Computer Science

Ultrasound Indoor Positioning System
for Localisation of a Moving Object

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BACHELOR THESIS

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30/08/2023

Abstract

Localisation systems like GPS and Bluetooth are now widely used to create, send and receive data to help cities become more efficient. Indoor small-scale environments have proven difficult for such systems and other Real-Time localisation Systems (RTLS) become relevant alternatives. Accurately locating moving children in a playground is a problem that can be solved using such an alternative method. Trilateration formulas based on Time-of-Flight measurements of ultrasound waves through air are used to calculate the location of a moving object.In this thesis we developed sensor range profiles using the reflective and direct method which are used to create the optimal basis for the 2D and 3D localisation experiments. 2D localisation had an average error of 1.30 centimeters and 3D localisation had an average error of 10.93 centimeters per location measured. 3D localisation is preferred for locating moving children in a playground, because 3D localisation covers a way larger area with the same amount of sensors and can be improved by removing miss measurements. Future work can also focus on a possible scale-up architecture that uses a measuring angle of 30 degrees per sensor and a measuring distance of more than 4 meters using the direct method.

Contents

1 Introduction

1.1 Background

In recent years, urban computing has become a fundamental part of cities' infrastructure. Through the combination of wireless networks, sensors and localisation systems, it has become exceedingly easy to create smart cities on a big scale.

Localisation systems like GPS and Bluetooth are now widely used to create, send and receive data to help cities become more efficient. However, indoor small-scale environments have proven difficult for such systems. The direct signal can disappear or it can bounce off a reflective surface and this reflection can result in measurement errors [1]. In these environments, other Real-Time localisation Systems (RTLS) become relevant alternatives.

Accurately locating moving children in a playground is a problem that can be solved using such an alternative method. Ultrasound is a possible and effective alternative. This thesis acts as the blueprint for a large-scale ultrasound indoor positioning system.

1.2 Objectives

This thesis aims to explore the use of ultrasound to locate a moving object in an indoor small-scale environment. Another aim is to locate the beacons' position using their relative distance to each other. The accuracy of a 2D and 3D ultrasound localisation system will be compared. Furthermore, a possible method for scaling the ultrasound indoor positioning system will be described.

RQ1: How do we accurately determine the location of a moving object using ultrasound waves propagating from the beacons?
RQ2: How do we accurately determine the locations of the beacons using their relative distance from each other?
RQ3: How well does the positioning accuracy of an 2D ultrasound localisation system compare to a 3D ultrasound localisation system?
RQ4: How could an ultrasound localisation system be implemented for large-scale environments?

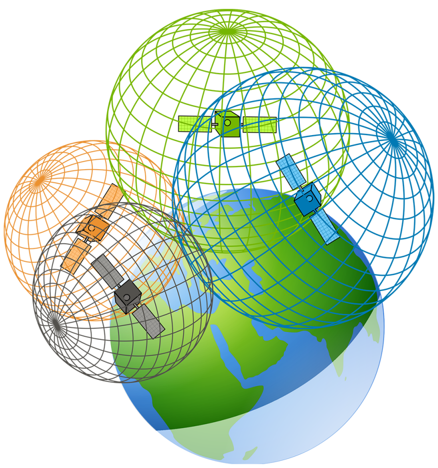
1.3 Thesis Overview

This thesis aims to explore the use of ultrasound to accurately determine the position of a moving object in a indoor small-scale environment. This document contains the bachelor thesis of Bas van Aalst conducted at the Leiden Institute of Advanced Computer Science (LIACS). In section 1 we present the Introduction. Section 2 covers Related Work. Section 3 shows the methods employed in our experiments. Section 4 includes all experiments. Section 5 describes the results of the experiments. Section 6 summarises the thesis and includes options for further research.

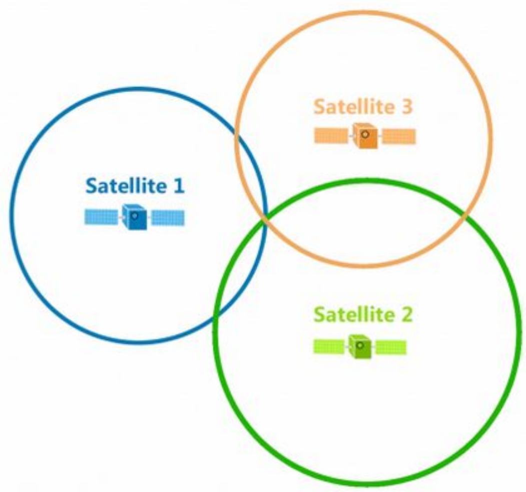
2 Related Work

2.1 Global Positioning Systems

Global positioning systems, or GPS, have served as a solution to a diverse range of navigation problems. The Navstar Global Positioning System is the most popular GPS that uses 31 active satellites. A GPS receiver that receives radio signals from at least four satellites can calculate a position on Earth. The distance between a receiver and these satellites is calculated using the time delay that a signal takes to be sent from the satellite to the receiver. After calculating one distance, we know that we are somewhere on a sphere around that satellite. After measuring at least four of these distances, the GPS calculates the intersection point between all the spheres which is your position (Figure 1a and Figure 1b). This technique of measuring a position is called Time-of-Flight multilateration and GPS is typically accurate to within 5 meters 95% of the time [2]. In 3D space, multilateration with at least four distances is standard in calculating a position. In 2D space, three distances are enough to calculate a position which is called trilateration.



(a) 3D view of satellites using Multilateration



(b) 2D schematic of satellites using Trilateration

Figure 1: Multilateration and Trilateration

$$\sqrt{(x_k - x)^2 + (y_k - y)^2 + (z_k - z)^2} = r_k \tag{1}$$

Equation 1 consists of the three coordinates x_k, y_k, z_k which are the receiver's position in 3D space. x, y, z is the satellite's position in 3D space and r_k is the distance between the satellite and the receiver. Once at least four of the navigation satellites have determined their r_k, this formula can be used to determine the location.

2.2 Local Positioning Systems

Local Positioning Systems, or LPS, are positioning systems that are not suited for world-scale localisation like GPS. LPS specialises in smaller, enclosed spaces and is more accurate than GPS.

LPS are a viable alternative to GPS when such systems cannot be used. A GPS signal from satellites can not be received indoors because its intensity is too low. Subsequently, LPS were developed to act as a positioning system for autonomous robots indoors. These systems require the use of beacons that act as satellites. LPS use different types of signals like ultra-wideband, ultrasound or bluetooth; and different types of signal measurement techniques and positioning algorithms.

