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ANALYSIS OF A SIMPLE RADAR COMMUNICATION SYSTEM FOR INTELLIGENT TRANSPORTATION

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Abstract

Radar communication systems have been widely used for various applications, including military surveillance, weather monitoring, and air traffic control. This research focuses on the concept of simple radar communication systems, which offers an accessible and practical solution for short-range communication needs. This aim of this research is to explore the fundamental principles and components of simple radar communication systems, how radar works by emitting radio frequency (RF) waves and analyzing their reflections to detect objects and gather information about their range, velocity, and direction. The architecture of a simple radar communication system which includes the transmitter, receiver, and signal processing components were used to execute the project. The research also addresses the challenges associated with interference, multipath propagation, and signal processing techniques to mitigate these issues in simple radar communication systems. This project aims to critically the design and construct a simple radar communication system which include an Arduino nano, an SG90 servo motor, an HY-SRF05 ultrasonic sensor, a 1602 LCD display, switches, LED's, Resistors, Lithium-ion batteries, boost converter and RF modules and its adapters. Radar communication systems employ the same basic principles as traditional radar systems, which are primarily used for object detection, ranging, and tracking. However, in the case of radar communication, the transmitted signals contain data or information that is intended for communication purposes.

Keywords: Radio frequency; Communication System; Interference; Multipath propagation; Signal Processing

1.0 Introduction

Radar communication systems have traditionally been used for detection and tracking purposes, utilizing the principles of radio waves and their reflections (Martone and Amin, 2021). However, there is a growing interest in exploring radar as a means of communication, especially for short-range applications where traditional wireless communication technologies may be limited or unreliable. The need for simple radar communication systems arises from various scenarios where conventional communication methods face challenges. In remote areas, such as rural or isolated regions, establishing reliable wireless networks can be expensive or technically difficult. Similarly, during emergency situations, where communication infrastructure may be damaged or overloaded, alternative communication solutions are crucial (Bica and Koivunen, 2019).

Simple radar communication systems offer a practical and accessible alternative by leveraging the existing radar technology and adapting it for communication purposes. These systems utilize the same basic principle of radar: transmitting radio frequency (RF) waves and analyzing their reflections. Radar systems have a wide range of uses, from routine daily tasks like parking cars to venturing into the unknown like space. They are able to map unidentified voids. However, to enable such applications, the system must be outfitted with trustworthy sensors, actuators, and an efficient algorithm. The sensors gather physical factors like size, angle, and distance information and feed it back to the system for processing (Liu *et al.*, 2020).

. The sensor's performance may be impacted by the various materials used in the environment that it gathers data from. Different geometries in the environment, such as a straight wall or a wall with corners, may also have an impact on how well the sensor function perform. A radar communication system is a technology that combines radar and communication principles to enable long-range wireless communication while also providing object detection and tracking capabilities. It utilizes radio waves to transmit and receive signals, allowing for the exchange of information between two or more radar-equipped devices or systems. The primary function of a radar communication system is to establish a communication link between two distant points using radar techniques. It involves the transmission of electromagnetic waves, typically in the radio frequency (RF) spectrum, from one radar device to another. These waves propagate through the medium, and upon reaching the receiving radar device, they are detected and processed to extract the transmitted information.
Radar communication systems employ the same basic principles as traditional radar systems, which are primarily used for object detection, ranging, and tracking. However, in the case of radar communication, the transmitted signals contain data or information that is intended for communication purposes, in addition to the usual radar functionalities. A simple radar communication system refers to a basic and straightforward implementation of radar technology combined with communication capabilities. It typically involves the use of a single antenna for both transmitting and receiving signals, making it a cost-effective and relatively uncomplicated solution for long-range wireless communication and object detection/tracking. In a simple radar communication system, the basic principles of radar are applied to establish a communication link between two or more radar-equipped devices. The system transmits radio waves, often in the form of pulses or continuous waveforms, and analyses the reflected signals to extract communication data. The sharing of a shared spectrum by a radar and a communication system has been made possible in a number of ways (Liu *et al.*, 2020). Three major categories can be made for the methods: 1. Cohabitation or Coexistence, 2. Cooperation, and 3. Codesign.

