Local Positioning System for Indoor Robot Navigation

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ABSTRACT

Local positioning systems for indoor robot navigation are in a developing stage using different technologies and algorithms. Many researchers and engineers have focused in improving the accuracy of the local positioning systems. The main focused era of local positioning systems is to predict the position of a robot using known landmarks or transmitting devices located in the indoor system. Most of the local positioning systems are in the experimental stage and some are developed as marketable products after testing under different conditions. Matter of fact exact positioning of a robot in an indoor environment is a fundamental problem in robot navigation. These local positioning systems are helpful in such environments where global positioning systems are not functional to provide accurate information of the position of the robot.

This paper describes a methodology that can be used in indoor navigation to determine the position of a robot. In the system developed ultrasound is used as the communication method. The system designed, consists with several transmitters which can emit ultrasound and a mobile receiver which is capable in receiving the transmitted sound. The ultrasound consists with frequencies above 20 kHz. These frequencies are beyond the sensitivity range of the human ear. Mostly these kind of signals are used by bats to find their path to fly avoiding the obstacles. In the developed system three ultrasound transmitters are used as the landmarks of the positioning system. One transmitter acts as the reference terminal in initiating the determining the process of the positioning system. The accuracy of the system is depend on the number of transmitters have been used. The minimum resolution of the developed system is 5 cm and tested up to 100 cm range in an obstacle free environment.

Keywords: ultrasound, navigation, positioning, robot

1. INTRODUCTION

Global Positioning Systems (GPS) which are widely used for estimating the position in globally can provide accurate estimation using high accuracy sensors in outdoor systems [1]. In indoor systems due to the lack of signal strength and due to the high expensive sensors have to use for position estimation GPS is not a reliable solution for estimating the position of a robot. Predicting the position of a robot in indoor navigation systems can be focused in different eras using different technologies. In 1989 James L. Crowley has built a mobile robot using 24 Ultrasonic sensors. Values recorded using each sensor were considered in estimating the position of a robot in an indoor system. In this scenario a model was presented for the uncertainty in ultrasonic range sensors and the projection of range measurements into external

Cartesian coordinates. A Kalman filter update equation was developed to obtain a precise reading for the position estimation of the mobile robot. The model is tested using real ultrasonic data and can be used to estimate the position of a mobile robot when the environment is not known [2]. Earlier systems of Crowley's included a technique for combining data from a 3-D sensors [3] and another system measured the movement of edge lines in motion sequences [4]. Matthies et al [5] who used a similar techniques for motion and stereo and Durrant-Whyte [6] also used similar techniques for combining touch and stereo.

In 1991 a model was developed using Extended Kalman Filter (EKF) to a known environment. In the above process the researchers have implemented two systems using sonar sensors. In the first implementation a simple vehicle with point kinematics equipped with a single rotating sonar sensor [7]. In the second implementation a mobile robot named "Robuter" used with six static sonar transducers to provide localization information of the vehicle. All the implemented systems were tested for a vehicle speed of 30 cm/s. The two researchers John J. Leonard and Hugh F. Durrant-Whyte built the algorithm based on EKF which utilized the match between the observed geometric beacons and a prior map of beacon localization.

Billur Barshan and Hugh F. Durrant-Whyte presented a system for Inertial Navigation of Mobile Robots using an integrated inertial platform consists with three gyroscopes, a tri-axial accelerometer and two tilt sensors. The platform required an additional information from some absolute position-sensing mechanism to overcome long-term drift. Using the same technique the two researches have described a low-cost inertial sensing systems could provide valuable orientation and position information particularly for outdoor mobile robot applications [8].

Using wireless sensor technologies such as Laser, Ultrasonic, Wi-fi, Radio Frequency (RF), Global System for Mobile Communication (GSM) and etc. many researchers are focused in developing an accurate model for estimating the position of a robot in an indoor environment i.e. a local area. The basic idea of estimating the position of a robot can be defined using the three dimensions. Hence most experiments were conducted using at least three reference terminals with known positions. Additional reference terminals can be used to improve the positioning accuracy and the coverage range [9]–[12]. Figure 1 illustrates a diagram of a local positioning system with the reference terminals (RTi) used and the mobile terminal (MT).

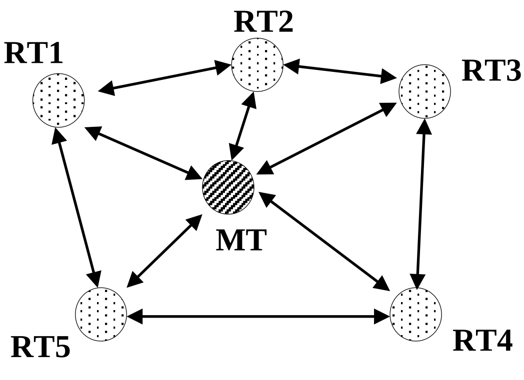

Figure 1: Illustration of a wireless sensor network for Local Positioning System

Ultrasound is cyclic sound pressure with a frequency greater 20 kHz, which is the upper limit of human hearing. A sound waveform with a frequency of 40 kHz is used as the ultrasound in modelling most of the Local Positioning Systems (LPS). In such systems ultrasonic transducers (receivers and transmitters) are used as the sensors. Ultrasound technology provides a great ranging accuracy with low cost electronics [12].

The model designed used ultrasound as the main technology of communicating. The modelled LPS is designed using a single ultrasound receiver and three ultrasound transmitters. As explained in Figure 1, receiver is the mobile terminal of the systems modelled while the transmitters can be taken as the reference terminals. The system is capable of determining the distance to two ultrasound transmitters taking one transmitter as a reference. Each of the transmitters are transmitting signals with a frequency of 40 kHz one after the other with a small time delay. Hence the speed of the sound is known as 344 ms^{-1} and the delay is known the distance can be calculated as in Eq. 01.

$$d = v_{us}\Delta t \qquad \text{[Eq. 01]}$$

Where d is the distance to be calculated, Δt is the ultrasound propagation time (delay) between the receiver and the transmitter and v_{us} is the speed of the sound. The transmission pattern of the ultrasonic transducer output can be shown as in Figure 2 [13]. As shown ultrasonic transducers transmit a signal with energy of 60 dB in the main lobe and less energy on the side lobes. Hence the ultrasonic transducers are capable of transmitting signals with an effective strength with angle of $\pm 20^o$. It is defined to space transmitter and receiver units for minimum distance about 5 cm apart for proper communication.

