DESIGN AND DEVELOPMENT OF COMPUTER CONTROLLED ACTIVE SONAR SYSTEM

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Original scientific paper

Nowadays computerization is the most popular, reliable and flexible design for various types of control and communication systems. Sound navigation and ranging (SONAR) is a modern ultrasonic range finding technique used for collecting the information of a distant object without any physical contact. In this paper, a personal computer (PC) based active SONAR system is presented. The developed SONAR system contains both transmitter and receiver parts in the same module. A pair of 40 kHz piezoelectric ultrasonic transducers is used to transmit ultrasound toward the object and receive the reflected from the object respectively. A driver-software named CURF (Computerized Ultrasonic Range Finder) is developed for this system, using Turbo C language aimed at IBM PC and its clone machines. The CURF software provides necessary support for interfacing the developed hardware as well as desired calculations. A number of tests have been done and it is found that the performances of the developed system are good in terms of accuracy, simplicity, cost and power consumption.

Keywords: ASDICS, computer interfacing, piezoelectric transducer, RADAR, SONAR, ultrasonic range finder, ultrasound, under water radar, WPESS

Projekt i razvoj aktivnog sonarnog sustava upravljanog računalom

Izvorni znanstveni članak

Danas je primjena računala najpopularniji, najpouzdaniji i najfleksibilniji projekt za različite vrste upravljačkih i komunikacijskih sustava. Zvučna navigacija i određivanje daljine (SONAR) je moderna ultrazvučna tehnika određivanja daljine primijenjena za prikupljanje informacija o udaljenom objektu bez ikakvog fizičkog kontakta. U ovom se radu predstavlja aktivni SONARNI sustav zasnovan na osobnom računalu (PC). Razvijeni SONARNI sustav u istom modulu sadrži i dijelove odašiljača i dijelove prijemnika. Par piezoelektričnih ultrazvučnih pretvarača od 40 kHz koristi se za prijenos ultrazvuka u pravcu objekta i prijem odbijenog zvuka od predmeta. Za taj je sustav razvijen program nazvan CURF (Computerized Ultrasonic Range Finder) koji koristi Turbo C jezik namijenjen za IBM PC i njegove kopije. Program CURF daje potrebnu podršku za održavanje veze s razvijenim dijelovima uređaja kao i za željene izračune. Nakon obavljenih brojnih ispitivanja ustanovljeno je da razvijeni sustav zadovoljava u odnosu na točnost, jednostavnost, cijenu i potrošnju energije.

Ključne riječi: ASDICS, održavanje veze u računalu, piezoelektrični pretvarač, podvodni radar, RADAR, SONAR, ultrazvučno određivanje daljine, ultrazvuk, WPESS

1 Introduction

Due to simplicity and low cost interfacing hardware, many data acquisition through the parallel port have been built in the past years [1 ÷ 4]. However, either those works have not been reported comprehensively or there have been too many complexities in the approached development system which might be hard to realize. This paper is to report a complete working system with less complexity computer aided active sonar system. The word sonar is an American term first used in World War II; it is an acronym for Sound, Navigation and Ranging. The British also called the sonar as ASDICS, which stands for Anti-Submarine Detection Investigation Committee. Later developments of sonar included the echo sounder or depth detector, rapid-scanning sonar, side-scan sonar, and WPESS (within-pulse electronic-sector-scanning) sonar [5]. Sonar uses sound wave to find the range to detect the object. It has tremendous uses in underwater because of the excellent sound carrying properties of the water, so sometimes it is called a kind of underwater radar. It uses 30 Hz ÷ 300 kHz low frequency band (LFB) or 300 kHz - 3000 kHz high frequency band (HFB) mechanical wave (sound wave) to locate an object. Where radar basically gathers information from a distant object or from a target by sending an electromagnetic wave and collects the wave reflected back from the object or target. Radar generally uses ultra-high frequency UHF or microwave frequency band to locate an object. The simplest form and the basic principle of both the radar and sonar is that both of them send a narrow beam of signal wave toward the target/object and wait for reflected wave back from the target. Once received the reflected signal, they measure the total travel time of the wave and the strength of the signal, these give the idea of the distance and the information about the target area respectively. There are different types of ultrasonic range finder according to the applications [7, 8] and these are sometimes very complex in circuitry due to high precision demand. A simple block diagram of the proposed system is shown in Fig. 1. The personal computer (PC) controls the overall function of the system as well as supports the required interfacing and calculation.
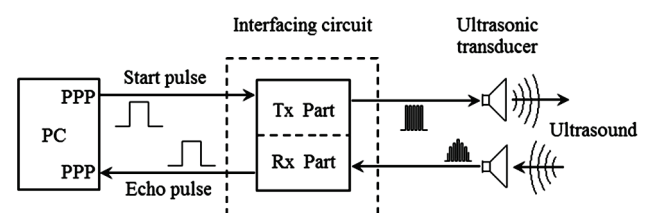