2.3 Signal Measurement Techniques

LPS use different signal properties to measure the distance, angle or signal between a receiver and a transmitter of a signal. The most prevalent ones are Angle of Arrival (AOA), Time of Arrival (TOA), Time Difference of Arrival (TDOA) and Received Signal Strength Indication (RSSI) [3, 4].

- The Angle Of Arrival is the direction from which the signal is received.
- The Time of Arrival is the moment the signal reaches the receiver. The elapsed time after transmitting the signal is called the Time of Flight (TOF). To calculate the TOF it needs to be known when the signal was transmitted.
- The Time Difference of Arrival is the difference in TOA measurements by at least two different receivers. For this method, when the signal was transmitted needs te be known.
- The Received Signal Strength Indication indicates the strength of the signal. The further away the signal's source, the lower the signal strength measured by the receiver.

Signal property	Measurement metric	Pros	Cons
AOA	Angle-based	High accuracy at room level	Complex, expensive and low accuracy at wide coverage
TOA	Distance-based	High accuracy	Complex and expensive
TDOA	Distance-based	High accuracy	Expensive
RSSI	Signal-based	Low cost	Medium accuracy

2.4 Positioning Algorithms

Local positioning systems use different positioning algorithms to measure our receiver's position using the different signal properties like triangulation, trilateration, proximity and scene analysis and fingerprinting [4].

- Triangulation uses angle measurements relative to at least three known points to determine the receiver's position.
- Trilateration uses distance measurements relative to at least three known points to determine the receiver's position. Multilateration uses four or more known points which is preferred over trilateration.

- Proximity calculates coordinates by how close they are to a known set of points.
- Scene Analysis and Fingerprinting examines a space from a particular viewing point.

Positioning algorithm	Signal property	Pros	Cons
Triangulation	AOA	Simple, low-cost and high accuracy at room level	Complex, expensive and low accuracy at wide coverage
Trilateration	TOA/TDOA	High accuracy	Complex and expensive
Proximity	RSSI	High accuracy	Complex and expensive
Scene analysis/ fingerprinting	RSSI	High performance	Complex, expensive, medium accuracy and time consuming

2.5 Ultrasound Indoor Positioning Systems

Multiple ultrasound indoor positioning systems have been designed to improve existing local positioning systems. One such example is the robust high-accuracy ultrasonic indoor positioning system (UIPS) [5]. This system extracts the envelope of a signal to determine the Time-of-Flight. The envelope of a signal is the boundary within which the signal is enveloped or, to put simply, contained.

The fully distributed ultrasound indoor positioning system by M. Minami at el. [6] demonstrates the difficulties of an of ultrasound indoor positioning system and discusses the potential solution to these problems. Problems such as no-line-of-sight signals and accumulated errors were discovered in this system.

The TELIAMADE system [7] is another ultrasound indoor positioning system that uses Time-of-Flight as signal measurement technique. A high accuracy in the estimation of the Time-of-Flight is achieved using parabolic interpolation. Parabolic interpolation is used to detect the maximum value of the signal to match it to the filter output. Furthermore, the signal phase information also increases the Time-of-Flight measurement accuracy.

Our research possesses a lot of similarities to these UIPS. Our experiments will employ trilateration and time-of-flight measurements to calculate a position in our coordinate system. This thesis focuses on methods for expanding these UIPS to larger areas. The experiments will be used to compare 2D and 3D UIPS configurations and to recommend one such system for further research.

3 Methods

3.1 Microprocessors

A comparison was made between the possible microprocessors to evaluate the arguments for and against the different hardware options. The two main contenders for this thesis were the Raspberry Pi 3 Model B[1] and Arduino UNO R3[2] because of their price, capabilities and large community. The specifications of these development boards are compared below [8]:

	Pros	Cons
Raspberry Pi 3 Model B	Supports operating system Supports large number of sensors More processing power	Closed-source More expensive
Arduino UNO R3	Open-source Faster development Less expensive	Cannot handle concurrent tasks Less processing power

As the literary research progressed, it became apparent that we did not need a lot of processing power to perform our experiments. This realisation steered our attention towards the Arduino since it costs less comparatively and can still handle the necessary tasks.

The Arduino UNO Rev3 became our main board for faster development of structured, usable code. The Arduino was programmed using its own Arduino Integrated Development Environment (IDE).

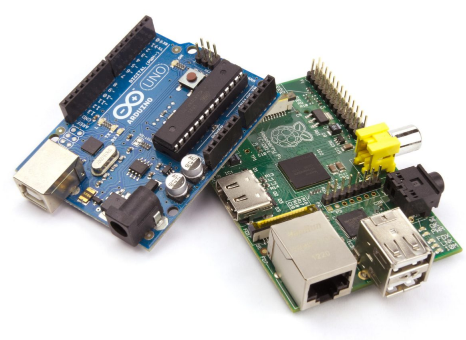


Figure 2: Arduino (left) and Raspberry Pi (right)

3.2 Ultrasonic Sensors

Multiple sensors were assessed in our literature research.
The HC-SR04 had the most potential as it is reasonably priced, has a well-documented user's manual, has a large community and produces similar results in terms of accuracy and distance to the other ultrasonic sensors we considered.

The HC-SR04 ultrasonic sensor specifications are as listed below. These specifications are listed in the HC-SR04 user's manual[3].

- Power Supply: +5V DC
- Quiescent Current: <2 mA

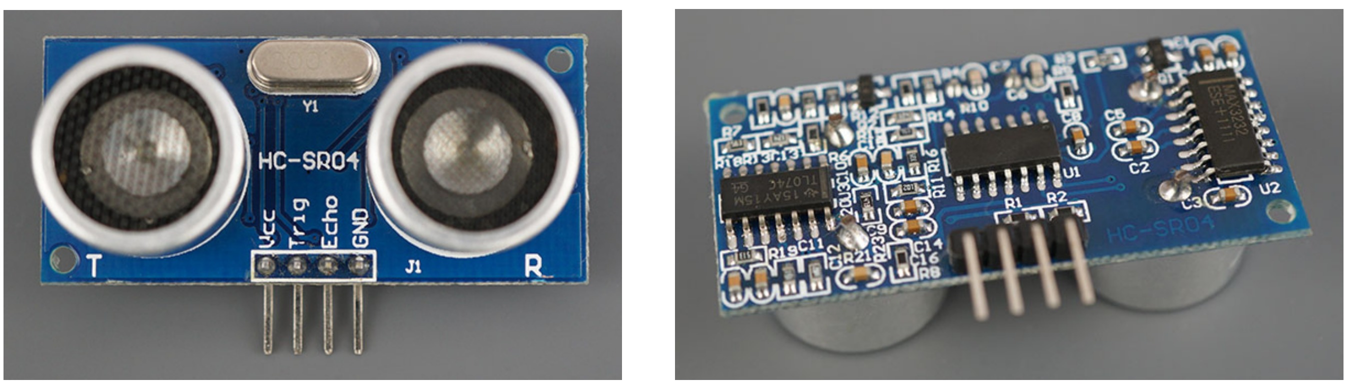
[1] https://us.rs-online.com/m/d/4252b1ecd92888dbb9d8a39b536e7bf2.pdf
[2] https://docs.arduino.cc/resources/datasheets/A000066-datasheet.pdf
[3] https://datasheetspdf.com/pdf-file/1291829/Cytron/HC-SR04/1