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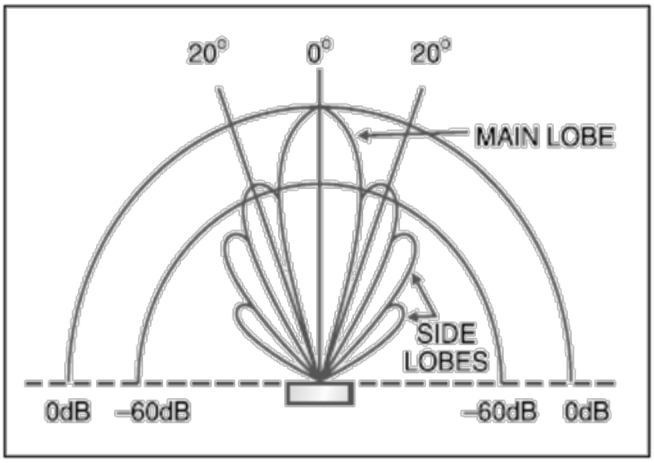


Figure 2: Two dimensional beam pattern of ultrasonic signal showing main lobe and side lobe energy levels [13]

1.1. Dependent Factors to Speed of Sound

The speed of sound in air depends on environmental factors such as media, temperature and relative humidity. Among those factors variation of the temperature affects most to the speed of the sound. In complete dry air the speed of sound depends only on the temperature T (in Kelvin) as in Eq. 02 [14].

$$v_{us} = 20.05\sqrt{T} \qquad \text{[Eq. 02]}$$

The speed of the sound has a relatively large sensitivity to temperature variations [12]. Hence the built model is tested considering the atmospheric temperature variations. In a practical environment due to the relative humidity in air Eq. 02 cannot be used in calculating the distance. Instead Eq. 03 can be used.

$$v_{us} = 331.3 + 0.606T_1 \qquad \text{[Eq. 03]}$$

Where T_1 is the temperature of the air in ^0C. Petr Cholasta in [15] shows the variation of the speed of the sound with the temperature of the air, Figure 3. Also Petr Cholasta explains the dependency of the frequency of the sound to the distance it is travelled, Figure 4. Hence when higher the frequency it is more likely to attenuate with the increasing distance. Which reveals that the accuracy of the built system also depend on the frequency range selected for the transmitting sound.

In developing the system the temperature effect of the air is considered in order to minimize error of distance estimation. In the developed system in order to estimate the position of the mobile receiver, knowing the position of each transmitter used is a must. In other words the receiver should be updated with the site map with the locations of the transmitters prior its mobility.

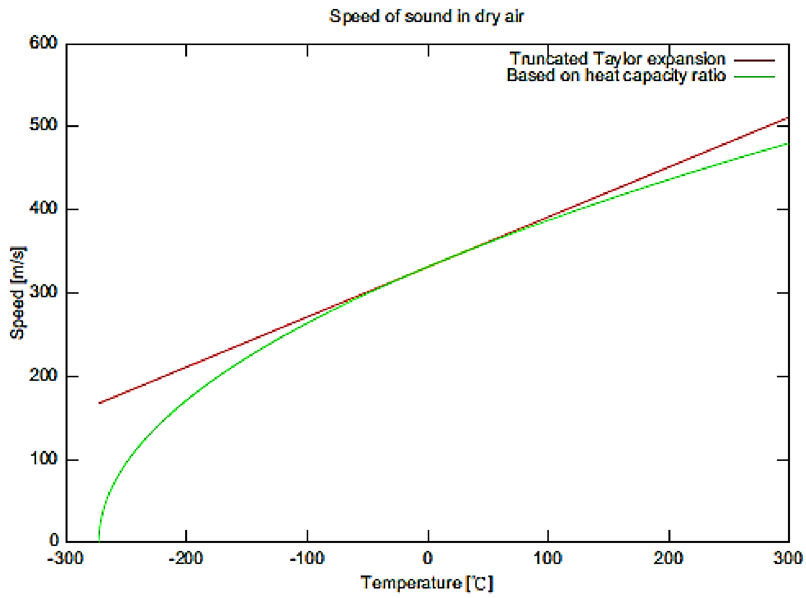


Figure 3: Dependency of the Speed of Sound to the Temperature of the air

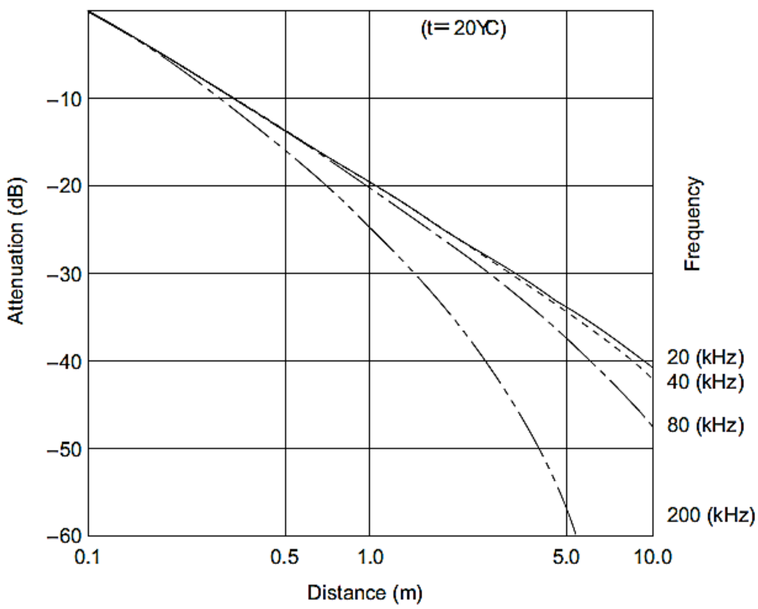


Figure 4: Ultrasonic wave’s strength attenuation with distance and wave frequency

2. METHODOLOGY

The systems designed was focused in ultrasound transmission and mainly consisted with two components. One is the ultrasound transmitters and the other is the mobile ultrasound receiver. For the developed LPS three transmitters were used with single mobile receiver.

2.1. Developing the transmitters

In designing the transmitters, three factors were considered, i.e. 1. echo effect of the transmitted signals, 2. Overlapping of the transmitted signals and 3. precise frequency for the transmitting signals with less attenuations. To remove the echo effect, each transmitter was designed to transmit a signal after the echo cancellation time defined as 10 s for the ultrasonic transducers. Between each transmission a known delay value has been added to remove the overlapping of the transmitting signals and according to the Figure 4, 40 kHz frequency was chosen as the transmitting ultrasound frequency of the designed system. For the each transmitting signal a square waveform was generated considering the above mentioned factors. Using different pulse width for the each transmitting signal, the positioning system can be designed to identify the transmitters separately by calculating the pulse width received at the receiving end. This scenario is not included in the developed system. Though the accuracy of the LPS systems increases when the number of transmitters are used, the system should consists with three transmitters as the minimum requirement to obtain somewhat accurate readings for the position of the mobile receiver.