Figure 1 Simple block diagram of a computer aided active sonar system

At the beginning, PC sends a start bit through pin 2 (D0) of a parallel printer port to command the control circuit to work as a transmitter unit. When the control circuit receives a start bit from the PC, it enables an electronic oscillator to generate 40 kHz frequency for the ultrasonic transducer. The on and off conditions of the oscillator depend on the control signal of the PC. The oscillator signal is then amplified to sufficient strength before it feeds to the input to the transmitting piezoelectric ultrasonic transducer. The transmitting transducer converts the electrical signal into a sound wave and transmits toward the target through a parabolic sound

reflector into the air. If there is a reflecting object in front of the traveling wave, a portion of the signal has a chance to reflect back to the receiving ultrasonic transducer through alternative parabolic sound reflector. Among with the other signals i.e. noise, the receiving transducer filters out most of the 40 kHz echo signal, since the central frequency response of the transducers pair used in the developed system is 40 kHz. The receiving piezoelectric transducer converts the received echo sound into an equivalent electrical signal. A receiving amplifier is used to boost the received signal strength, since it loses strength in air due to absorption, scattering and diffusion. The amplified signal then follows a filter circuit to improve the signal to noise ratio (SNR). A comparator circuit compares the received signal with a reference voltage and allows the desired signal to control an SR flip-flop. The flip-flop [9] would set or reset according to transmitted and received echo signals respectively. So the time difference between the rising edge of the transmit signal and rising edge of the receive signal can be found from the interval state of the SR flip-flop.

2 Range calculation

In an active sonar system a short acoustic pulse is emitted from the transducer and at this time the system works as a transmitter unit. The system then switches to receive mode and would wait for receiving an echo signal. When the echo signal is detected, the range S can be found by multiplying the sound velocity with half of the measured time. The measured time in this case is the round trips of the sound wave. The distance of the target from the transducers can be calculated by using the following equations [6].

$$S = vt/2, \tag{1}$$

where, v is the speed of sound m/s in air and t is the total round trip time in second.

If it assumes air as an ideal gas, the speed of sound v can be calculated by Eq. (2).

$$v = \sqrt{\delta R T_K}, \tag{2}$$

where, $\delta = 1{,}4$, $R = 287$ m$^2/$(s^2 − K) and T_K is the absolute temperature in Kelvin. Using these constants' values, the approximate velocity can be calculated by using Eq. (3).

$$v \cong 20\sqrt{T_K}. \tag{3}$$

In most of the cases the error between direct sound velocity measurement and velocity measurement by Eq. (3) is only $\pm 1\%$. The relation between absolute temperature T_K in Kelvin and Celsius (C) degrees is shown in Eq. (4).

$$T_K = 271{,}15 + \vartheta_{\circ C}. \tag{4}$$

Combining Eq. (1) and Eq. (2), the distance can be represented by Eq. (5).

$$S = 10\sqrt{T_K t}. \tag{5}$$

3 Design of transmitter section

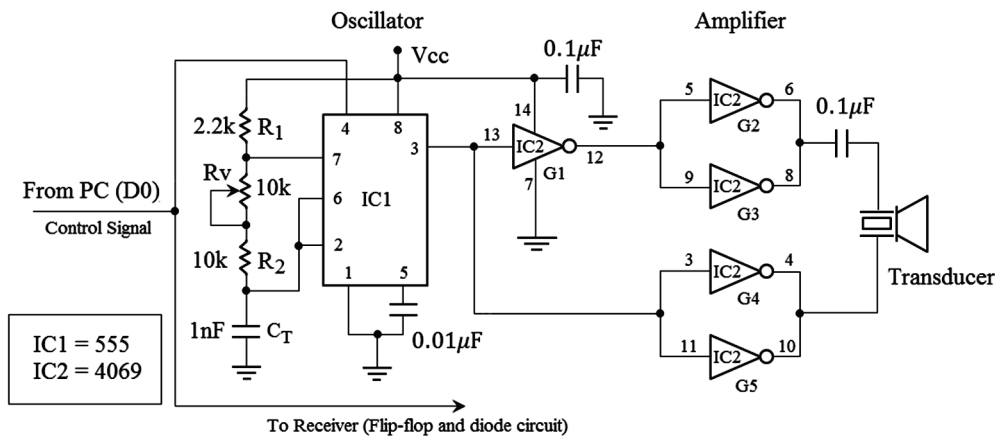The schematic of the proposed transmitter section is shown in Fig. 2.