Codesign, which implements both communication and radar systems on the same platform, is the most inventive and promising technique among these. As a result, they have a lot of similar hardware and functional parts, such as RF front end and signal processing components.

Challenges and Feasibility of Radar Communication System Design

JCR/JRC design and execution provide a number of difficulties. There are some differences between the radar and communication standards in terms of actual use. This is due to the fact that the two systems have usually been created and implemented separately. For instance, a mono-static radar needs a somewhat higher transmit power since the signal must travel a two-way path, resulting in more path loss in addition to scattering losses. Similar to how existing communication systems use a considerably smaller bandwidth, military radars operate in the ultra-wide band (UWB) frequency ranges (Hassanien *et al.*, 2016). There are numerous applications, though, in which cutting-edge new technologies are filling in these gaps. For instance, mm-wave communications have substantially greater bandwidths available that can be used to create radar systems on moving objects (Kumari *et al.*, 2015). New signal processing techniques are also being developed that are discovered to give better trade-offs among the system parameters as a result of the growing demand for V2V communication applications and automotive radars (Hassanien *et al.*, 2016, Liu *et al.*, 2019). The integration of V2V, V2P, and V2I communications with car radars is now practical.

The main obstacle in the design of joint systems is an integrated waveform, or the ability of the system to execute both communication and radar functions by sending one waveform (Hassanien *et al.*, 2016; Kumari *et al.*, 2017a; Hassanien *et al.*, 2019). As a result, an integrated waveform should be able to incorporate information, transmit it to a communication receiver, and have the necessary properties (such as an adequate ambiguity function) to identify and estimate target parameters. Past research on passive WiFi radars has been extensive (Berger *et al.*, 2010; *Chetty et al.*, 2011; Colone *et al.*, 2012; Maechler *et al.*, 2012; Ivashko *et al.*, 2014). Instead of emitting its own signal, a passive radar detects objects by utilizing available signals. This kind of radar offers a cost-effective option in particular circumstances, such as border protection, when there are fewer projected targets and less congestion. Although it cannot start the detection and ranging operation independently of other nearby Wi-Fi resources, its capacity is still limited. The primary focus of this essay is the current JCR or JRC. In the case of JCR/JRC, a combined communication transmitter and active radar transmits a waveform that is received, decoded, and returned to the source where target characteristics are selected by a communication user. In Section 4, we discuss the system and channel models that have been adopted in the literature to describe the JCR functions. In this survey, we mainly focus on the recent developments in JCR system.

Other challenges include the issue of data security as the broadcast data across the vehicles can be easily spoofed. Moreover, since for the radar functions, the signal has to traverse a two-way path, the path loss and losses due to scattering result in a much smaller received power at the JCR receiver, as compared to the power received at communication receiver. An optimal power and beam forming protocol needs be investigated that would result in a sufficient SNR at both receivers.

Another important and challenging problem is the simultaneous reception of radar echo and a communication signal. Further changes in the existing standard may be required to enable this function on IEEE 802.11-based JCRs. The reception problem remains an open, multi-faceted research problem in both JCR and JRC domains. Moreover, the application of JCR has been mostly limited to V2V scenarios. While this is a huge market and a challenging problem, future research may include exploring joint communications with other emerging radar applications, such as those in healthcare and security.

Performance and Radar Communication Trade-Offs

The performance trade-offs between the radar and communication functions in an IEEE 802.11ad-based JCR systems are studied in (Kumari *et al.*, 2017b). Conventionally, since radar and communication systems are designed separately, different performance metrics are used to qualify them. Communication system is mainly characterized by a data rate whereas range and velocity estimation accuracy in radar is generally determined by the respective Cramer-Rao Lower Bounds (CRLBs). The CRLB provides a minimum bound on the variance of an estimator. Actual variance depends on the chosen estimator. Generally, the CRLB decreases with the increase in the training data length. It is desirable to have a low CRLB for better estimation accuracy.

where SNR_c is the SNR of the one-way communication channel. The CRLB for the range estimator is given as follows (Kumari *et al.*, 2017b):

$$\sigma_{\rho}^{2} \geq \frac{c^{2}}{32\pi^{2}B^{2}(1-\alpha)KSNR_{r}}, \qquad (2.2)$$

where SNR_r is the SNR at the radar receiver, c is the speed of light and B_{rms} $B/\sqrt{12}$is the root mean square bandwidth of the preamble when flat spectrum is assumed. The CRLB for the velocity estimation is given as (Kumari *et al.*, 2017b)

$$\sigma_{\frac{2}{r}} \geq \frac{6\lambda^2}{16\pi^2(1-\alpha)^3 K^{-3} T^2{}_s SNR,} \quad (2.3)$$

where λ is the carrier wavelength.