- Working current: 15 mA
- Effectual Angle: <15º
- Ranging Distance: 2-400 cm
- Resolution: 0.3 cm
- Measuring Angle: 30º
- Trigger Input Pulse width: 10 uS
- Dimension: 45 mm x 20 mm x 15 mm

3.2.1 How does the sensor work?

The sensor has four outputs. The four outputs are as follows:

1. VCC: Power supply pin
2. TRIG: Triggering input pin
3. ECHO: Transistor-transistor logic output pin
4. GND: Ground pin



(a) Frontside HC-SR04 Module

(b) Backside HC-SR04 Module

Figure 3: Overview HC-SR04 Module

The power supply is between 3.3V and 5V. Each output is connected to the Arduino using jumper wires.

Once all outputs are connected to an Arduino, the HC SR-04 ultrasonic sensor can start taking measurements. The sensor has a transmitter (T) and a receiver (R). A pulse is sent to the trig pin for 10 uS. A 8-cycle 40 kHz burst is transmitted through the transmitter, reflected and then received by the receiver. The Time of Flight is given to the user which is used to calculate the distance to the reflecting object.

For calculating the distance, the following formula is used:

$$s = v * (T/2)$$

which is derived from $s = v * t$. T is the Time of Flight and the duration of the echo signal. t is the time in microseconds. t is T is divided by 2, because the signal has to travel to and back from the object instead of just to the object. To get the distance s in centimeters, we use the speed of sound v (340 m/s or 29 μs per cm) to go from microseconds to centimeters. Effectively, the formula becomes s (cm) = T (μs) / 29 / 2.

The NewPing Arduino library [9] we used was designed to reliably ping multiple sensors and calculate the distance from the object to each sensor. We will further elaborate on this library and its methods in the Software section.

The speed of sound differs in certain temperatures. The colder it is, the lower the sound velocity. We used a speed of sound of 340 m/s in our calculations which would put the estimated temperature in the room at 15° Celcius [10]. This is below average room temperature, but the method from the NewPing Arduino Library internally uses this parameter for its calculations.

3.3 Connecting Hardware Components

Multiple other hardware components were used to connect the Arduino boards and HC-SR04 ultrasonic sensors with the laptop.

3.3.1 USB Hub

The USB 3.0 Hub 7 Port connects the four Arduino boards to the laptop using USB cables. Now, the laptop is required to have only one USB port instead of four USB ports.

3.3.2 USB Cables

The four USB-A to USB-B cables (5 metres) connect the USB hub to the Arduino boards.

3.3.3 Breadboard Jumper Wires

The thirty-two breadboard jumper wires (Male-Male, 30 centimetres) connected the breadboards to the Arduino boards. Each breadboard has four wires plugged in that connect the Arduino board to the HC-SR04 ultrasonic sensor using its four outputs: VCC, GND, TRIG and ECHO.

3.3.4 Breadboards

The eight breadboards connected the breadboard jumper wires to the HC-SR04 ultrasonic sensors and formed the base for the sensors to stabilise them.

3.3.5 Moving Object

The moving object was used as a reflective material to 'bounce off' the ultrasound waves. According to the user's manual of the HC-SR04 sensor[4], an object of at least 0.5 m2 should be used for better results. We opted for a smaller object since the experiments were done on a 1.33 m^2 area.

Different objects were tested for the intensity of reflection and angle of reflection. A cardboard rectangular object and a ceramic cylindrical object were considered for the object of choice.

3.4 Setup Motion Detection

To test whether the HC-SR04 sensors were sufficient in accuracy and range, we tested the ultrasonic sensors in a few experiments.

Initially, a small program was written in Arduino IDE which measured the distance from the sensor to an object. Then a Python program was written to extract the data from the Arduino serial monitor and plot the data in a diagram.

3.5 Sensor Range Profiles

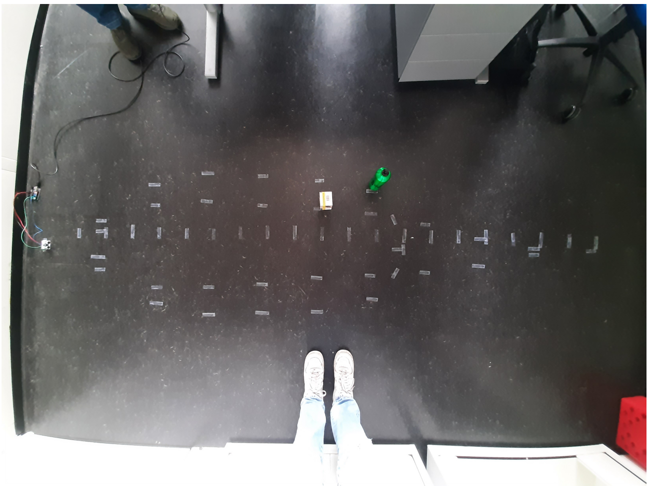
The reach of the HC-SR04 ultrasonic sensor was estimated by conducting an experiment. The maximum reach of the sensor was estimated by sending out a signal and having that signal bounce off of an object. On the corner case for which the signal could still be received, some adhesive tape was used to identify that point. This was done for every 30 centimeters up to 3 meters. These points showed the combined range of the sensor which could be used to further improve our setup for other experiments. In Figure 4a, we see the reach of the HC-SR04 ultrasonic sensor using two objects. One object is a rectangular carton container and the other is a round aluminum bottle.

As can be seen in Figure 4a, the rectangular shape performs better at longer distances but has less reach at shorter distances. The round shape is preferred because the rectangular shape is too dependent on the angle of the carton container. We found that the round object is consistent at every angle.

