AIS - MACHINE LEARNING – ML1

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Reliability test and improvement of a sensor system for object detection

1. Introduction

Research and development efforts in contemporary autonomous systems have focused on object-sensing techniques tailored for applications such as autonomous driving, navigation, and security systems. However, as these automated applications become increasingly prevalent, ensuring community safety poses a substantial challenge. Consequently, there is a clear demand for a system capable of detecting objects, and their position using different Machine Learning algorithms to safeguard humans from accidents involving autonomous systems. On the other hand, implementing the embedded system for object sensing in autonomous systems is promising due to its low cost and high level of reliability compared to literature approaches.

This project centers on the exploration and implementation of the ML method to improve an existing embedded sensor system designed for object sensing and distance measurement by detecting the first echo detection of an ultrasonic sensor (US). To measure distance, it is necessary to reliably determine the position of the first echo to calculate the time of flight, and subsequently, compute the distance. The traditional approaches seem to focus on finding the maximum amplitude to discover the first echo position. Despite their efficiency in utilizing minimal computing time, these approaches are error-prone in cases where the later echo exhibits a higher amplitude than the first one. To address this, Machine Learning (ML) models such as NLP or CNN can be trained to reliably detect the position of the first echo, contributing to the precision of distance measurement.

In this project, the primary goal is to evaluate and enhance the reliability of the implemented ML model. For a reliable evaluation, the distance measurement obtained by using the implemented ML method will be assessed through the detection of various objects with different heights and positions.

2. Theoretical Basics and State of the Art

This project is to improve an embedded system with an ultrasonic sensor and the embedded system Red Pitaya (RP) for reliable object detection. The system can detect objects and measure the distance by calculating the time of Flight (ToF). The key objective is to detect the position of the first echo and analyze the frequency spectrum of the reflected ultrasound waves from the reflecting surface.

As shown in Fig. 1, the ultrasonic pulse-echo method is used to calculate the distance of the object from the sensor. For that, the time of Flight is measured by the sensor i.e., the time taken by the ultrasonic wave to travel from the sensor to the object and back. The ToF is measured using the time it takes for the ultrasonic signal to be transmitted, reflected off an object, and returned to the sensor. The ToF is then used in the Formula 2.1 to calculate the distance:

$$\text{Distance (x)} = \frac{\text{ToF (t)} \times \text{Speed of Sound (c)}}{2} + offset$$

Formula 2.1: Distance calculated from the Time of Flight (ToF)

where,

- Distance is the distance between the object and the sensor.
- Time of Flight is the time taken for the ultrasonic signal to travel from the sensor to the object and back.
- Speed of Sound is the speed at which sound waves travel in the medium (air, in most cases).

The commonly used speed of sound in air at room temperature is approximately 343.2 meters per second. The division by 2 in the formula is because the ToF represents the total time it takes for the signal to travel to the object and back. To get the one-way distance, it is then divided by 2.