In constructing the transmitters two methods were implemented and tested as mentioned in section 2.1.1. and 2.1.2. Examining the results obtained one method was considered as the most accurate system to construct the transmitters.

2.1.1. 555 Timer driven ultrasound Transmitter

A 555 timer based circuit was used to generate the 40 kHz square signal as shown in Figure 5. In the Figure 5 the trigger input provided using a microcontroller to start and stop the transmission of the pulses. Figure 6 illustrates the trigger pulses used for the three transmitters.

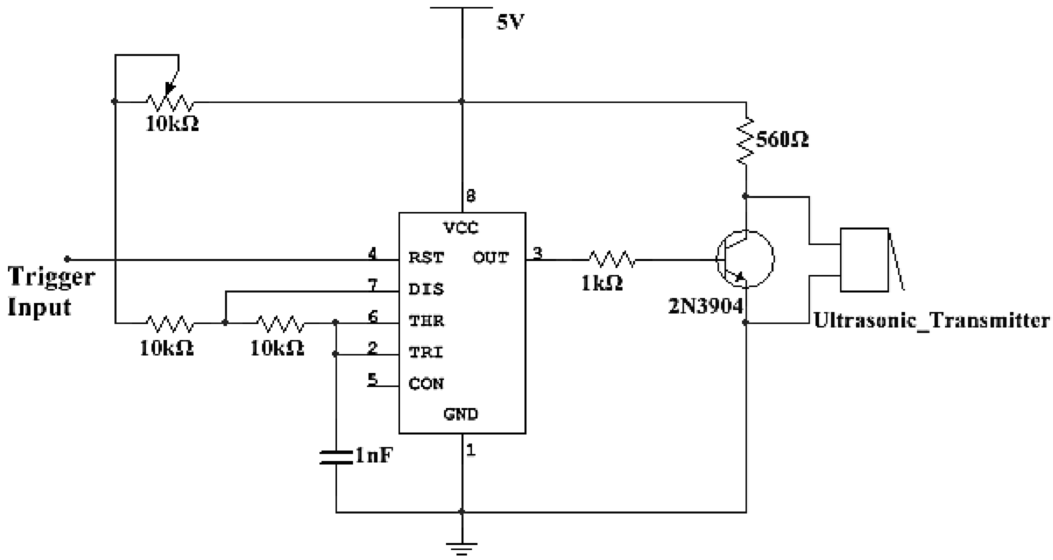


Figure 5: 555 timer circuit for Ultrasonic Transmitter

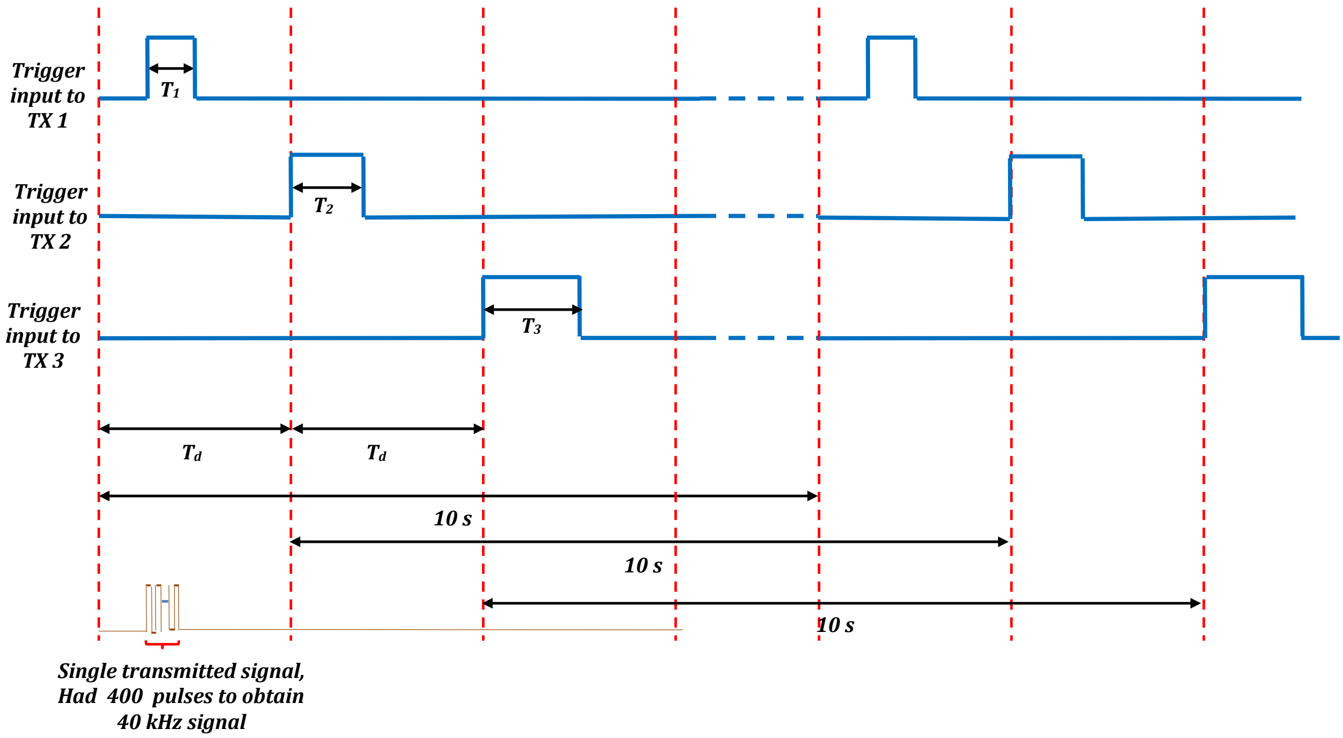


Figure 6: Trigger pulses used for the three transmitters, TXi are the transmitters used

In Figure 6 TX1, TX2 and TX3 are referred to the transmitters used in the system and T1, T2 and T3 are the pulse width of the each transmitted signal respectively. T_d is referred to the time difference from one transmission to the other transmission. So in the above design it was set to have same time for T_d for each transmission.

2.1.2. Microcontroller based ultrasound Transmitter

In this method as the microcontroller board an arduino mega 2560 board was used. Figure 7 illustrates the construction of the transmitter. As shown in Figure 7 arduino mega board consists with 9 communication pins, 11 PWM pins, 31 digital pins and 16 analogue pins. Those pins are named according to the special features consists with. But as the main function each pin is capable of serving as input or an output. Hence to increase the accuracy of the system the number of transmitters used can be increased up to the maximum number of output pins the mega board has. If the environment is too large it is observed using large number of transmitters cause to increase the accuracy of the positioning system.