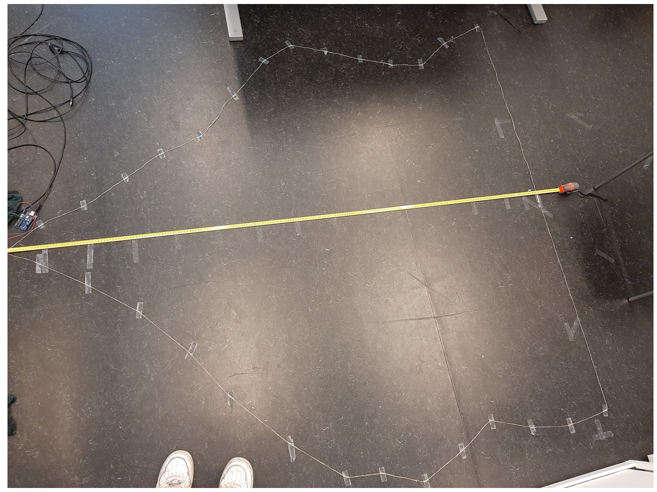
Since round objects performed better in the reflection profile experiment, we tried using a mug which is made of a denser material. A mug had a larger reach in the reflection profile experiment, so we used that object to perform the 2D localisation experiment.

In Figure 4b, the reflection profile of the direct method is shown. In comparison with the reflective method in Figure 8a (ref), this approach created a larger reflection profile in both width and length. However, this method can not be used in 2D localisation since the sensor attached to the moving object can only look in one direction. Therefore, the reflective method is preferred in 2D localisation and the direct method is preferred in 3D localisation.

[4]https://datasheetspdf.com/pdf-file/1291829/Cytron/HC-SR04/1



(a) Sensor Range Profile Reflective Method



(b) Sensor Range Profile Direct Method

Figure 4: Experiments Sensor Range Profiles

3.6 Determining Locations of Sensors

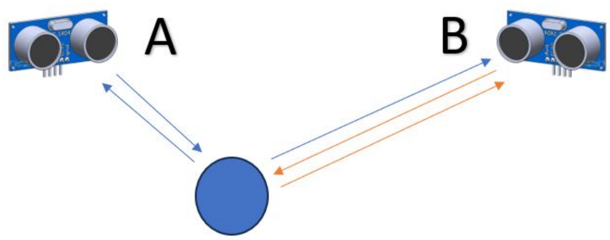
The locations of the sensors were determined by a measuring tape. The idea was to determine the distance between sensors the way we determined the distance between a sensor and the object. However, our experiments were conducted on such a small scale that, in this case, a measuring tape was more efficient than using ultrasound.

3.7 Calibration of HC-SR04 Sensors

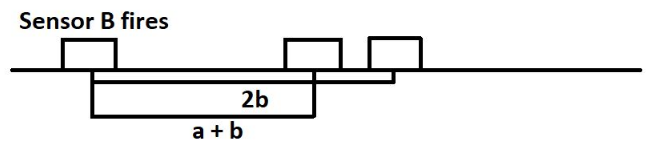
Calibration of the sensors was needed to ascertain if the positions measured were accurate. An experiment was conducted in which we determined the location of the mug relative to the sensors using a tape measure and then determined the location of the mug using our sensors. Noticeably, firing the sensors simultaneously caused interference between sensors.

In Figure 5a, sensors A and B fire a signal simultaneously toward the reflective object but at different distances. Take the distance from sensor A to the object as a and the distance from sensor B to the object as b. Since $a + b$ is smaller than $2b$, it is possible that sensor B receives a signal from sensor A faster than it receives a signal from itself. This is shown in the schematic in Figure 5b. The results are therefore inaccurate and can not be used for calibrating the sensors.

A flat surface only reflects the signal back in one direction, but a cylindrical object reflects the signal back in multiple directions. The reflection profile demonstrates that the signal is wider than the mug itself and reflects the signal at different angles.
Instead of firing all signals from the sensors at the same time, the sensors now fire two at a time. Each side fires separately. Calibration was no longer inaccurate because each pair of sensors waited 300 ms before the last pair was fired. This gave the sensors enough time to receive the reflected signal from their own sensor.



(a) Calibration Error in Sensor B caused by interference from Sensor A



(b) Schematic of received signals in Sensor B

Figure 5: Example Calibration Error

We compared the actual location of the mug with the results of the sensors. The sensors' results differed by 0-3 centimeters in multiple locations. That is within reasonable limits.

3.8 Setup 2D Localisation

For the 2D and 3D localisation experiments, a part of the office of my daily supervisor Richard van Dijk was utilized to set up all the sensors and execute the experiments. The area we used was 1.33 m^2. A larger area could not be utilized, because the sensor range profiles helped in calculating the optimal area for the localisation experiments. As seen in Figure 6, there are 8 sensors placed around the area. The sensors were fired in pairs per side because sensors that fired in the same direction did not experience interference from each other.

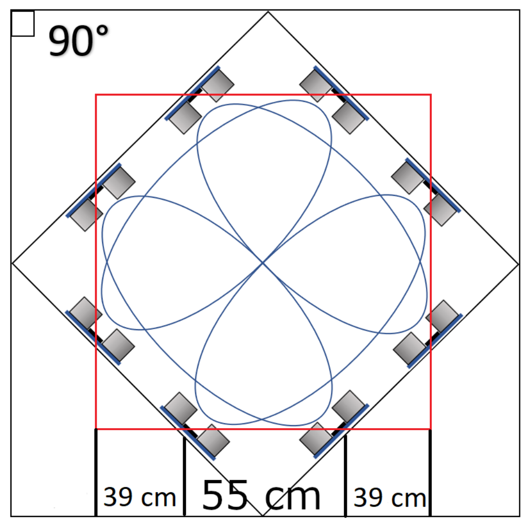


Figure 6: Setup 2D Localisation Experiment

Two sensors per side were placed such that both sensors aimed inwards with a 45-degree angle. The distance between every two sensors on the same side was 55 centimeters. The distance between two sensors on the same line was also 55 centimeters. The shape of the setup is an octagon with sides of 55 centimeters. 133 - 55 = 78 = 2 times 39 centimeters. So the outer sides of the square are both 39 centimeters.

Formulas were utilized to calculate the position of the moving object. The formulas were derived from these equations for triangulation in 2D space:

$$(x - x_1)^2 + (y - y_1)^2 = r_1^2 \tag{2}$$

$$(x - x_2)^2 + (y - y_2)^2 = r_2^2 \tag{3}$$

$$(x - x_3)^2 + (y - y_3)^2 = r_3^2 \tag{4}$$

These formulas can be reduced to a formula for x and y which are the coordinates of the moving object. r_k is the distance from sensor k to the object with k being a positive integer. x_k and y_k are the coordinates of sensor k itself. This equation must be solved for at least three sensors. Because this formula is difficult to rewrite for x and y, a coordinate system was used to make that easier. As seen in Figure 6, the sensors are all aligned on the red square. This red square eliminates some of the problems with rewriting Equation 2. We calculate a position in this coordinate system using three sensors. At least two of those sensors are on the same straight red line. The origin point is indicated by the red circle in the top right. All sensors' positions will be expressed as (x,y) using the measurements of our setup.