Figure 2 Schematic of the transmitter section

3.1 Oscillator

A 555 timer IC based as table multi-vibrator circuit is used to generate 40 kHz square wave for driving the transmitting ultrasonic transducer. The 555 timer [10] is a TTL-compatible integrated circuit that can be used as an oscillator for generating the square wave signal. Two external resistors and a single timing capacitor are capable to accurately control the frequency as well as duty cycle of the oscillator. During the oscillation, the timing capacitor C_T charges toward $+V_{CC}$ through R_1 and R_2 and discharges through R_2 toward ground potential. The charging and discharging times can be calculated by Eq. (6) and Eq. (7) respectively.

$$T_{\text{high}} = 0{,}693(R_1 + R_2)C_T, \tag{6}$$

$$T_{\text{low}} = 0{,}693\,R_2 C_T, \tag{7}$$

where T_{high} is the time when output wave remains high voltage and T_{low} is the time when output wave remains low voltage.

Combining Eq. (6) and Eq. (7), the total time period T and the frequency f of the oscillating wave can be calculated by Eq. (8) and Eq. (9) respectively.

$$T = T_{high} + T_{low} = 0{,}693(R_1 + 2R_2)C_T, \qquad (8)$$

$$f = 1/T = 1{,}44/(R_1 + 2R_2)C_T. \qquad (9)$$

The percentage of duty cycle $\% D$ of the wave can be calculated by Eq. (10).

$$\% D = (T_{high}/T) \times 100 = (T_{high} \times f) \times 100. \qquad (10)$$

3.1.1 Components value calculation

Assume $R_1 = 2{,}2 \text{ k}\Omega$, $C_T = 1 \text{ nF}$ and $R_V = 10 \text{ k}\Omega$ variable resistor and desired frequency of the transmitter is $f = 40 \text{ kHz}$, using Eq. (9)

$$40 \times 10^3 = 1{,}44/[2{,}2 \times 10^3 + 2(R_2 + R_V)] \times 10^{-9},$$

or, $R_2 + R_V = 16{,}9 \text{ k}\Omega$.

Let $R_2 = 10 \text{ k}\Omega$, by adjusting R_V the frequency $f = 40 \text{ kHz}$ can be achieved at $R_V = 6{,}9 \text{ k}\Omega$.

Percentage of the duty cycle of the wave $\% D$, can be calculated by using Eq. (10).

$$\begin{aligned} \% D &= (T_{high} \times f) \times 100 \\ &= [0{,}693(2{,}2 + 16{,}9) \times 10^3 \times 10^{-9} \\ &\quad \times 40 \times 10^3] \times 100 = 53 \text{ \%}. \end{aligned}$$
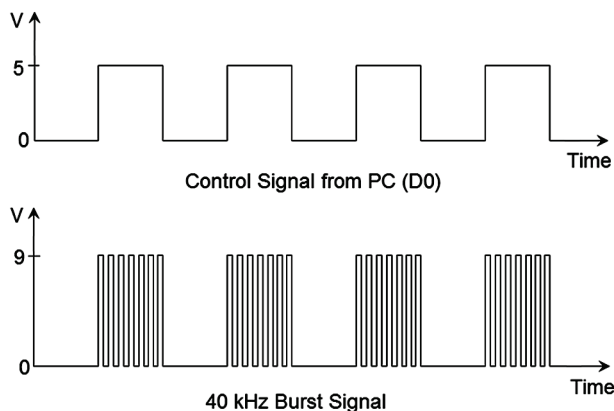

Figure 3 Control signal and output wave shape

3.1.2 Oscillator control

The oscillator is enabled or disabled by the PC command signals. The PC parallel port adapter is specifically designed to attach the printer through a parallel port interface. The reset pin of the timer IC-555 (pin 4) is connected to pin 2 (D0) data pin of the parallel printer port. The output voltage level of the LPT parallel printer port is 5V but the designed oscillator circuit is operated by a 9V supply, so it needs to amplify the D0 (pin 2) output voltage before it applies to the reset pin of the timer IC 555. The output of pin 2 (D0) is a square wave pulse and the developed software is capable to adjust its width and repetition rate according to the distance measure. The small pulse width for short

distance and extend pulse width for long distance measurement are used respectively. The oscillator can generate 40 kHz square wave frequency when the voltage level of D0 is high and it would be stopped to generate frequency when the voltage level of D0 is low. As a result is a 40 kHz burst signal at the output from the oscillator as shown in Fig. 3.