It can be seen from the above equations that if we increase the communication data rate by keeping α large, both the CRLBs increase, which means the accuracy of range and velocity estimation decrease. In order to improve the estimation accuracy, a longer preamble is needed, which would decrease the communication rate. From Eq. 29, we see that the velocity estimation is more sensitive to preamble length, due to which the use of multiple frames is proposed in (Kumari *et al.*, 2017a). This approach is found to lower the CRLB of the velocity estimator (Kumari *et al.*, 2017a).

2.0 Materials and Methods

2.1. Procedure for the Implementation of the work

This project presents the systematic approach adopted in achieving the proposed simple radar communication system that uses RF transceivers, an Arduino Nano, an Ultrasonic sensor and servo motors. The project involves designing a simple radar communication system that utilizes an ultrasonic sensor and servo motor, which will be connected to the Arduino processing, this provides a detailed account of each stage of the methodology involving hardware setup, data collection, data encoding and transmission, data receiving and processing, data displaying. The hardware setup section details how we setup and configure all necessary components required to detection and transmission. The data collection section outlines the process involved in gathering raw data relation to the position and angle of the object detected by the ultrasonic sensor. We then move on to pre-processing this raw data into standardized input data through C and C++ programming language.

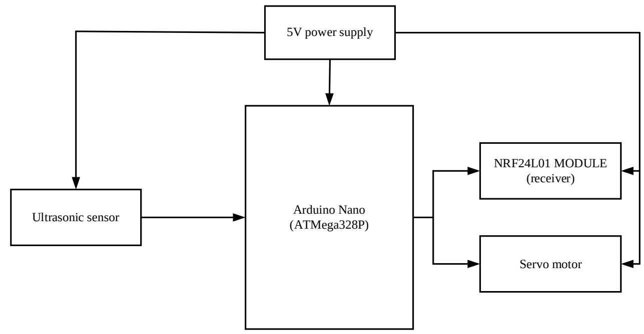

Figure 1: The block diagram of the transmitter of the radar system

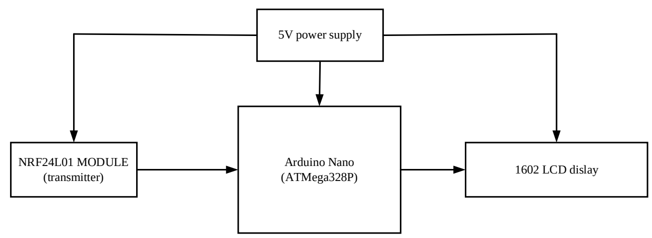

Figure 2: The block diagram of the receiver of the radar system.

Programming the Arduino: The Arduino Nano Board serves the purpose of instructing/running of all the components for each of the units (transmitting and receiving). A code is loaded into the Arduino which will instruct it on how the components will run. The Arduino is programmed using the C++ and C programming language for the transmitting unit, the code will include instructions on the [pulse firing time, the angle of rotation of the SG-90 motor and will also encode the data which will be sent to the nRF24LO1 for transmission of data.

Setting up/Connecting the Arduino to the servo motor, ultrasonic sensor and the RF module: The SG-90 servo motor, ultrasonic sensor and RF module are connected to the Arduino with the aid of jumper wires and soldering. These connections are made as follows:

The Trigger point is connected to D3 on the Arduino board and the echo is connected to point

D4 while the VCC is connected to the 5V power supply. Grounding is done via GNO.

Programming the Arduino: A code is loaded into the Arduino which will instruct it on how the components will run. The Arduino is programmed using the C++ and C programming language for the transmitting unit, the code will include instructions on receiving of signal from the transmitting unit, decoding data and displaying on the LCD.