As an example, we use sensors 2, 3, and 5 to calculate the coordinates. The example is shown in Figure 7. The corner with the red dot is our origin point. Sensors 2 and 3 are on the y-axis. The axes are rotated 180 degrees. The coordinates of the sensors are (0, a), (0, a + c) and (a + c, 2a + c) where a = 0.39 and c = 0.55.

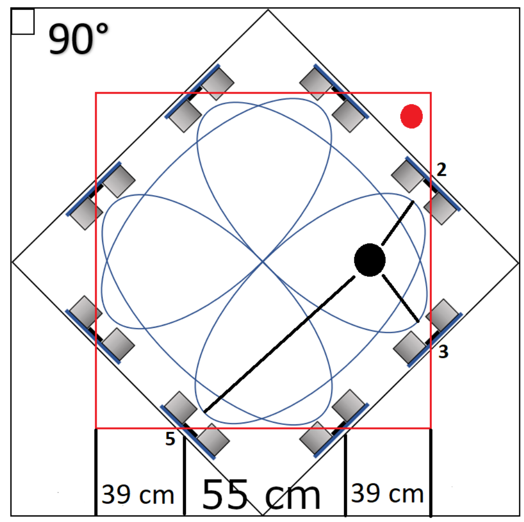


Figure 7: Example 2D Localisation Experiment

All the zeroes in the coordinates simplify the equations and rewrite them to x and y in just a few steps. After rewriting for x and y, the equations become Equation 5 and Equation 6. We have all the information to fill in these equations and get the position of the moving object. Every combination of three sensors has a different system that needs to be solved because the sensors have a different location as well.

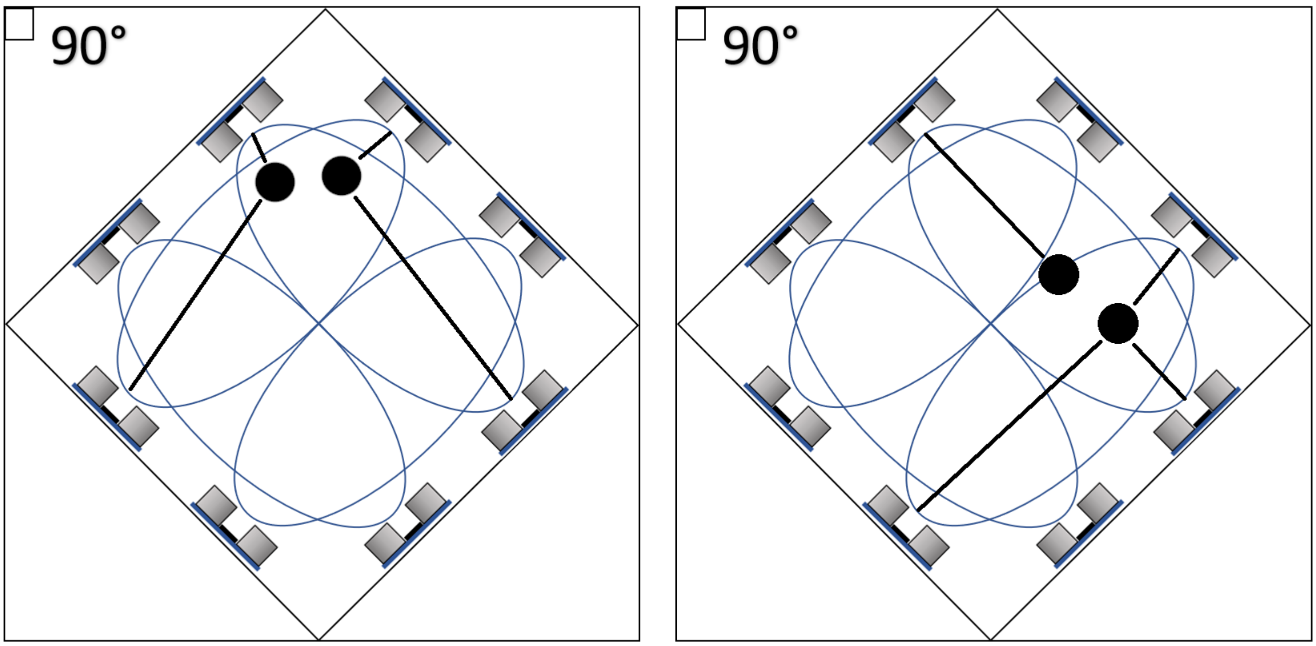
$$y = \frac{r_1^2 - r_2^2 - a^2 + (a+c)^2}{2c} \tag{5}$$

$$x = \frac{r_1^2 - r_3^2 - a^2 + (a+c)^2 + (2a+c)^2 + y * (2a+2c)}{2a+2c} \tag{6}$$

3.8.1 Multiple Objects

Initially, a reflective method was implemented for all experiments. However, during our experiments, we gained new insights on how to approach the problem of locating multiple objects. We experimented with the reflective method but found that this method was not well-suited for this particular problem because incidentally, the sensors only receive one reflected signal. The HC-SR04 sensors are designed to stop measuring once a signal is received. Only the closest object is measured and other objects behind it will not be taken into account.

As seen in Figure 8a and Figure 8b, some of the configurations would be difficult to accurately determine. In Figure 5a, the two objects both do not have enough measurements to determine their location. At least three measurements are needed to determine an object's location. Since both objects only reflect two signals, this is an impossible configuration. In Figure 5b, one of the objects reflects three signals which means it has enough measurements to determine its location. On the other hand, the other object only reflects one signal which makes it impossible to determine its exact location. When these configurations occur, we can estimate their potential location, but not with the accuracy of the other configurations.