For the design pin 3, 4 and 5 were used to connect the transmitters. In the software the three pins were programmed to generate a 40 kHz signal in different times.

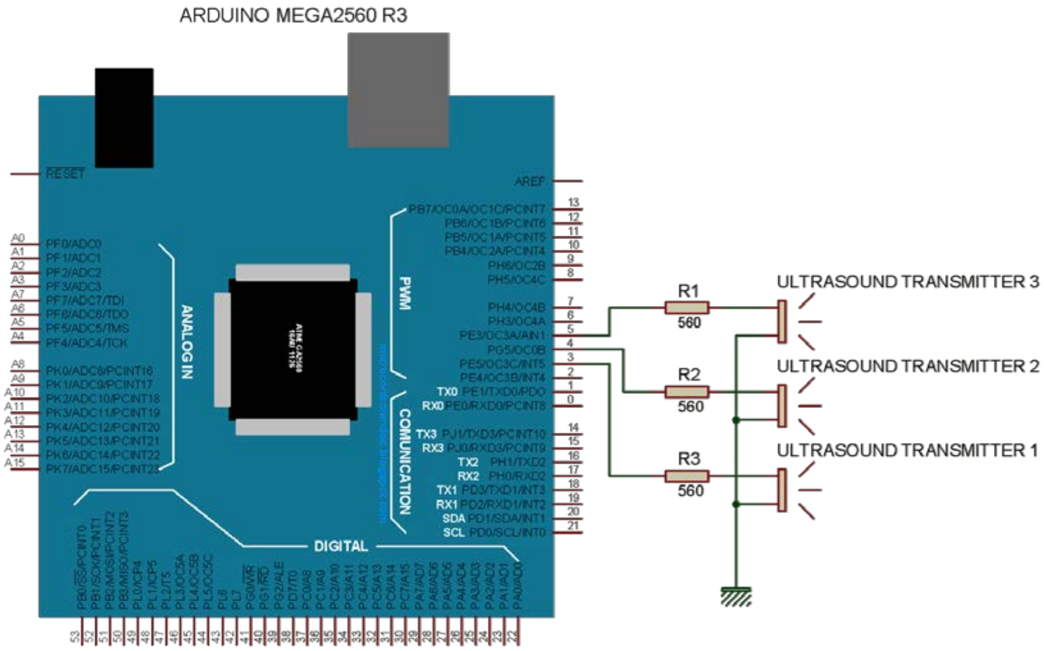


Figure 7: Illustration of microcontroller based ultrasound transmitters

Following code illustrates how the three transmitters were programmed to operate.

```
pulse40KHz (tx1_trig);      //Transmitter 1
delay (1000);
pulse40KHz (tx2_trig);      //Transmitter 2
delay (1000);
pulse40KHz (tx3_trig);      //Transmitter 3
delay (8000);
```

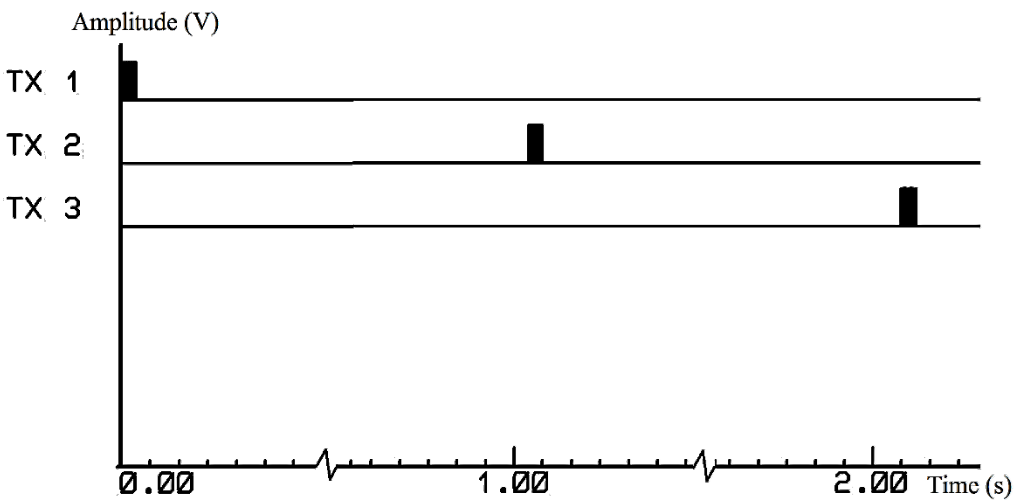


Figure 8: Illustration of transmitted signals

In order to generate a 40 kHz signal the following programme was used. The code illustrates the generation of 40 kHz pulses for 10ms of time. Hence the three transmitters used were turned on for a same period of time but in different times. Generated transmitting signals are illustrated in Figure 8.

```
for (i=0;i<390;i++){
   digitalWrite (pin,HIGH);
   delayMicroseconds(5);
   digitalWrite(pin,LOW);
   delayMicroseconds(5);
  }
}
```

2.2. Developing the Receiver

As the receiver an ultrasonic receiver module was connected to an Arduino Uno board as in Figure 9. And a LCD display was connected in order to display the estimated position of the receiver.

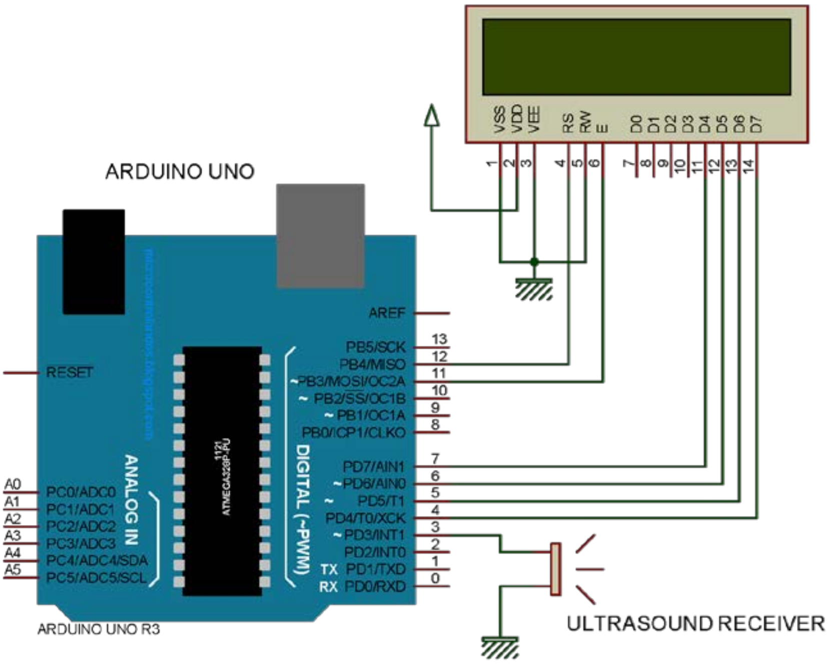


Figure 9: Illustration of Receiver with the LCD Display without the temperature sensor