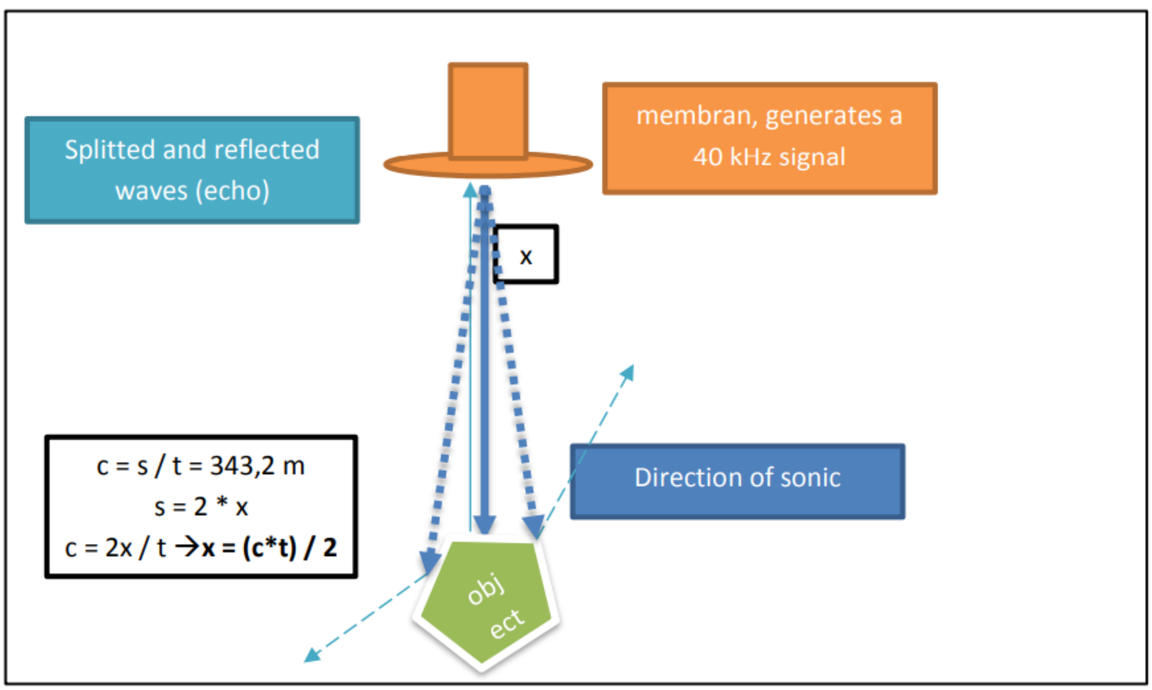

Figure 1: Ultrasonic pulse-echo method

2.1 Hardware and Experimental Setup

This project employs the SRF-02 ultrasonic sensor to determine the position of an object. An analog-digital conversion (ADC) input of the RP is connected to receive the signals from the US sensor in analog form and digitize them. The RP stores and analyzes the data internally. The RP runs a Linux operating system with GCC2 (GNU compiler collection) to compile C code. The RP program is operated in the background and can deliver the data to any PC through UDP. The system utilizes ultrasonic pulsed waves to ascertain the object's position. A graphical user interface (GUI) is employed to both save data in a text file and present visualized results to the user. Figure 2 illustrates the actual hardware of the Red Pitaya (RP) embedded system with ultrasonic sensor. Figure 3 illustrates the simple data flow within the system.