(a) 2D Setup with both objects reflecting only two signals

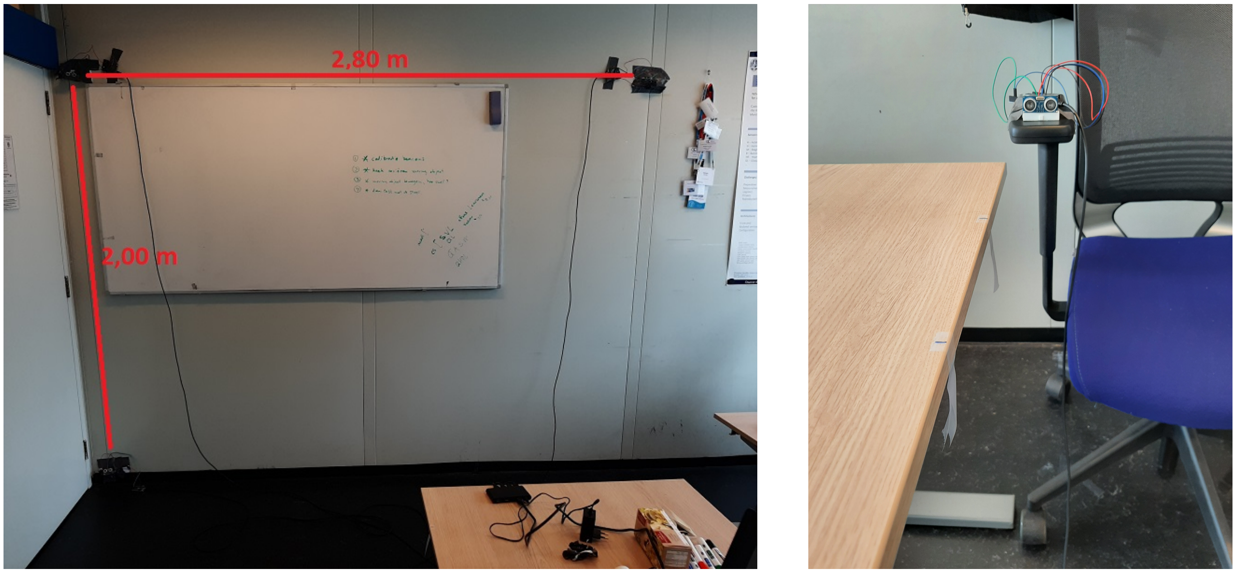
(b) 2D Setup with one sensor reflecting only one signal and one sensor reflecting three signals

Figure 8: Impossible configurations for our 2D setup

3.9 Setup 3D Localisation

For the 3D experiment, we opted for the direct method in the paper by C. Medina et al. [7] instead of the previously used reflective method. The moving object cannot reflect the signals adequately in a 3D space, because of the angle of the signal. The direct method employs an ultrasound sensor placed on the moving object that can receive the signal instead of reflecting it. This method has the added benefit that the reflection angle on the object does not matter anymore. Also, the range of the sensors is now twice as long since the signal does not have to reach the sensor that transmitted the signal.

In Figure 9a, the sensors are shown in the setup and their x, and y dimensions. Three sensors were attached to the wall and aimed towards the middle of the room. The higher two sensors were aimed down in a 30-degree angle and the lower sensor was aimed up in a 30-degree angle. In Figure 9b, the receiving sensor is shown attached to a chair 80 centimeters above the ground. The chair was moved around during the experiment.



(a) Office of Richard van Dijk with 3 sensors set up in 3 different corners

(b) Receiving sensor attached to a moving chair

Figure 9

In Figure 10, the configuration of the experiment is shown in a 3D schematic. S1, S2 and S3 are the transmitting sensors. M is the moving object with the receiving sensor. R1, R2 and R3 are the distances measured between the transmitting sensors and the moving object.

To calculate the coordinates of the moving object, Equations 7, 8 and 9 are derived using Pythagoras Theorem. In these calculations, m_x, m_y and m_z are the coordinates of M. r_1, r_2 and r_3 are the distances between S1, S2 and S3 and the moving object. t_x and t_y are the distances between sensors S1, S2 and S3. As seen in Figure 9a, t_x = 2,80 m and t_y = 2,00 m.

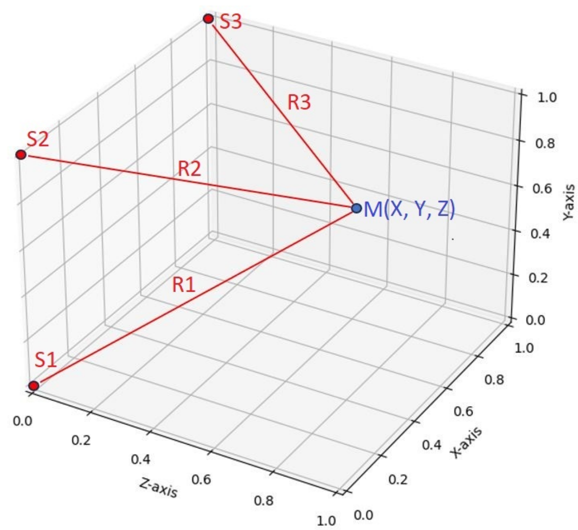


Figure 10: Sensor Placement in the 3D Localisation Experiment

$$m_x^2 + m_y^2 + m_z^2 = r_1^2 \tag{7}$$

$$m_x^2 + (m_y - t_y)^2 + m_z^2 = r_2^2 \tag{8}$$

$$(m_x - t_x)^2 + (m_y - t_y)^2 + m_z^2 = r_3^2 \tag{9}$$

m_x, m_y and m_z need to be isolated to be able to solve the equation. For m_y, Equation 7 minus Equation 8 needs to be solved. After simplification that can be rewritten as equation 10. m_x can be isolated by subtracting Equation 9 from Equation 7 and rewritten as Equation 11. We need m_y to solve this equation. Lastly, Equation 12 is derived from Equation 7 and is solved using m_x and m_y. Only positive axes are used in our coordinate system, so m_z will always be positive in this experiment.

$$m_y = \frac{r_1^2 - r_2^2 + t_y^2}{2t_y} \tag{10}$$

$$m_x = \frac{r_1^2 - r_3^2 + t_x^2 + t_y^2 - 2t_y m_y}{2t_x} \tag{11}$$

$$m_z = \pm\sqrt{r_1^2 - m_x^2 - m_y^2} \tag{12}$$

With this setup, multiple experiments were executed to calibrate the sensors, to locate the moving object over a period of time and to explore upscaling possibilities.

3.10 Upscaling

To explore the possibility of a large-scale ultrasound indoor positioning system, a few experiments were conducted to measure the optimal angle and position for the sensors. The parameters for an optimal setup may differ from our setup, so the angles in which the sensors were directed need to be examined.