External interrupt was used to detect the receiving pulse. Interrupt was programmed to trigger when a rising edge received and the interrupt was detached in order to avoid interference of unwanted signals for a define period of time. In the interrupt service routine for each receiving signal three timer values were stored, i.e. t1, t2 and t3 as shown in the below program. Difference between t1, t2 and t2, t3 were recorded as the delay values measured.

```
if(flag1==2){            //first pulse rising edge detected
   detachInterrupt(digitalPinToInterrupt(3));            //disable interrupt
   t1 = micros();                                      //takes time the program run
}
if((flag2==1) &&(flag1==4)){          //second pulse rising edge detected
   detachInterrupt(digitalPinToInterrupt(3));            //disable interrupt
   t2 = micros();                                      //takes time the program run
}
if((flag3==1) &&(flag1==6)){          //third pulse rising edge detected
   detachInterrupt(digitalPinToInterrupt(3));            //disable interrupt
   t3 = micros();                                      //takes time the program run
}
```

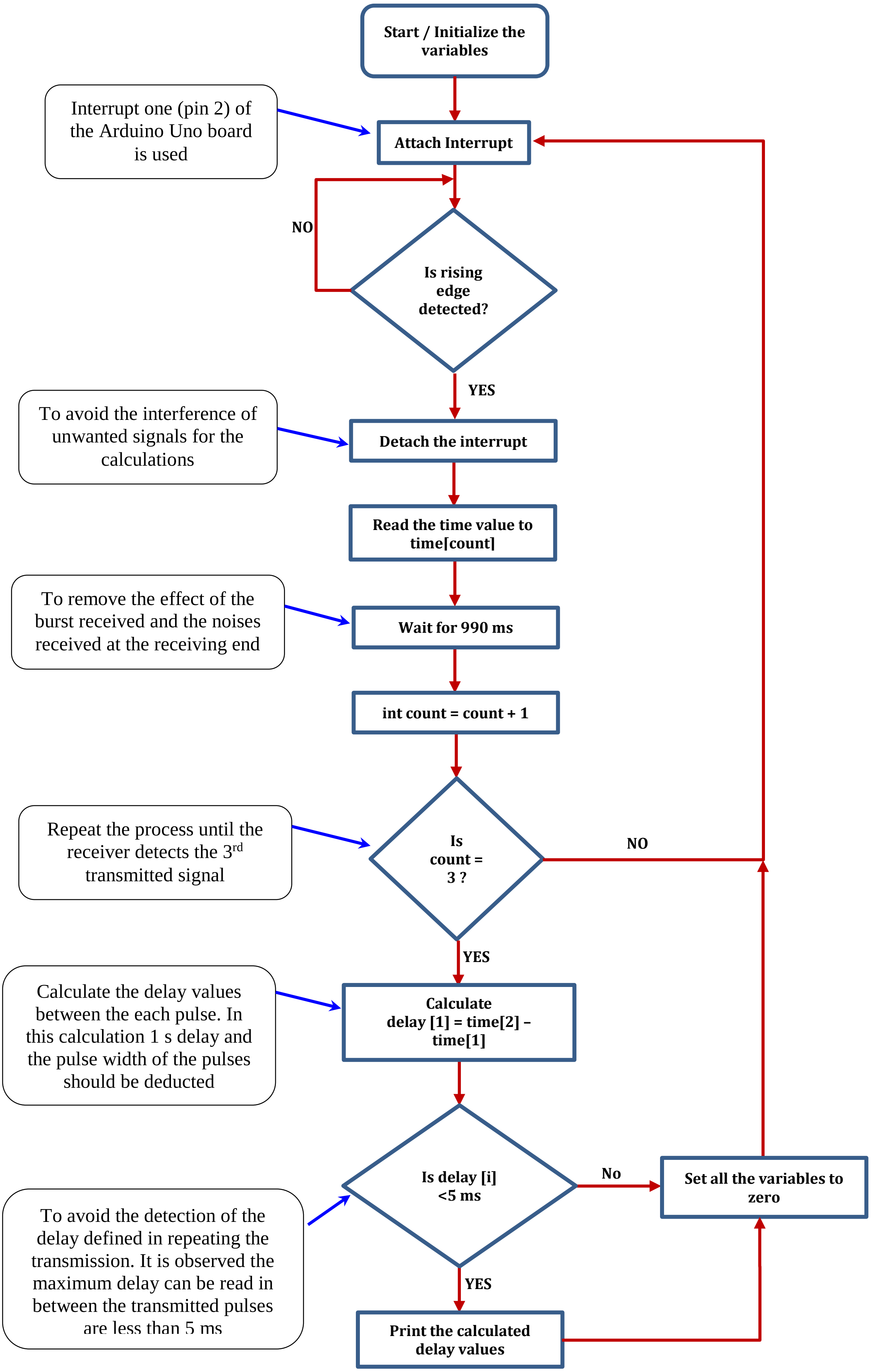


Figure 10: Flow chart of the process

2.3. Combined System

As shown in Figure 11, the built system consisted with a receiver and three transmitters. For the developed system, as the transmitters the microcontroller based system was used to obtain much precise signal at the receiving end. In section 2.2 the illustrated code was tested with the selected transmitters.

As explained in section 2.1.2. a transmitter capable of transmitting a pulse burst with a frequency of 40 kHz for a specified time. Hence, each transmitter was programmed to transmit a pulse burst for a 10ms of time. At the receiving end the receiver was programmed to determine the time between one transmissions to the other transmission by ignoring the pulse burst of each transmission received as explained in section 2.2. Figure 10 illustrates the flow chart of the modelled system. The developed system consists with a Liquid Crystal Display (LCD) to display the calculated results and a temperature sensor [16] in order to include the effect of the atmospheric temperature for the calculations.