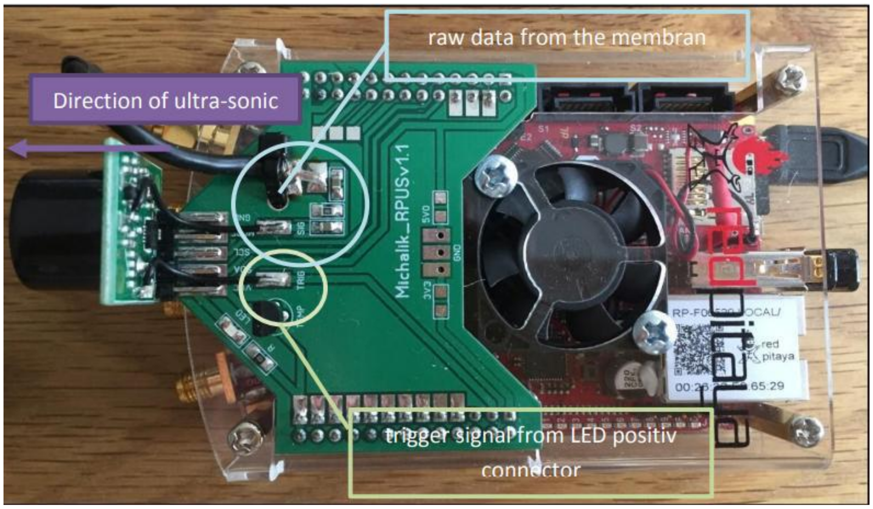

Figure 2: Hardware of Red Pitaya embedded system with ultrasonic sensor

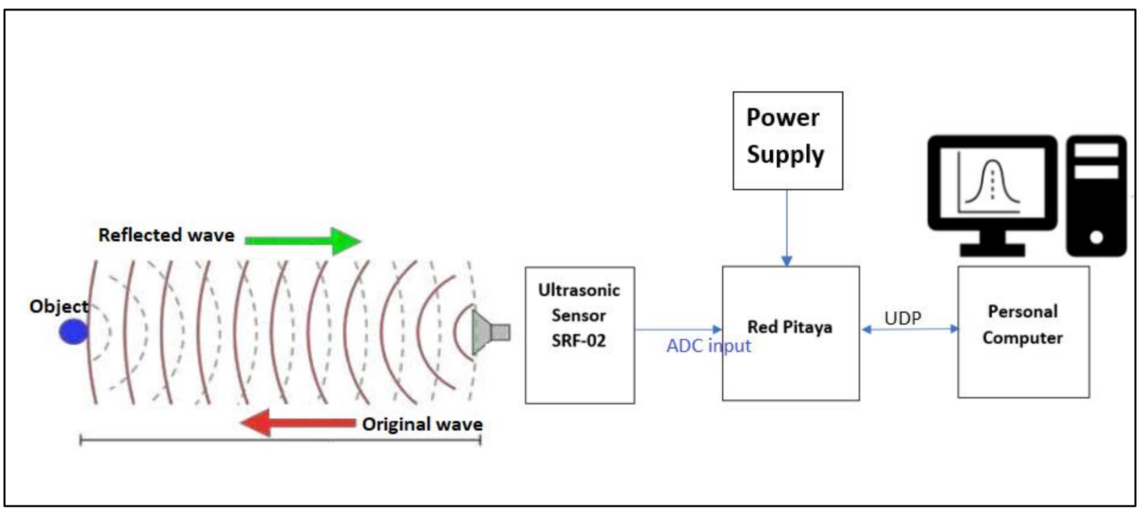

Figure 3: Block diagram of Ultrasonic sensor with Red Pitaya (RP)

The ultrasonic sensor is affixed to a vertical stand in a downward-facing orientation, as depicted in Figure 4. The sensor is positioned at a height of 2 meters and 7 centimeters from the floor. Measurements are conducted using this configuration, focusing on an object, a blue box with a height of 28 centimeters (Figure 5). The analysis involves the examination of ADC measurements to comprehend the functionality of the US waves' ADC feature. Various object positions are explored to observe the alterations in the ADC plots corresponding to reflections.

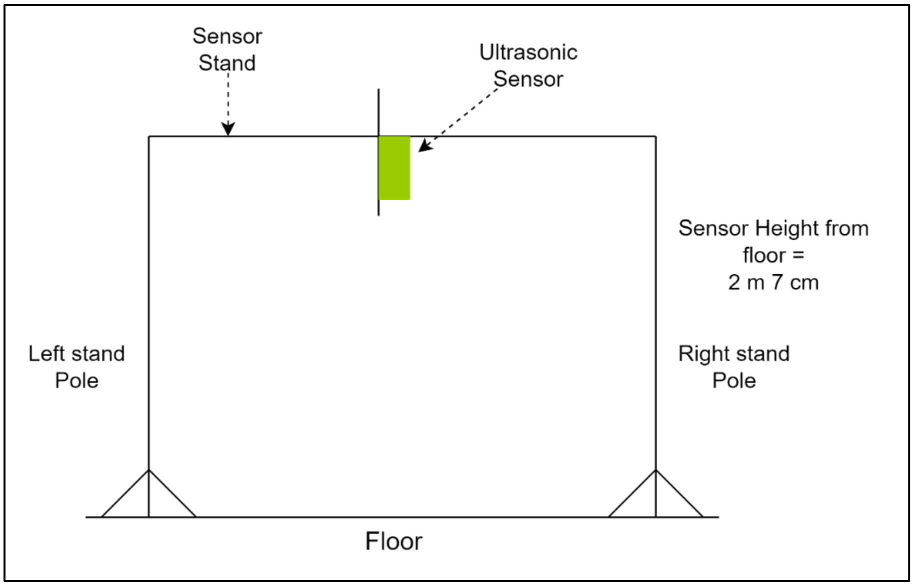

Figure 4: Diagrammatic Representation of Experimental Setup

Figure 5: Blue Box (an object used for measurement)

2.2 Software

All the software for RP is written in C programming language. The software for Microsoft Machine is written in C#. To read, write, modify, compile, and save any kind of software, the following programs are used in this project: VS Code, UDP client, WinSCP, and Putty.