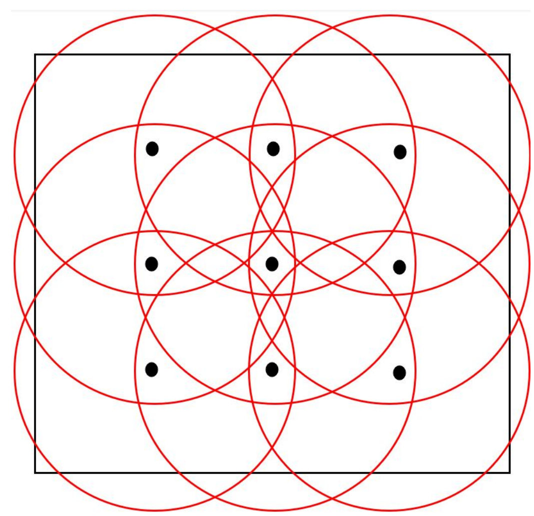


Figure 11: Possible scale-up architecture

One possible scale-up architecture is shown in Figure 16. The black dots are 360 degree sensors on 2,00 m high poles. The same height as our sensors in the 3D experiments. The red outline is the reach of the sensors. To create this architecture, the amount of sensors needed to create a 360 degree angle needs to be determined. The optimal distance between these sensor poles should also be determined.

3.11 Software

The software can be found on Github[5]. To run the software, a few libraries need to be installed. The libraries needed are matplotlib [11], numpy [12], pandas [13] and pySerial [14].

First, a function was implemented to save the all the readings of the sensors in a span of 30 seconds and show them in a graph. The data that was extracted from the sensors was stored in .csv files. The .csv files were loaded in to calculate the position using a function. The function based on the triangulation formulas (Equations 2, 3 and 4) and its derivations was used to transform

[5]https://github.com/LiacsProjects/UltraSoundlocalisation

the distances measured by the sensors into a position for the moving object and display that position in a scatterplot. The code for 2D localisation and 3D localisation were located in separate files.

Data was extracted from the sensors using the Arduino Integrated Development Environment (IDE). A program was written in the Arduino IDE which sent signals through the HC-SR04 sensors using the NewPing Arduino IDE library [9]. This library had a useful method to measure distance and was easy to use. The method is called sonar.ping_cm() which returns the distance in centimeters. The baud rate was set to 19200, because the speed of communication over the serial monitor in the Arduino IDE with the default rate of 9600 was too slow to get accurate measurements.

4 Experiments

4.1 Overview of the experiments

Motion detection experiments were used to determine the HC-SR04 ultrasound sensor's accuracy of depth perception and its measuring angle as mentioned in the HC-SR04 User's Manual. After that the sensors were calibrated by measuring the actual distances to the object at different locations and comparing those distance to the measured distances by the sensors. Then, the range profiles were determined by finding the edges of the area where the sensor measured accurate distances using the reflective and direct method. The sensor range profiles provided a basis for the setup for the 2D and 3D localization experiments. The sensor range profiles indicated the ideal position for the sensors and the optimal coverage for our localization experiments. This coverage was ideal because the sensors covered the largest area possible while having at least 3 sensors cover every part of the area. This is necessary to be able to use the trilateration formulas.

4.2 Motion Detection experiments

An experiment was conducted using two sensors placed opposite to one another to measure their absolute distance to an object between the two sensors. This experiment was to test the depth perception of the HC-SR04 sensors. The object used was a book, because of its flat surface and large surface area. The object was then moved during the experiment to see if the distances measured by the two sensors added up to the same integer.

The second experiment was to test the measuring angle of the HC-SR04 sensors. The second experiment was conducted using 3 sensors, all at an 30 degree angle from each other relatively. According to the user's manual of the HC-SR04 sensor, the best measuring angle is 30 degrees. This makes the total angle we measure 90 degrees. The object was then moved in front of these 3 sensors such that the object went back and forth from side to side until each sensor was passed three times.

4.3 2D Localisation Reflective Method experiment

To calibrate the sensors we measured the distance from each transmitting sensor to the receiving sensor with a measuring tape. We then measured the distance using the sensors and the reflective object to examine the difference.

The trajectory of the moving object was tracked during a circular movement within the x-axis and y-axis to investigate the coverage of the sensors.

4.4 3D Localisation Direct Method experiment

To calibrate the sensors we measured the distance from each transmitting sensor to the receiving sensor with a measuring tape. We then measured the distance using the sensors to examine the difference.

For the localization experiment, we used adhesive tape to indicate the distance along a bureau. The distance between the bureau and the wall was 140 centimeters on the x-axis and 144 centimeters on the z-axis. Every 20 centimeters, a piece of adhesive tape was placed on the side of the bureau along the z-axis. Then, we measured the distance at every piece of tape for a few seconds for 30 seconds total.

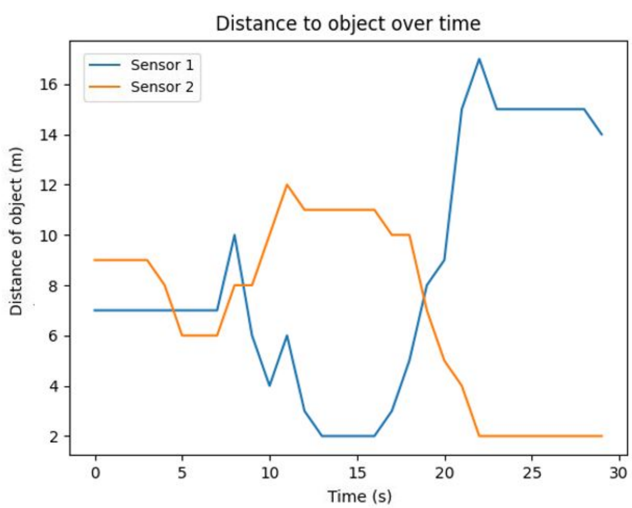
The trajectory of the moving object was tracked for 30 seconds during a circular movement within the x-axis and z-axis to investigate the coverage of the sensors.

5 Results

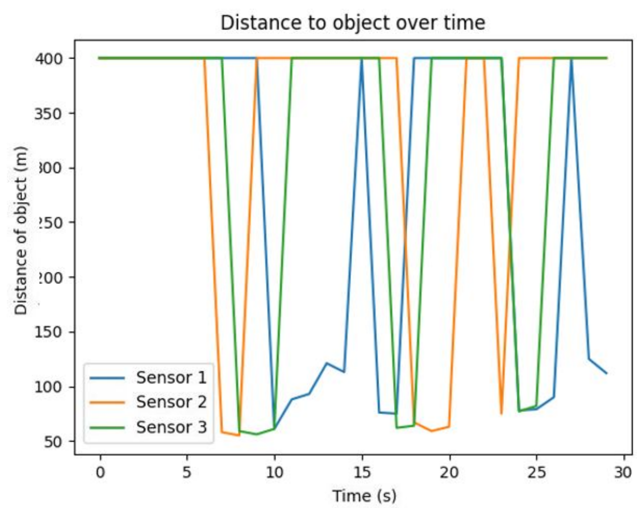
5.1 Motion Detection HC-SR04

As seen in Figure 12a, the distances measured by the two sensors are not error-free, but as expected when sensor 1 gets closer, sensor 2 gets farther away and they add up to the same integer with a minor average error. The average error was under 2 centimeters.