Setting up/Connecting the Arduino to the LCD and the RF module:

The RF module and LCD display are connected to the Arduino as follows:

The LCD is first fitted with a 10k variable resistor in order to step down the 5V supply coming from the power source. The RW ports connected to the VSS when connects to the VSS and the ground. The VEE is connected to the 10k ohms resistor. Point VDD is connected to the power supply and the other end of the resistor connected to it. Point D7 of the LCD is connected to point D2 of the Arduino, point D6 to D3, point D5 to D4, point D4 to D5 and point E to D6 The RF module is connected to the Arduino as follows:

The VCC is connected to the power supply CSN point is connected to the D10 point of the Arduino MOSI point is connected to the D11 point of the Arduino Point MISO is connected to point D12 of the Arduino SCK point is connected to point D13 of the Arduino Point CE is connected to the point D9 of the Arduino. Grounding is made via point GNO.

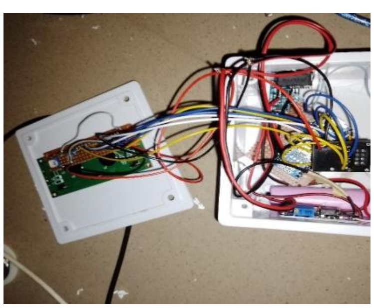

Figure 3: Receiving Unit Setup

Object Detection and Transmitting Unit of the Radar

The object detection and transmitting unit is composed of an Arduin8o Nano board which makes use of an ATMega-328p micro controller, a charging module, boost converter, an nRF24L01 transceiver and an HC-SR04 ultrasonic sensor. The Arduino Nano Board is connected to the ultrasonic sensor via in D3 and D4. The Arduino serves the function of control and programming to the ultrasonic sensor. It sends pulses to the ultrasonic sensor and also sends signals to the motor which helps the network synchronously so that as soon as the ultrasonic sensors starts sending pulses, the servo motor rotates at the same time. The sensor sends those pulses and receives the echo that is received on the surface of objects in the path of the ultrasonic waves. The Arduino Nano board serves the function of processing the received echo and determining the angle and distance at which the object is detected. The Arduino board performs all these actions as a result of the program which has been uploaded on the Arduino and instructs the Arduino. This Arduino board then encodes this data and sends it to the nRF24L01 transceiver which serves the purpose of transmitting this data to the receiver. The entire transmitting unit is powered by a lithium-ion battery of 3.7V and is stepped up to 5V using a boost converter, the battery is charged by a TP4056 charging module.

Signal Receiving and Display Unit

The signal receiving and display unit is composed of an Arduino Nano board which makes use of an ATMega-328p micro controller, a charging module, boost converter, an nRF24L01 transceiver and a 1602 LCD display. The Arduino Nano is connected to the 1602 LCD which serves the function of sending the received data for display, The 1602 LCD is also connected to the 10k (ohms) resistor, which serves the function of stepping down the 5V used to power the setup at the transmitting unit. The data encoded by the Arduino board at the transmitting unit is received by NRF 24L01 transceiver at the receiving unit. The Arduino Nano board decodes this data, and sends the result (the angle and distance of the object detected) to the 1602 LCD, which displays the angle and distance of the object. And when no object is detected, the 1602 LCD displays "No object detected". The Arduino board performs all these actions as a result of the algorithm which instructs the processing unit.

The signal receiving and display unit is powered by a lithium-ion battery of 3.7V and is stepped up to 5V, using a boost converter. The battery is charged by a TP4056 charging module.

Components of the Radar Communication System

The entire system comprises of the following components;

Arduino Nano boards (ATMega328P): The Arduino Nano is an open-source breadboard-friendly microcontroller board based on the Microchip ATmega328P microcontroller (MCU). In this setup, on the transmitting end, the Arduino Nano serves the purpose of controlling the ultrasonic sensor, servo motor as well as data encoding. Another Arduino Nano board is used on the receiving end for decoding data and for controlling and display of data on the 1602 LCD unit.