3.2 Power amplifier

An inverter buffer amplifier circuit is used to boost the oscillator signal power before feeding it to the transmitting ultrasonic transducer. TTL logic gate, especially buffer or inverter, is usually used as a digital amplifier. The inverters in Fig. 2 are used to function as a push-pull amplifier. The inverter G1 works as a phase shifter. When the inverter G1 input is high its output becomes low voltage as a result, the upper two inverters G2 and G3 outputs are changed to high voltage. Simultaneously the lower two inverters G4 and G5 outputs develop low voltage and current flows through the 0,1 μF capacitor to the piezoelectric transducer. Similarly when G1 input becomes low, the current would flow through the transducer in opposite direction i.e. from piezoelectric transducer to the capacitor. The upper two inverters G2 and G3 are connected in parallel and these are collectively used to amplify the half wavelength of the input signal. Similarly the lower two inverters G3 and G4 are connected in parallel and these are jointly used to amplify the remaining half wavelength of the input signal. Both parts of the amplified electrical waves are passed through the transmitting ultrasonic piezoelectric transducer and generate a high power ultrasound wave which can transmit through the air.

4 Design of receiver section

This section consists of many electronic devices or circuits to rebuild a recognizable form of the received signal for the PC. The schematic of the receiver section is shown in Fig. 4. The entry stage of the receiving end uses a piezoelectric ultrasonic transducer. The piezoelectric transducer pairs used in this research have the maximum response at frequency 40 kHz as shown in Fig. 5. So the receiving transducer can detect about 40 kHz echo signal and converts it into an electrical signal. As a result, these piezoelectric devices work as a bandpass filter as well as a transducer.

Usually the ultrasound signals lose their strength during the journey into the air and a fraction of echo signal from the target may be backed to the receiving transducer. So the electrical output signal strength of the receiving transducer is very weak and needs to be amplified before using it in the next process. Two stages integrated amplifiers are used to amplify the received signal and the overall approximate gain of the amplification can be calculated as follows.

$$A_v = (R_{F1}/R_6) \times (R_{F2}/R_8) = (10^6/10^4) \times (10^5/10^3)$$
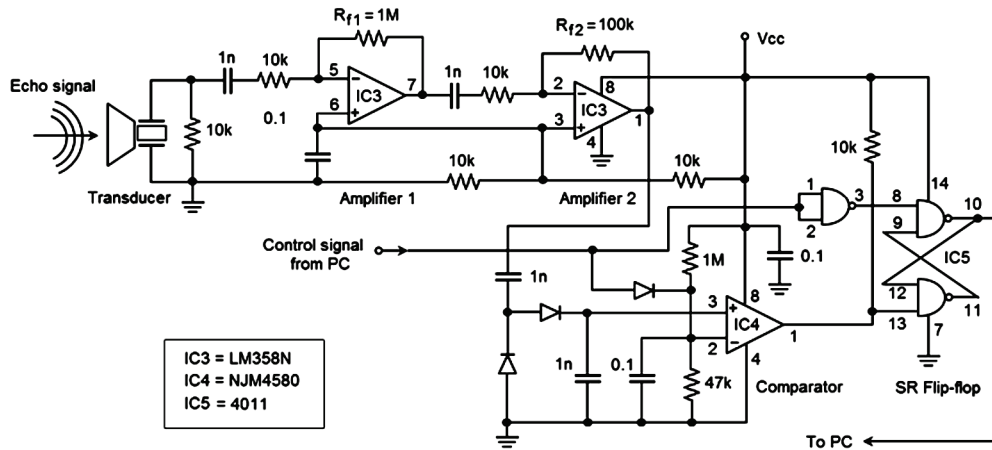
$$= 10000.$$

Figure 4 Schematic diagram of the receiver section

The amplified signal then passes through a full-wave rectifier circuit and a low pass RC filter circuit. The cut-off frequency f_C of the lowpass filter can be calculated by Eq. (11).

$$f_C = 1/(2\pi RC). \tag{11}$$

In this work, $f_C = 40 \times 10^3$ kΩ and $C = 1{,}0 \times 10^{-9}$ F

So, $R = (2\pi f_C C)^{-1} = (2 \times 3{,}14159 \times 40 \times 10^3 \times 1{,}0 \times 10^{-9})^{-1} = 3978\ \Omega \approx 4{,}2$ kΩ (a commercial value).