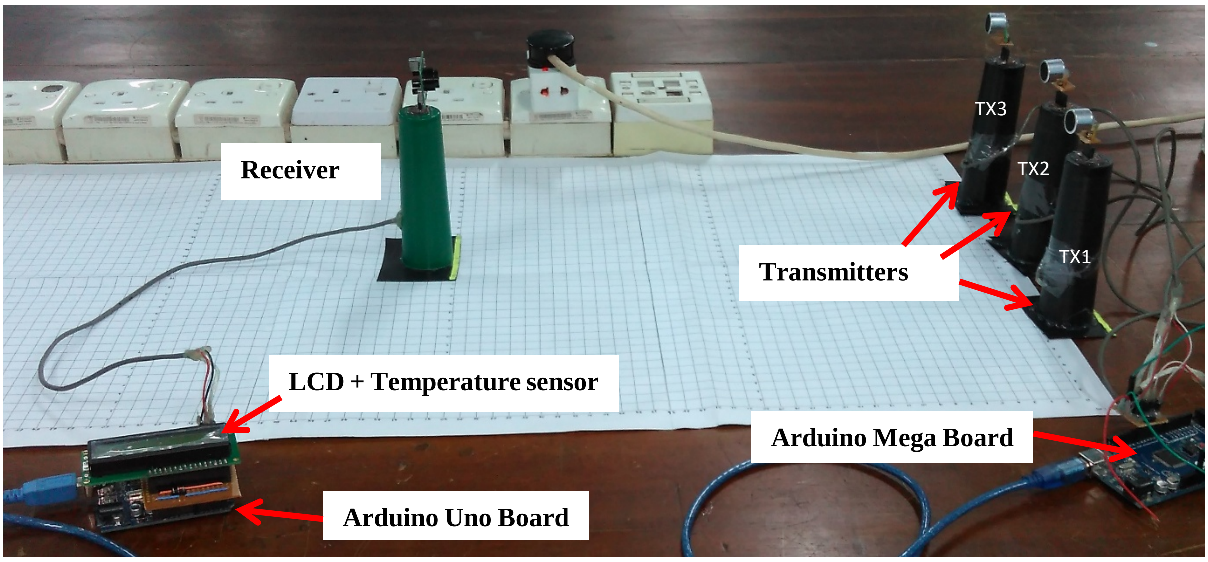


Figure 11: Illustration of the complete system

2.4. Mathematical Analysis

The modelled system can be illustrated in a Cartesian plane as shown in Figure 12. Mathematical analysis of the developed system was determined using the illustrated approach. TX1 was used as the reference terminal. Hence, delay values were calculated with respect to TX1. Also determining the d1 was not necessary for the system designed. The task was to calculate the d2 and d3 values in order to generate a formula to determine the position of the receiver.

$$\boldsymbol{delay\ between\ each\ transmission} \quad = \boldsymbol{t}$$

$$\boldsymbol{measured\ delay\ of\ TX2\ with\ reference\ to\ TX\ 1} \quad = \boldsymbol{\Delta t_1}$$

$$\boldsymbol{measured\ delay\ of\ TX3\ with\ reference\ to\ TX\ 2} \quad = \boldsymbol{\Delta t_2}$$

Removing the effect of the predefined delay and the estimated error in each transmission, the delay values were calculated as in Eq. 04 and Eq. 05

$$\boldsymbol{estimated\ error\ in\ delay\ received\ for\ \Delta t_1} \quad = \boldsymbol{t_{err,1}}$$

$$\textbf{\textit{estimated error in delay received for}}\ \Delta t_2 \qquad = t_{err,2}$$

$$\textbf{\textit{calculated delay for TX2 with reference to TX1}} = \Delta t_1 - (t + t_{err,1}) \qquad [Eq.04]$$

$$\textbf{\textit{calculated delay for TX3 with reference to TX2}} = \Delta t_2 - (t + t_{err,2}) \quad [Eq.05]$$

Hence according to the Eq 01, the distances to RX from TX2 and TX3 were calculated as in Eq. 06 and Eq. 07.

$$\textbf{\textit{distance from TX2 to RX}}\ (\textbf{\textit{d2 in cm}}) = v_{us}\left(\Delta t_1 - (t + t_{err,1})\right)/10^4 \qquad [Eq.06]$$

$$\textbf{\textit{distance from TX3 to RX}}\ (\textbf{\textit{d3 in cm}}) = v_{us}(\Delta t_2 - (t + t_{err,2}))/10^4 \qquad [Eq.07]$$

$$\textbf{\textit{where}}\ v_{us} = 340\ ms^{-1}$$

According to the Eq 03, the distances to RX from TX2 and TX3 were calculated as in Eq. 08 and Eq. 09.

$$d2_{temp}\ \textbf{\textit{in cm}} = [331.3 + (0.0606 \times T)] \times \left[\Delta t_1 - \left(t + t_{err,1}\right)\right]/10^4 \qquad [Eq.08]$$

$$d3_{temp}\ \textbf{\textit{in cm}} = [331.3 + (0.0606 \times T)] \times \left[\Delta t_2 - \left(t + t_{err,2}\right)\right]/10^4 \qquad [Eq.09]$$

$$\textbf{\textit{where T is the atmospheric temperature in celsius}}$$

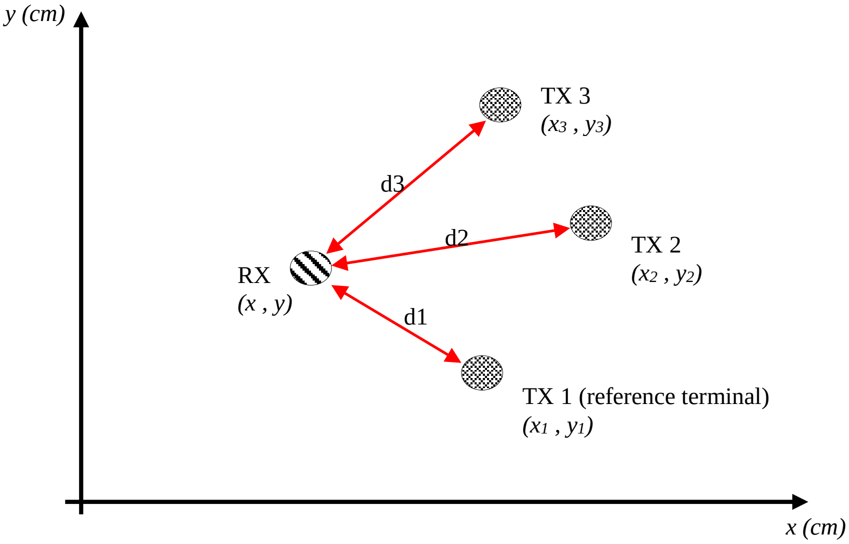


Figure 12: Cartesian representation of the modelled system

3. RESULTS AND DISCUSSION

3.1. With 555 Timer driven Ultrasonic Transmitter

Figure 13 illustrates the transmitted signal and received signal at the receiving end. In the both signals received and transmitted are having added noise. When increasing the distance the effect of noise at the receiving end increased.