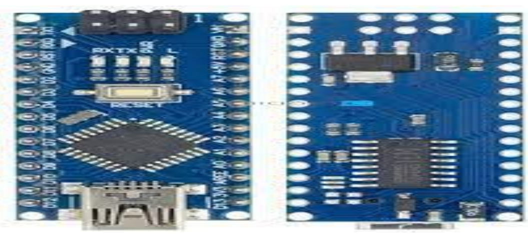

Figure 4: Arduino Nano Board

Ultrasonic sensor (HC-SR04): A well-liked module for distance measurement based on ultrasonic technology is the HC-SR04 ultrasonic sensor. It operates by releasing ultrasonic waves and measuring the amount of time it takes for the waves to bounce back after hitting an item. It is made up of an ultrasonic transducer and a control circuit.

Figure 5: HC-SR04 Ultrasonic Sensor

2.2. Bluetooth Module Hc-05

Bluetooth technology has revolutionized wireless communication. An example of such a development is the Bluetooth HC-05 module, a widely utilised medium for short-range communication. This module abides by Bluetooth 2.0 communication protocols, promoting easy integration into a variety of systems. The mathematical foundation of Bluetooth technology, including the HC-05, is centred on algorithms to hop frequencies quickly and achieve fast device connection. Frequency-hopping spread spectrum (FHSS) occurs over 79 different frequency bands across the $2.4GHz$ ISM band, hopping 1600 times per second. The mathematical equation that depicts this is $F = 2.402GHz + k * 1MHz,$ where F is the frequency in $GHz,$ and k is an integer from 0 to 78. Equally, the Bluetooth HC-05 module incorporates the Gaussian frequency-shift keying (GFSK) modulation scheme. GFSK minimizes the use of bandwidth by smoothing the signal's phase changes, leading to a reduction in spectral width. In essence, this equation models the GFSK: (Fridholm *et al.*, 2012

$$f(t) = f\_c + \Delta f * sin(\Phi(t))$$

Where $f(t)$ is the instantaneous frequency, f_c is the carrier frequency, Δf is the frequency deviation, and $\Phi(t)$ is the integrated data signal (Bao and Xia, 2015). The HC-05 Bluetooth module operates at a supply voltage varying between $3.6 - 6V$, with a standard voltage of 5V. It has a default baud rate of 9600bps, which allows for a transmission distance of approximately 10 metres. Additionally, the HC-05 module's electrical properties involve parameters like output power and working current. For instance, the module consummates a working current of 30mA, while its pairing mode current is 40mA, and the module's average current during sleep mode is $1mA$. The output power is typically rated at $+4\,dBm$, which is vital for the module's operation within the effective distance. Interestingly, its power consumption relies on its operating modes. For example, in communication mode, the module operates at full power, requiring the entire $30-40mA$ of current. Conversely, the sleep mode current reduces to an average of $1mA$, minimising energy usage when the module is not actively utilised, contributing to a vastly improved battery lifespan.

Figure 6: Bluetooth Module

2.3. Battery Management System

A Battery Management System (BMS) is a system that manages a rechargeable battery's charging and discharging, specifically in electric vehicles to maintain safety, prolong battery life and maintain optimum performance (Yang *et al.*, 2020). One useful way of handling battery arrays is the 3-Series system or '3S'. This essay delves deeper into understanding the mathematical equation and electrical properties of 3S BMS. The primary role of a BMS includes measuring voltages and currents, estimating state-of-charge (SOC), stating health (SOH), and predicting remaining useful life (RUL). From a mathematical perspective, the simplest form of cell-balancing algorithm is the equalization of cell voltages. The equations for voltage, current, and temperature are typically expressed as: (Duggal *et al.*, 2020).

- Voltage (Equalization) = $Vmax - Vcelli$
- Current = $\sum Icell\ i$
- Temperature $= \beta/(ln(R/R0) + \beta/T0) - 273.15$

Where $Vmax$ is the maximum desirable voltage, $Vcelli$ is the voltage of each cell, $Icell\ i$ is the current for each cell, R is the total resistance, and β and $R0$ are specific constants (Fridholm *et al.*, 2012).