For this project, the experiment aims to determine the distance of the first reflection utilizing the GUI designed for the Red Pitaya (RP) System. This software initiates the ultrasonic sensor "SRF-02" and retrieves the reflected signal captured by the sensor. The obtained data is temporarily stored on the RP System and later analyzed internally. The Red Pitaya software operates as a background daemon, sending data to any PC in the foreground through UDP. The graphical user interface (GUI) of the software can save data in a text file and display real-time data from the RP.

In this context, version GUI SW V0.23 is employed, as illustrated in Figure 6, to comprehend the pattern of object reflection by the ultrasonic sensor. The ADC measurements from the ultrasonic sensor, when plotted, reveal peaks with significantly higher amplitudes, indicating the presence of an object.

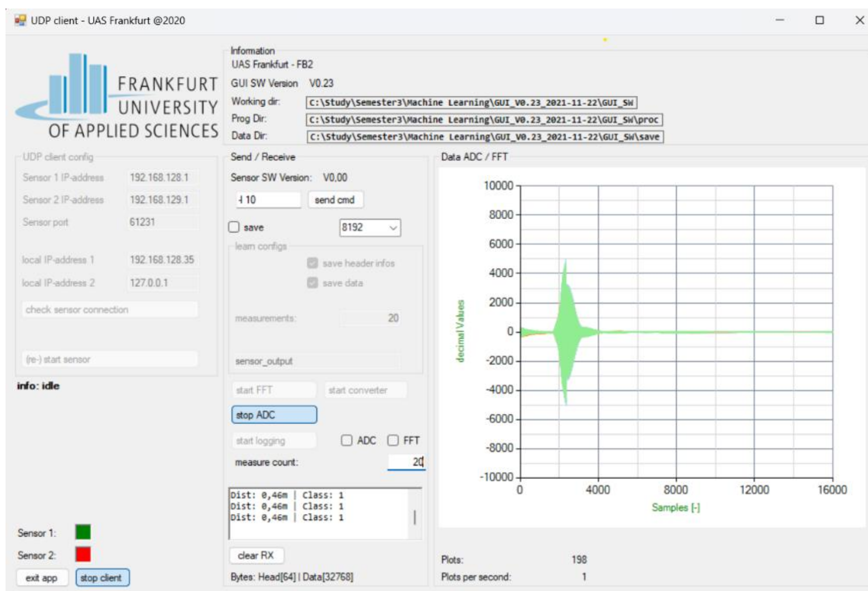

Figure 6: GUI SW V0.23

Implementing Machine Learning method for first echo detection.

Central to this project is the integration of Machine Learning (ML) for the detection of the first echo. The implemented ML method leverages the CNN model to detect the position of the first echo. The idea is to divide the ADC data into small sections. The frequency spectrum of each section is calculated and assessed. A section with a small amplitude will be designated as an empty section with no echo. The spectrogram of the section containing the echo will have a higher amplitude compared to the other sections. The CNN model can be trained with all the spectrograms to differentiate empty sections and an echo. If there are multiple echoes detected, only the first echo is considered.

3. Experiment

In this section, the measurement distances and the ADC data are collected for assessment. There are three measurement distances available, including the inbuilt distance (**d_{FIUS}**), the distance calculated from the first echo position given by the ML-driven model-driven first echo detection algorithm (**d_{ML}**), and the actual distance between the sensor and the detecting object measured by using a folding meter stick (**d_{MAN}**). The inbuilt measurement distance calculated from the ToF is already explained in Formula 2.1. To calculate the distance from the first echo position, the traveling time of the ultrasonic wave from the sensor to the object is computed from the position of the first echo within the ADC buffer detected by the ML model. Finally, the manually measured distance is obtained by measuring the distance from the sensor to the first reflecting surface using a folding meter stick. These three measurement distances are collected and analyzed to assess the performance of the ML model for detecting the first echo position. Unfortunately, the first echo position detected using the ML approach is currently not available. Hence, some experiments will be conducted with different detecting objects to analyze the characteristics of the reflecting ultrasonic wave. Different objects will be placed right under the sensor for detecting and the distance between the sensor and the objects will be changed. On the other hand, the difficulties in detecting the first echo position for some specific scenarios using the traditional approaches are discussed.

3.1 Experiment set up:

Experiment setup 0:

For the first setup, there was no detecting object. The sensor was supposed to measure the height of the mounted sensor with respect to the ground. The experiment setup is shown in Figure 3.1.