Then the filtered signal is compared with a reference voltage by a comparator circuit (IC4).

Figure 5 Frequency response and transmitting sound pressure level (SPL) of the transducer

If the input voltage is larger than the reference voltage, the comparator produces a high output voltage. Similarly when the input voltage is less than the reference voltage, the comparator produces a zero output voltage. A gated SR flip-flop is used to store the output data of the comparator and the SR flip-flop would reset when the comparator output is high. The set-pin of the SR flip-flop is inverted and connected with the computer's LPT parallel printer port pin 2 (D0). The D0 signal is also connected with the input reference voltage of the comparator through a switching diode to prevent the miss triggering of the SR flip-flop. This diode also prevents the DC current flow into the reset pin of the timer IC 555 (oscillator). The reset pin of the SR flip-flop is connected to the output data pin 2 (D0) of the PC for recording the pulse send time. When the oscillator gets a start command signal from the PC at the same time a pulse signal triggers the set-pin of the flip-flop. Ones the output of the flip-flop is set to logic '1' its value would remain logic '1'

until it would receive a reset signal from the comparator. The LPT parallel printer port of the PC is programed as a bidirectional mode of operation by setting the control bit C5 equal to logic '1'. The output of the SR flip-flop is connected to the pin 3 (D1) of the D-connector of the LPT parallel printer port as an input data bit. The exact start time of the transmitted signal is stored in the PC and at the same time as the start signal (D0) would be triggered both the oscillator and the set pin of the flip-flop. Similarly, the exact time of the received signal can also be stored in the PC (D1) when the echo signal would appear at the reset pin of the flip-flop. The round trip time of the ultrasound is the difference of these two times.
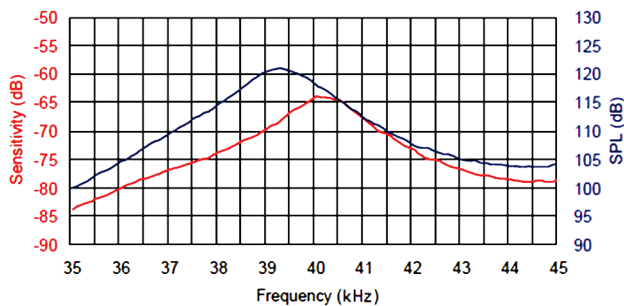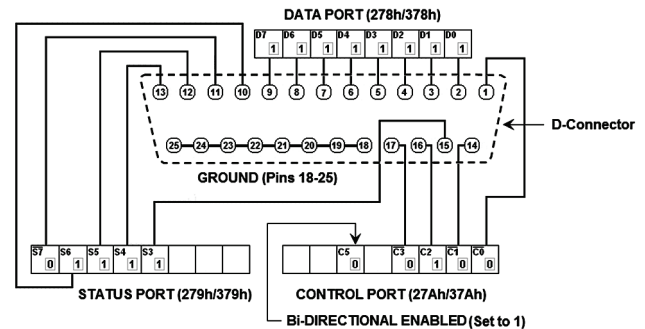

Figure 6 Standard LPT parallel printer port D-connector pin connections and signals [6]

5   Parallel port interfacing

The LPT parallel printer port is the most commonly used interfacing port for a simple to moderate projects of the researchers. The LPT parallel port was originally developed by IBM [6], as a way to connect a line printer to the PC. The port is composed of 4 control lines, 5 status lines and 8 data lines. These are found commonly on the backside of the PC as a D-type 25 pins female connector as shown in Fig. 6. The base address of the port is usually called the data port or data register and is simply used for outputting the data through the data lines (pins 2-9) of the parallel port. In this project data bit D0 (pin 2) is used for signal out from the PC. The status register (base address + 1) is a read only port. The status port is composed of 5 input lines pins 10, 11, 12, 13 and 15 ($\overline{S}_7$, S_6, S_5, S_4 and S_3), an interrupt request (IRQ) status bit and two reserved bits respectively. Finally, the control register (base address + 2) is a programmable

read/write register, whose data bit C_5 can be programed to use the parallel printer port as a unidirectional or a bi-directional mode of operation.