3.0 Results and Discussion

Constructing a functioning simple radar communication system using Arduino involves assembling various components and implementing receiving unit. The integration of an ultrasonic sensor with an Arduino and RF module provides a cost effective and efficient radar communication system that is capable of detecting objects at certain distances and angles as well as transmitting this data over a mid-range distance and display this parameter correctly.

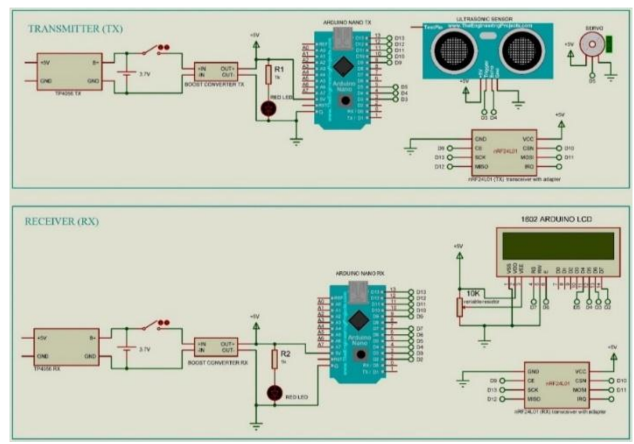

Figure 7: Circuit diagram of the transmitter and receiver of the radar system project

The diagram above outlines the layout of the connection of the components for both the transmitting and receiving part of the system.

3.2.2 Arduino Nano Flow chart

The major software used for the system is the Arduino (Integrated Development Environment) IDE for programming the Arduino Nano. The Arduino IDE uses a combination of C and C++ programming language.

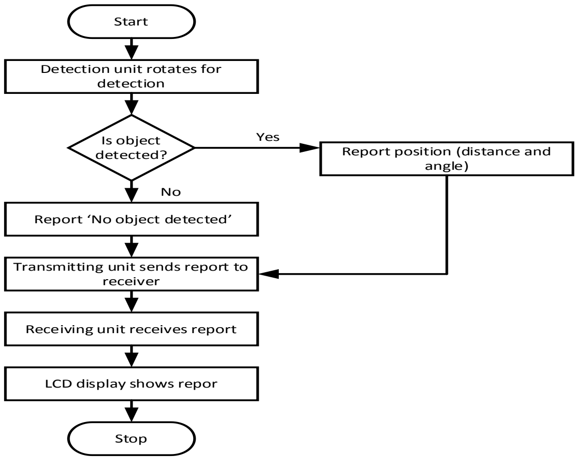

Figure 8: The flowchart showing how the program codes work

Study of Sensor Performance with Obstacles with Different Physical Properties

Plots and analyses of the distance measurements collected from the ultrasonic sensor under several specified circumstances are included in this. Accurate scale measurements are used to confirm the values that were acquired after being taken from the ultrasonic sensor. Wooden plank, sponge sheet, and plastic sheet are the testing materials utilized for various physical qualities, and the distance values are given along with the standard deviation and correlation coefficient (in centimeter scale). The parameters "Ultrasonic Distance" and "True Distance" should give information about how well the ultrasonic sensor is working. These tests provide an estimate of the HC-SR04 ultrasonic sensor's accuracy, which is then contrasted with the manufacturer's claim. Various materials with various physical qualities were used in accuracy tests, and these data were recorded and analyzed. Tests were conducted multiple times, the greater the number of the tests, the more reliable the data can prove to be. Figure 4 displays the distance determined by an ultrasonic sensor when a wooden board is the obstacle in a lab-like setting and is confirmed by scale measurements (the obstacle is positioned every 15 cm in the 0-150 cm range). The ultrasonic readings are consistent, and the surface of the wood is smooth yet microscopically irregular. Despite the fact that it returns the sound well enough to produce a stable graph. The plot displays a relatively low level of variance.