Figure 3.1: Experiment set up 0 – 187cm.

Figure 3.2 shows the ADC data graph for the experiment Setup 0. As it is observed that since the floor surface is hard, flat and the surface area is also large (due to consideration of floor as an object), the ultrasonic waves are reflected in much amount and detected by the sensor having more power in the reflected wave. Therefore, there is a much greater spike in the ADC data graph for the first echo as shown in Figure 3.2 and the accuracy for this measurement is also reliable.

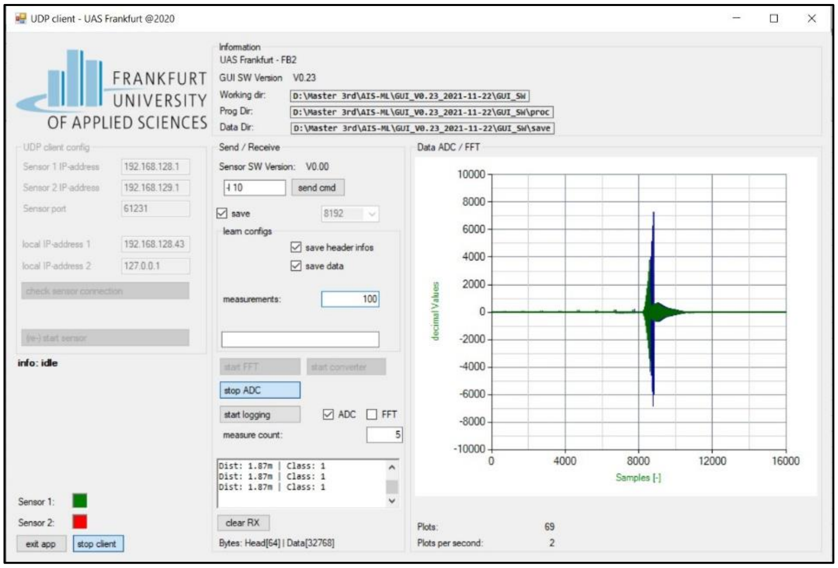

Figure 3.2: Experiment set up 0 – ADC Data Graph

Experiment setup 1:

For the second setup, the detected object was a small table. The sensor was supposed to give the distance between the sensor and the table. Figures 3.3, 3.4, 3.5 illustrate the experiment setup for this case.

Figure 3.3: Experiment setup 1 – 126cm

Figure 3.4: Experiment setup 1 – 104,5cm

Figure 3.5: Experiment set up 1 – 91.4cm

Now for experiment setup 1, a small table acts as an object, making the surface area lesser than the surface area of the object in experiment setup 0, therefore the magnitude of the spike is less for experiment setup 1 as compared to experiment setup 0 as shown in Figure 3.6. Moreover, the reflected signal power is also much reduced. Moreover, it is observed that if the object is closer to the sensor, the first echo spike formation is nearer to the y-axis indicating that the object is placed at a lesser distance.

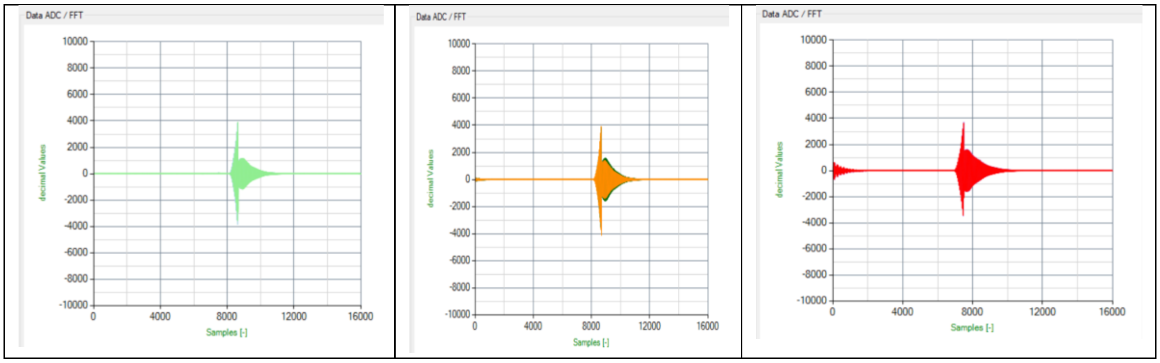

Figure 3.6: Experiment set up 1 – ADC Data Graph for a) 126cm b) 104.5cm c) 91.4cm

Experiment setup 2:

For the third setup, the detected object was a carton box which is shown in Figure 3. The sensor was supposed to give the distance between the sensor and the top surface of the box. Figures 3.7, 3.8, 3.9 illustrate the experiment set up in this case. Figure 3.10 shows the ADC data graph for these respective cases in this experiment setup.