6 Interfacing algorithm

The interfacing software CURF is developed by using Turbo C for IBM PC and its clone machines. The developed software can support the interfacing between the external sonar hardware circuit and the PC in addition to the desired calculations. The algorithm is as shown below.

// $T_S =$ start time, $T_E =$ end time, $T_D =$ time difference and $S =$ distance in m
1. Set, $T_D = 0, S = 0$
2. Output, $D_0 = 1$hex
(Through port 278 hex for start the oscillator & set the f/f)
3. Set, $T_S =$ time of the PC system clock
4. Output, $C_5 = 1$ hex
(Through port 27 A hex, to set the data port as input port)
5. Input I = D_1 (through port 378 hex)
6. If (I = 0) then go to step 3 otherwise go to step 7
7. Set, $T_E =$ time of the PC system clock
8. $T_D = T_E - T_S$
9. Input, $\vartheta =$ surrounding temperature in Celsius degrees
10. $V_s = 20\sqrt{273{,}15 + \vartheta_{\circ C}}$
11. $S = V_s \times \frac{T_D}{2}$
12. Print S, T_S, T_D
13. Exit from program

7 Results and discussion

This paper described the technology and the theory that governs the performance of the transducers used in the research. The satisfactory experimental results are obtained from the proposed system and the developed system follows the theoretical calculations. A variety of obstacle materials are used in this research such as, concrete wall, vinyl board, paper books, cloth bag, etc. and it is found that the result is almost the same. The uncertainty of the maximum distance measured mostly depends on the target's physical geometry, texture and its orientation. Some of the observed data and its graphical representation are shown in Tab. 1 and Fig. 7 respectively.

Table 1 Some observed data

Obs.	Actual distance in meter (m)	Measured distance in meter (m)
1	0,3	0,25
2	0,6	0,51
3	1,2	1,08
4	1,8	1,71
5	2,4	2,46
6	3,6	3,69
7	4,2	4,35
8	4,8	4,95
9	5,4	5,58
10	6	6,24

Overall experiment is done under laboratory control environment by placing the transmitting and receiving transducers inside of two separate large parabolic sound reflectors. The experiment was limited between the ranges 0,3 m to 6,0 m due to the constraint of transducer output power and the receiver sensitivity. An electronic temperature sensor was used to measure the ambient temperature to calculate the velocity of the sound in the air. From Fig. 7 it is found that the system has best performance between 1,5 m to 2,5 m ranges. The overall performance of the system ranges between 0,3 m to 6,0 m is tested and ±5 % errors are observed.
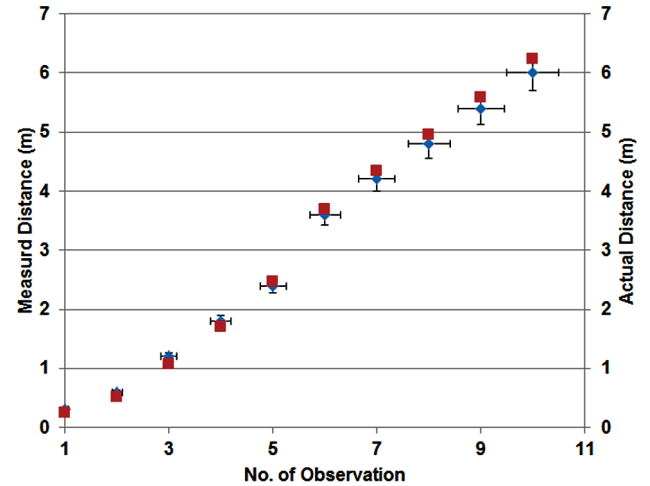

Figure 7 Measured and actual distances within 5 % error scale

8 Conclusion

The strength of the reflected echo signal mostly depends on the size, shape, texture and orientation of the reflecting surface. A large flat surface and hard materials can reflect more echo signal compared to the small surface and soft materials. Depending on the shape of the target, some wave may cause dispersion or may focus the reflected beam, as a result the signal to noise ratio is changed and it is difficult to detect the echo signal specially long distance measurements. Sometimes the measured distance completely differs from the actual value due to the object's surface orientation. A simple low-cost steady state platform was designed and constructed for investigation purpose. However, a sophisticated algorithm and advanced control techniques can be investigated to develop a high efficient system which can be applied for a dynamic sonar system. The main attraction of this research is a static PC based active sonar range finder system of low-cost, easy to implement and inherently safe to use.

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