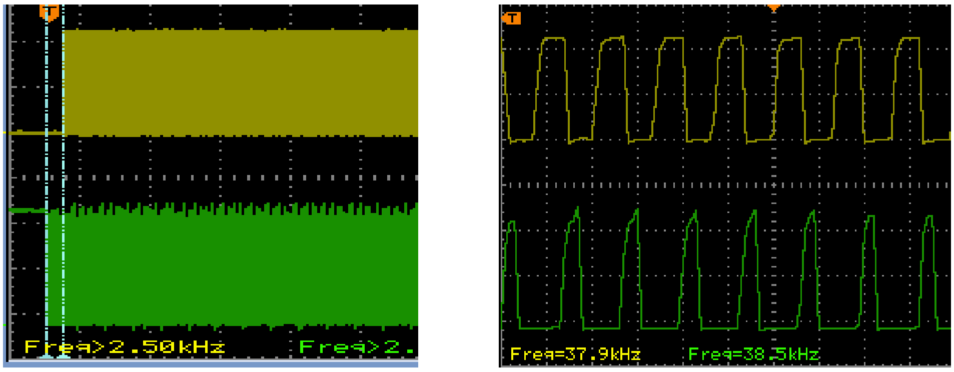


Figure 13: Yellow colour plot is for the received signal and the green colour plot is for the transmitted signal.
(a: figure obtained using oscilloscope, b: expanded view of the obtained plot)

3.2. With microcontroller based Ultrasonic Transmitter

Figure 14 illustrates the transmitted and received signal. As shown the transmitted signal contains less noise effect than the transmitted signal in Figure 13. The received signal consisted with the effect of noise up to 50ms of time for a transmitted signal of 10ms. With the increasing distance it was observed lesser attenuation than the system in section 2.1.1. Hence the developed positioning system was designed using the microcontroller based ultrasonic transmitters and the receiver was programmed to avoid the effect of the noise effect observed in each transmission.

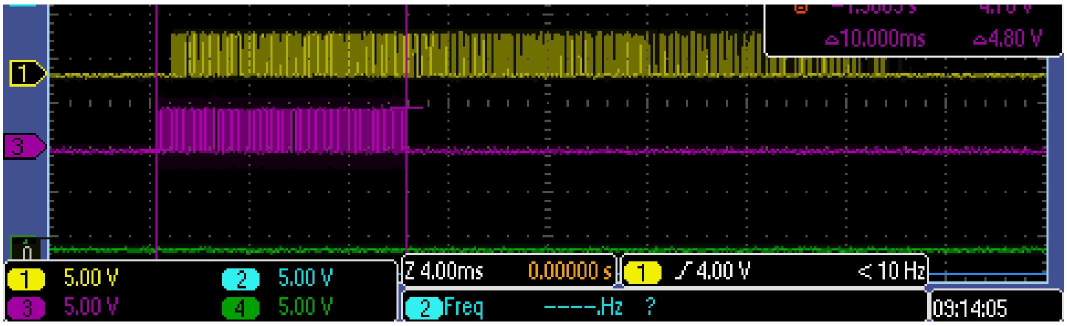


Figure 14: Yellow colour plot is for the received signal and the pink colour plot is for the transmitted signal.

3.3. Complete Structure

3.3.1. Results obtained with a single transmitter

Developed positioning system was tested for the three transmitters separately. Using an oscilloscope with respect to the transmitted signal the delay was measured in the received signal as shown in Table 1.

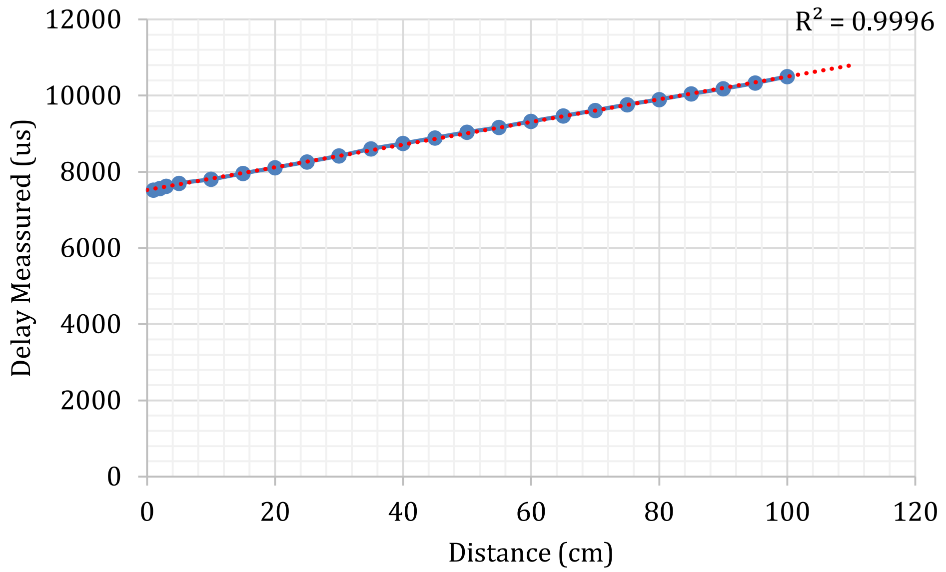
Deviation of the theoretical and the delay values measured increased with the increasing distance as in Table 1.

Table 1: Theoretical and practical delay values and the deviation of theoretical and practical delay values