Figure 3.7: Experiment setup 2 – 91cm

Figure 3.8: Experiment setup 2 – 72.5cm

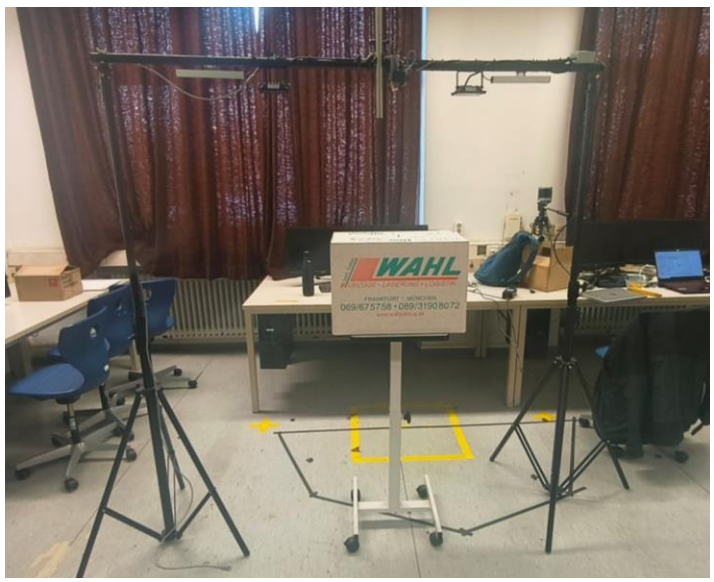

Figure 3.9: Experiment setup 2 – 53cm

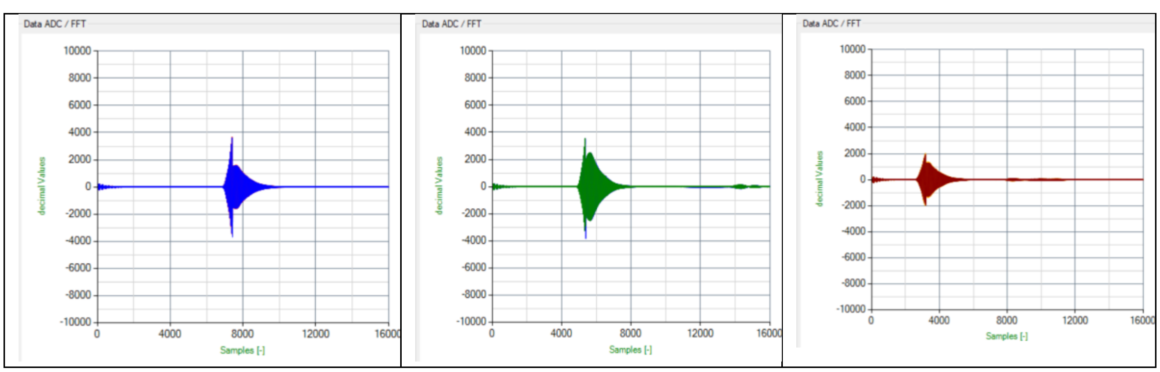

Figure 3.10: Experiment set up 2 – ADC Data Graph for a) 91cm b) 72.5cm c) 53cm.

Experiment setup 3:
For the fourth experiment, the soft plane in Figure 3 was used as the detected objects. Figures 3.11, 3.12, and 3.13 show the experiment setup.

Figure 3.11: Experiment setup 3 – 104cm

Figure 3.12: Experiment setup 3 – 89cm

Figure 3.13: Experiment setup 3 – 80cm

As the fourth object is having a soft surface therefore, most the signal power is observed by the object's surface itself therefore, the power of the reflected signal is low and as shown in Figure 3.14, the magnitude of the spikes is low in the ADC data graph for this experiment setup.