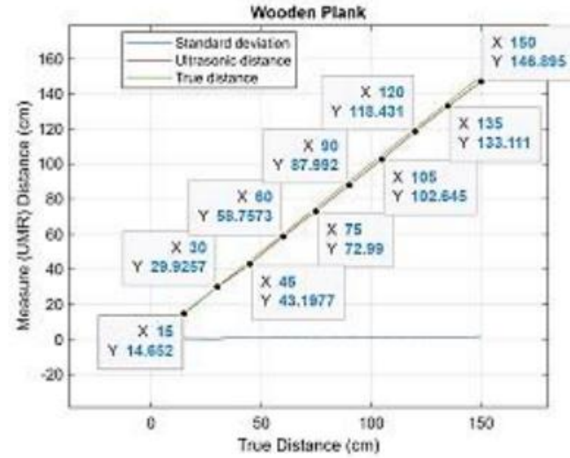

Figure 9: Graph Plot for Wooden Plank Test

Figure 5 displays the distance determined by an ultrasonic sensor with a sponge sheet obstacle in a lab-like setting and validated using scale measurements (obstacles spaced every 15 cm from 0-150 cm). The plot of the ultrasonic sensor exhibits extremely perceptible changes in distance measurements at first, then becomes rather smooth (from 105 to 150 cm in actual scale measurement). This fluctuation may have occurred because the sponge, which is porous, initially absorbed the sound before reflecting it back with a delay. Therefore, even though the measurement of the time of flight is accurate, the method of distance calculation is incorrect for determining when a sponge is an impediment.

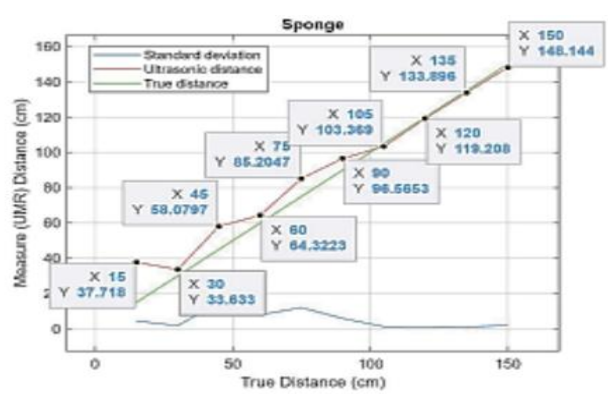

Figure 10: Graph plot for sponge test

Figure 6 depicts the distance determined by an ultrasonic sensor with a plastic sheet obstacle in a lab-like setting and scale measurements (obstacles spaced every 15 cm, from 0-150 cm). Since the surface of plastic is smooth and even, it reflects the majority of sound waves, as shown in Figure 5.4, the plot is observed to be stable and steady.

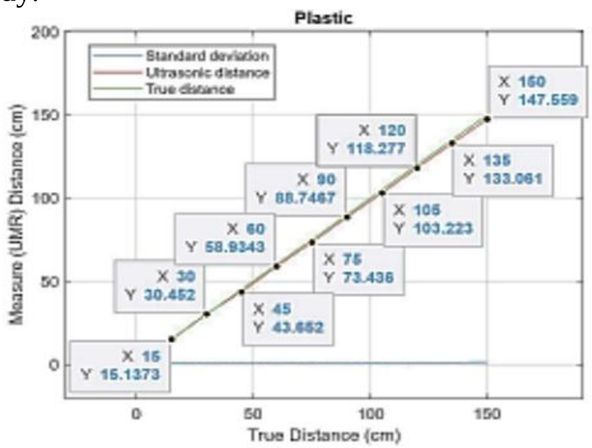

Figure 11: Graph for Plastic test

Distance measured using an ultrasonic sensor with a cardboard box as the barrier in a lab setting (figure 5.6) and confirmed with scale measurements (obstacle put every 5 mm from 15-20 cm). The sensor's ability to distinguish between variations in input is represented by this graphic. The sensor responds well to changes in the scaled position of obstructions.