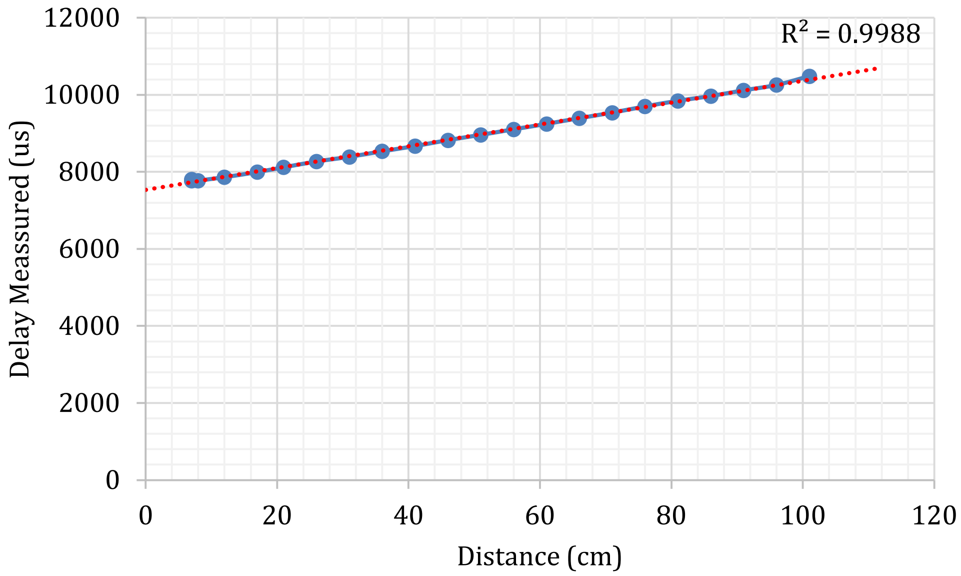
Distance between RX & TX	Theoretical value	With TX 1 (10 ms)	Deviation of TX 1	With TX 2 (15 ms)	Deviation of TX 2	With TX 3 (20 ms)	Deviation of TX 3
10	294 µs	480 µs	38.75	480 µs	38.75	520 µs	43.46
20	588 µs	800 µs	26.50	800 µs	26.50	720 µs	18.33
30	882 µs	1.08 ms	18.33	1.12 ms	21.25	1.04 ms	15.19
40	1.18 ms	1.28 ms	7.81	1.36 ms	13.24	1.32 ms	10.61
50	1.47 ms	1.64 ms	10.37	1.68 ms	12.50	1.64 ms	10.37
60	1.76 ms	1.96 ms	10.20	1.92 ms	8.33	1.92 ms	8.33
70	2.05 ms	2.20 ms	6.82	2.40 ms	14.58	2.20 ms	6.82
80	2.35 ms	2.56 ms	8.20	2.48 ms	5.24	2.44 ms	3.69
90	2.65 ms	2.80 ms	5.36	2.88 ms	7.99	2.80 ms	5.36
100	2.94 ms	3.12 ms	5.77	3.20 ms	8.13	3.12 ms	5.77

3.3.2. Results obtained with the three transmitters

Keeping TX1 and TX3 in steady positions, changing the position of the TX2 transmitter, the measured delay values and keeping TX1 and TX2 in steady positions, changing the position of the TX3 transmitter, the measured delay values are illustrated in Figure 15 (a) and Figure 15 (b).



(a)



(b)

Figure 15: Analysis of the delay values measured for TX2 and TX3 with reference to TX1 and TX2 respectively

The estimated errors in Eq. 04 and Eq. 05, $t_{err,1}$ and $t_{err,2}$ were calculated using the data shown in Figure 15. Hence, $t_{err,1} = t_{err,2}$ = 7523.9 µs and t was defined for the transmitters as 1 seconds, i.e. 1000000 µs in order to avoid overlapping of the received signal.

For the developed system Eq. 06, Eq. 07, Eq. 08 and Eq. 09 were modified as in Eq. 10, Eq. 11, Eq. 12 and Eq. 13 respectively.

$$\boldsymbol{d2\ in\ cm = 340 \times \left(\Delta t_1 - (1000000 + 7523.9)\right)/10^4} \qquad [\boldsymbol{Eq.10}]$$

$$\boldsymbol{d3\ in\ cm = 340 \times (\Delta t_2 - (1000000 + 7523.9))/10^4} \qquad [\boldsymbol{Eq.11}]$$

$$\boldsymbol{d2_{temp}\ in\ cm = [331.3 + (0.0606 \times T)] \times [\Delta t_1 - (1000000 + 7523.9)]/10^4} \qquad [\boldsymbol{Eq.12}]$$

$$\boldsymbol{d3_{temp}\ in\ cm = [331.3 + (0.0606 \times T)] \times [\Delta t_2 - (1000000 + 7523.9)]/10^4} \qquad [\boldsymbol{Eq.13}]$$

Distance values observed using equations in Eq. 10 – Eq. 12 are illustrated in Table 2. The delay values were measured by varying the position of the TX2 while keeping the TX3 in a known position and by varying the position of the TX3 while keeping the TX2 in a known position. For each and every measurement TX1, the reference terminal was placed in a known position and for the experiment TX1 wasn’t changed.

Table 2: Distance values measured using for *d2* and *d3*

Theoretical Distance (cm)	Distance (d) *d2* or *d3* (cm)	Distance (d_{temp}) $d2_{temp}$ or $d3_{temp}$ (cm)	Error rate of *d* %	Error rate of d_{temp} %
100	98	101	-2.04	0.99
95	94	97	-1.06	2.06
90	89	91	-1.12	1.10
85	84	86	-1.19	1.16
80	79	81	-1.27	1.23
75	74	76	-1.35	1.32
70	70	72	0.00	2.78
65	65	67	0.00	2.99
60	59	61	-1.69	1.64
55	54	56	-1.85	1.79
50	50	51	0.00	1.96
45	44	46	-2.27	2.17
40	39	41	-2.56	2.44
35	34	35	-2.94	0.00
30	3	31	0.00	3.23
25	25	26	0.00	3.85
20	19	20	-5.26	0.00
15	14	15	-7.14	0.00
10	9	10	-11.11	0.00
5	5	5	0.00	0.00

3.3.3. Discussion

According to the observations the designed system is functional for a minimum distance of 5 cm and tested up to a maximum distance of 100 cm. As in Table 2with the increasing distance error rate of the readings increased. By considering the atmospheric temperature in calculating the distance the accuracy of the measured values is greater than the readings taken without considering the atmospheric temperature. For a smaller distance error is negligible.

4. CONCLUSIONS

The local positioning system was designed using the ultrasound as the communication technology with a frequency of 40 kHz. Developed system was experimented with and without the effect of the atmospheric temperature for a distance up to 100 cm. The complete system was consisted with three ultrasonic transmitters and a single mobile receiver. From the three transmitters used one transmitter was counted as the reference terminal in order to initiate the calculation of delay values. In the developed system the receiver was isolated from the transmitters hence keeping one transmitter as the reference terminal is a must to initiate the process of predicting the position of the mobile receiver. In the developed system the receiver is capable in determining the distance it is located from the transmitters except from the reference terminal. The system has a resolution of 5 cm and the minimum distance the transmitters should is 5 cm from the receiver for effective calculations.

The designed system can be modified to obtain the exact position of the receiver using the calculated delay values. The receiver should be updated with a site map which includes the position of each transmitters used, prior the transmission to determine the exact position of the mobile receiver. The receiver can be mounted on a robot and using the developed system can be used in determining the exact position of the robot.

As a disadvantage in such systems high probability of interference from other ultrasound sources reduces the reliability of the ultrasound-based systems. Also the system provides inaccurate readings when the environmental noise is higher. The system designed does not provide accurate readings for smaller distances, i.e. distances less than 5 cm.

5. ACKNOWLEDGEMENTS

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