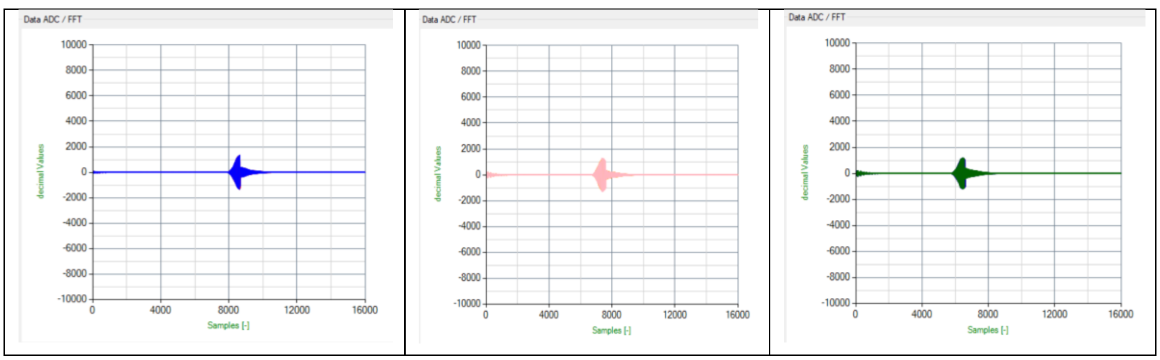

Figure 3.14: Experiment set up 3 – ADC Data Graph for a) 104cm b) 89cm c) 80cm.

Experiment setup 4:

In the fifth experiment, the detected object was a bottle placed on a small table. The sensor was supposed to measure the distance to the top small surface of the bottle. The experiment set up in this case is shown in Figure 3.15.

Figure 3.16 represents the ADC data graph for this experiment setup. As observed, there are two spikes in the ADC graph. The first spike having lesser magnitude is due to the small bottle and the second spike having larger magnitude is due to the table on which the small bottle is placed. The sensor is supposed to measure the distance for the first spike, but it measures the distance concerning the second spike. Since the magnitude of the first spike is much less than the magnitude of the second one, the sensor considered the first spike as a noise and neglect it.

Figure 3.15: Experiment setup 4 – 97.5cm

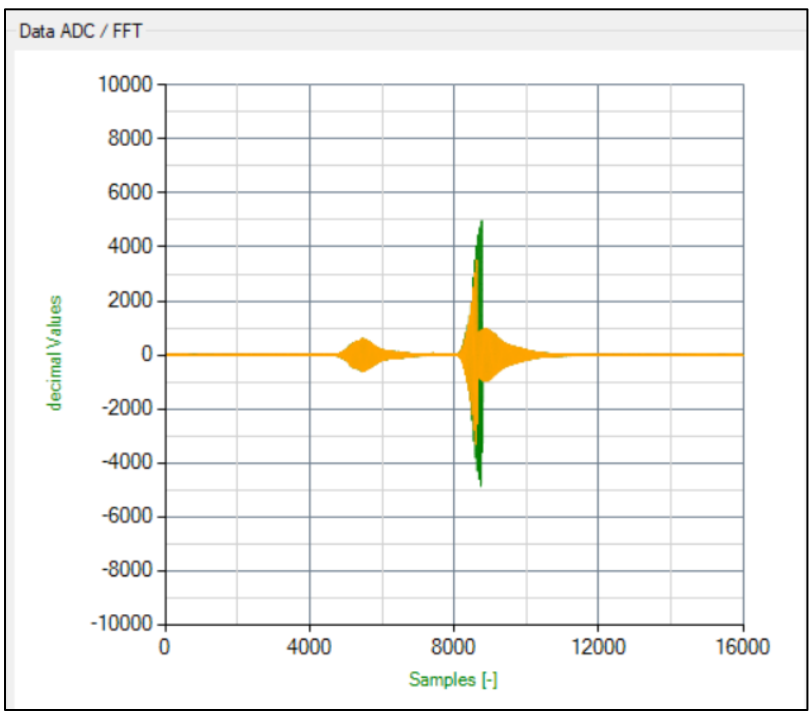

Figure 3.16: Experiment set up 4 – ADC Data Graph

Experiment setup 5:

In the last experiment, the detected object was a person sitting under the sensor. The person had different postures to identify how it affected the measurement result. The experiment setup is shown in Figures 3.17 and 3.18. Figure 3.19 represents the corresponding ADC data graph for these two cases in this experiment set up. As shown in Figure 3.17, person X is simply sitting on the chair, therefore, the surface of the object is uneven and therefore the ADC data is not correctly measured by the sensor as shown in Figure 3.19a. There is too much noise in the detected signal and the distance measured by the sensor is also inaccurate. However, in the second case, person X is sitting having a compressed posture as compared to the first case, having an even surface distribution, therefore there is some spike seen in the ADC data graph as shown in figure 3.19b. This shows that for humans, there could be errors in the measurement if the sensor is placed vertically to the human.

Figure 3.17: Experiment setup 5 – 57cm

Figure 3.18: Experiment setup 5 – 115cm

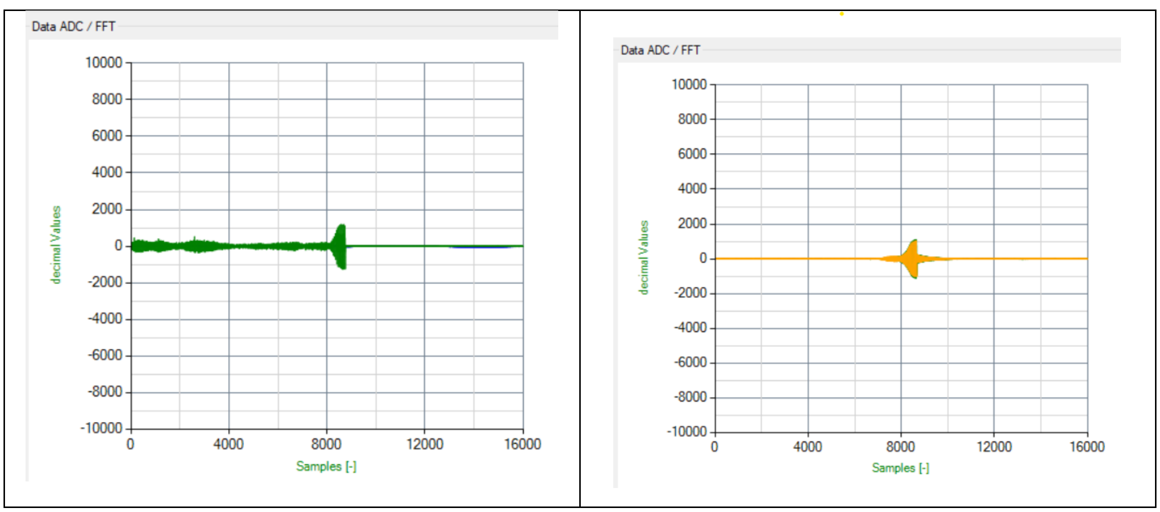

Figure 3.19: Experiment set up 5 – ADC Data Graph for a) 57cm b) 115cm.

3.2 Results

Table 3.1 shows the results of the above experiments.

Experiment set up	Manual distance (d_{MAN})	Sensor measurement distance (d_{FIUS})
0	187cm	186.5cm
1.1	126cm	127cm
1.2	104.5cm	105.2cm

1.3	91.4cm	92cm
2.1	91cm	91.5cm
2.2	72.5cm	73.1cm
2.3	53cm	54cm
3.1	104cm	107cm
3.2	89cm	91.2cm
3.3	80cm	83.4cm
4	97.5cm	127.1cm
5.1	57cm	100.2cm
5.2	115cm	203.9cm

4. Requirements

The objective of the project is to assess and improve an existing measurement system for detecting the position of the first echo (i.e. first reflection) of a pulsed ultrasonic beam. The measurement data of different objects and persons has to be collected for assessment. The measurement distance has to be automatically calculated by software using the ML first echo detection. To test the precision of the distance calculation, it is compared to the distance that is measured manually, the test results will be used for creating a confusion matrix. On the other hand, further research and implementation on improving system performance (decision speed, measurement accuracy), developing software, and GUI can be done.