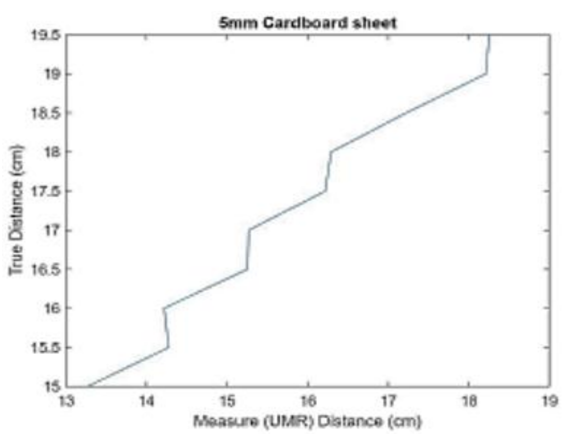

Figure 12: 10mm Cardboard Test

This graph figure 7 represents the comparison between different materials that were used to perform the experiment. Wood and plastic respond well to ultrasonic scanning unlike sponge.

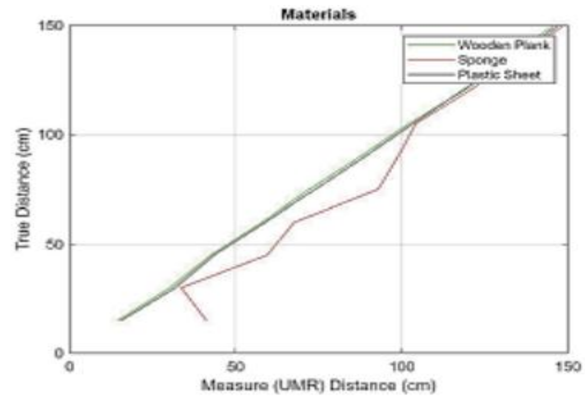

Figure 13: Comparison between materials

Figures 8 and 9 represent the plots of the experiment that was conducted to measure the distance from the sensor to obstacle with different physical properties to examine the effects that various materials have on ultrasonic sound. Each experiment has been carried out ten times, and the mean values of the Ultrasonic scans have been used to plot the graph.

For each unique data set, standard deviation parameters were produced. This parameter was calculated to reflect uncertainty in an ultrasonic scan. These findings aid in expressing uncertainty in ultrasonic scans by using several materials with various physical properties. The correlation between measured and actual distance values was calculated. The parameters established for the readings are very high correlation (0.9 and above), high correlation (0.7 to 0.9), medium correlation (0.5 to 0.7), low correlation (0.3 to 0.5), and low correlation (0.3 and below).

Table 1: Mean of Distance's acquired (in "cm")

True Distance	15	30	45	60	75	90	105	120	135	150
Ultrasonic scan (Wool)	14.6520	29.9257	43.1977	58.7573	72.99	87.992	102.6447	118.4313	133.11	146.8947
Ultrasonic scan (Wool)	37.718	33.633	58.0797	64.3223	85.2047	96.5653	103.3693	119.2083	133.8963	148.1437
Ultrasonic scan (Wool)	15.1373	30.452	43.652	58.9343	73.436	88.7467	103.2233	118.2773	133.061	147.559

Table 2: Standard deviation and Correlation coefficient

Statistical analysis of sensor data for different obstacles		
Material	**Standard deviation "s"**	**Correlation coefficient "r"**
Wooden plank	± 1.1380	± 0.996
Sponge	± 5.2587	± 0.9301
Plastic sheet	± 1.1380	± 0.998

4.0 CONCLUSION

In conclusion, the development of a simple radar communication system presents a valuable and engaging project topic. Throughout the project, various concepts and principles from the fields of electronics, signal processing, and communication technology are explored, making it an excellent learning opportunity for students and enthusiasts. By designing and implementing a radar communication system, you gain hands-on experience in working with components like antennas, transceivers, and microcontrollers. This project allows you to delve into the intricacies of signal propagation, target detection, and data transmission, fostering a deeper understanding of how radar systems function. Furthermore, the project encourages creativity and problem-solving. As you address challenges related to signal interference, noise reduction, and synchronization, you will develop critical thinking skills and innovative approaches to overcome these hurdles. In the process of building a radar communication system, you also gain insights into real-world applications. Radar technology finds applications in fields such as aviation, defense, weather monitoring, and autonomous vehicles, highlighting the relevance and significance of your project.

Overall, a simple radar communication system project not only provides a platform for hands-on technical learning but also offers a glimpse into the broader context of radar technology's impact on modern society. It's an opportunity to combine theoretical knowledge with practical skills, fostering a well-rounded learning experience.

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