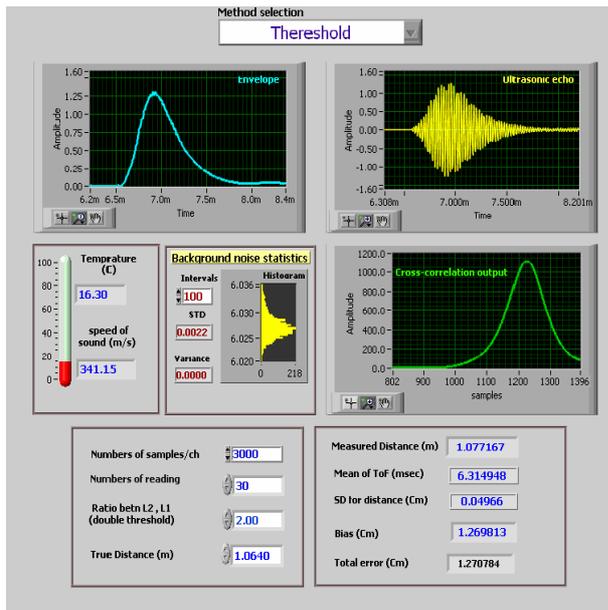


Figure (7) the system front panel

A LabVIEW program is called a virtual instrument (VI). It has two main parts, the front panel and the block diagram. The front panel is used for user interactions and display of results. The block diagram is the source code constructed in LabVIEW's graphical programming language, 'G'. This pictorial block diagram is the actual executable program. The front panel allows the user to enter input such as the number of acquired samples, number of trials that will be stored, the ratio between the two threshold levels in the double threshold method. It also displays the outputs such as waveform graphs of the ultrasonic signal, its envelope, temperature information, noise statistics, and cross-correlation output. Figure (7) presents the system front panel showing all the controls and indicators of ranging system

A flat object has been positioned in the front of the system and its range was varied from 0.4 m to 3 m. Bias, standard deviation, and total error were recorded. Figure (8-a) shows the bias error dependence on range variation. It is clear that as the range (R) increases the amplitude of the ultrasonic waves decreases due to beam spreading. It can be implied According to equation (7) that the amplitude parameter of the ultrasonic wave's a_o will decrease (a_o). Consequently according to equation (15) the bias error for threshold method will increase. On the other hand this bias error can be reduced in the double threshold method, since the estimated TOF usually falls to the left of the threshold estimate.

Finally the bias error obtained in Correlation detection technique wobbles between 1mm and 2mm over the whole range.

Figure (8-b) shows the standard deviation at regular distance intervals. We observe that for the threshold method the effect of increasing (R) is to degrade the range measurement accuracy. Since the noise level is

kept constant, this degradation is mostly caused by the decreasing SNR due to the decrease in signal amplitude with increasing R , for example when the target is moved from $R = 0.4$ m to $R = 3$ m, SNR changes from 64 to 30 dB. We observe also that double threshold method has largest standard deviation which reduces measurement accuracy. This may be due to some sources of errors in the estimation of TOF which is estimated from equation (19), these errors include;

1. The estimation of initialize time t_0 , which may contain random delay, uniformly distributed in the interval $[0, T_S]$, since t_0 can take on values that are only a discrete multiples of the sampling time T_S .
2. the estimation of t_1 and t_2 may contain random delay, in the interval $[0, T_S]$
3. The validity of the parabolic assumption of the leading edge of the ultrasonic pulses.

All this factors may be combined which leads increasing of the standard deviation of the measured range.

For correlation detection the standard deviation seems to be constant about 0.04 cm. This small standard deviation means that all measurements do not spread about the mean value.

5. Conclusions

In this work we design and implement a fully integrated system for the measurement of ultrasonic signals. The system is used mainly for range measurement applications. The system has the advantages of flexibility and easy to use. It can be relatively easy adapted to operate also in other similar applications since it has a friendly graphical interface. The designed system has been used to implement three different techniques for range measurements and to compare performances. The comparison is presented in terms of the change of bias, standard deviation, and total error as function of range.



(a)



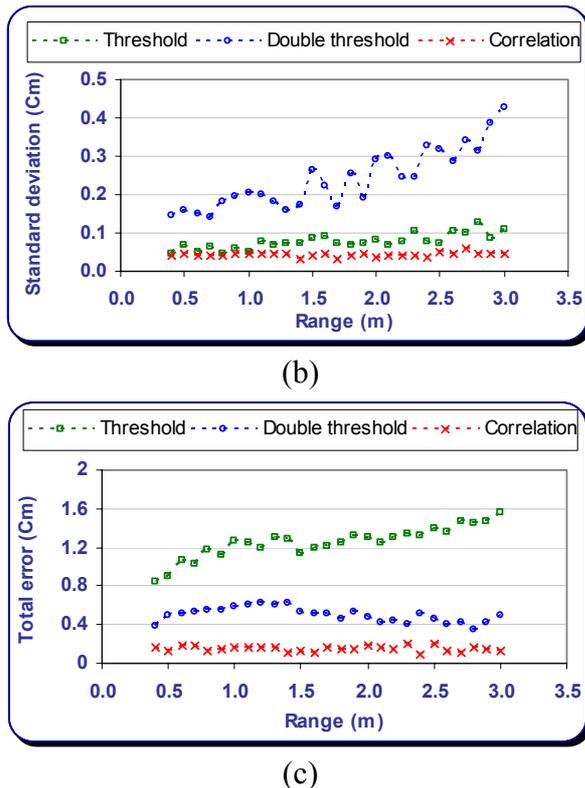


Figure 8 Variation of the bias (a), the standard deviation (b), and the total error (c) with range

The double threshold method reduces the bias relative to threshold but on the other hand has the largest standard deviation among the three methods, i.e. in terms of standard deviation; double threshold method is not as good as the simple threshold method and correlation which offers the smallest standard deviation. For the threshold and correlation methods the total error turns out to be dominated by the bias and therefore has a shape which resembles the bias curve.

The double threshold method accuracy can be improved by judicious choice of the threshold levels and the threshold ratio (V). Setting these levels too low increase the probability of false triggering by noise spikes. On the other hand, setting the levels too high limits the useful range obtained by this technique, since at longer distance the signal level decrease (also SNR decrease) which implies that the thresholds correspond to levels closer to the signal peak where pulse shape deviations from parabolic model are greater.

Correlation increases the accuracy of time of flight measurements as compared to threshold. However, correlation is obtained through a higher computational load than threshold, which might prevent its use

6. Future work

The future work can be divided into two aspects of the theoretical study for ultrasonic ranging techniques and the implementation of the proposed techniques.

In the theoretical study aspect, two interesting areas closely related to the current work can be investigated:

The first case would be the analysis of another curve fitting algorithm based on non linear least square curve fitting which reduce the standard deviation considerably

The second case would be the analysis of phase shift based ultrasonic ranging technique used for small range measurement.

In the implementation study aspect, we recommend the study of the implementation of the correlation detection technique on digital signal processing systems at moderate cost

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