Figure 12b shows how 3 sensors in a 30 degree angle relative to each other measure the moving object going back and forth side to side. The sensors properly track the object when it passes the sensors three times. Once sensor 1 can not track the object anymore, sensor 2 takes over. And once sensor 2 stops tracking the object, sensor 3 has overtaken the tracking of the object. The best way to place the sensors next to each other is in a 30 degree angle. Other degrees of angles were experimented with but have too much overlap or have gaps where the sensor cannot track the moving object. The angles were measured with a protractor triangle.



(a) Motion Detection with 2 Sensors



(b) Motion Detection with 3 Sensors

Figure 12: Experiments Motion Detection with 2 and 3 Sensors

5.2 2D Localisation Reflective Method

During calibration, he sensors differed 0-3 centimeters from the actual distance. As seen in Figure 13, we moved the object in a circular-shaped trajectory for the 2D localisation experiment. The moving object's trajectory was fully tracked by the sensors but contained a few small errors.

The actual position of the moving object was partly estimated. The actual location of a few points were measured and can be compared to the measured location. Four points in a rectangular shape inside the 1.3 m^2 area were measured and can be compared to the measurements. The total error over all four points that were compared was 5.18 centimeters. So the average error per point is 5.18 / 4 = 1.30 centimeters. The four corners are well covered by the sensors, so that explains the low average error.

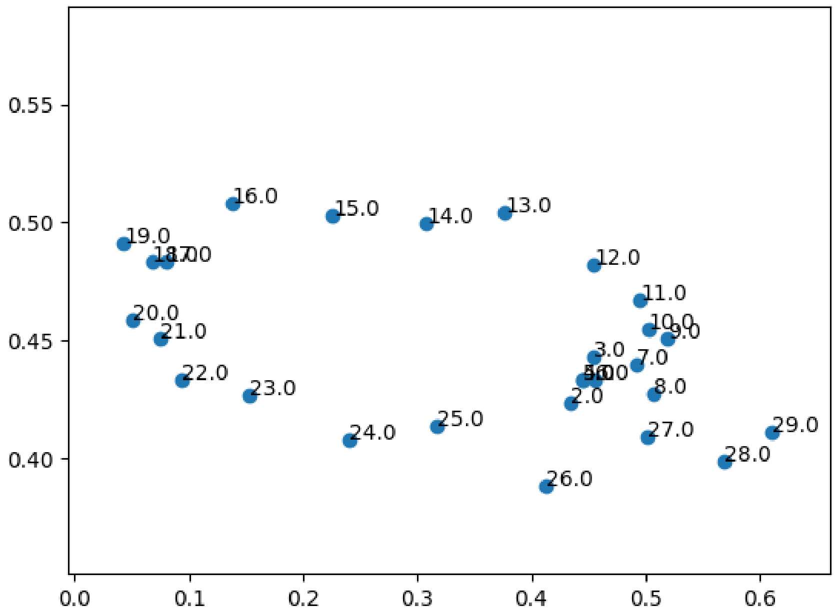


Figure 13: Scatterplot 2D Localisation of Moving Object over Time. The data points are annotated with the time of the measurement

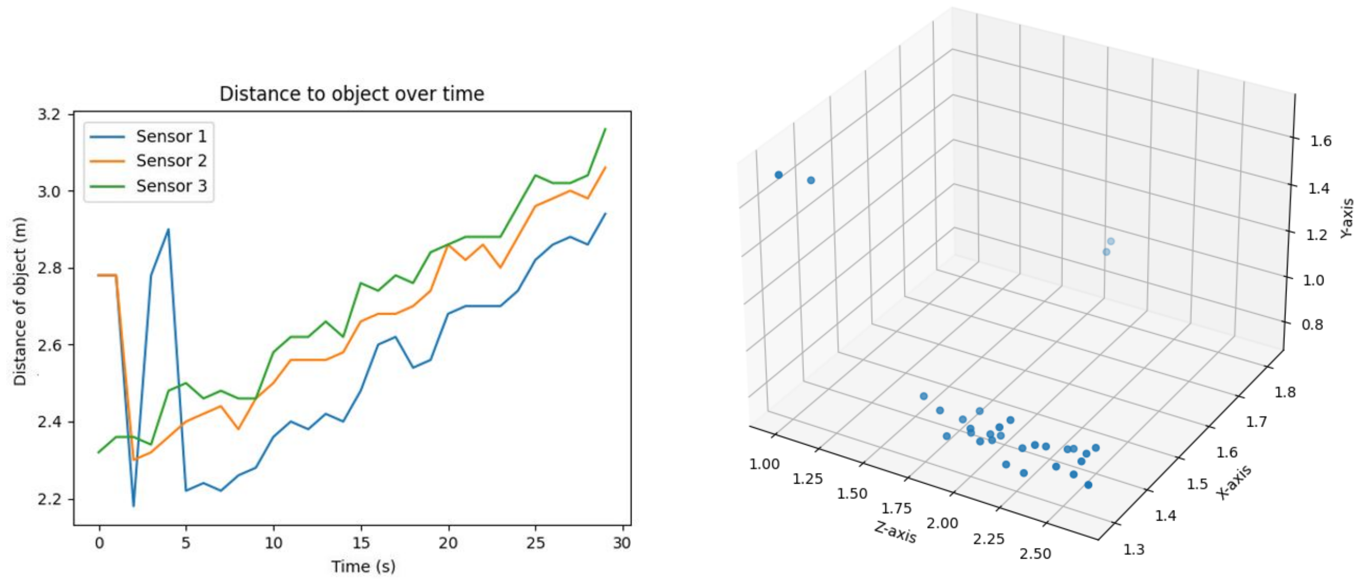
5.3 3D Localisation Direct Method

During calibration, the sensors differed 0-3 centimeters from the actual distance. As shown in Figure 14a, the sensors are not accurate for the first five seconds of the experiments. The chair is too close to the wall to receive all signals directly. After the first five seconds, the receiving sensor catches on to the transmitting sensors and manages to locate the moving object to a certain degree.

In Table 1, the results of Figures 14a and 14b, the estimated position and the measured position of the points are shown. The total error over all 30 points in the z-axis is 3.28 meters, divide by 30 points gives an average error per point of 0.1093 meters = 10.93 centimeters. The first few points are very inaccurate and therefore increase the average error.

The points in the scatterplot are the position of the moving object at that moment. The 3D scatterplots were cluttered when the time of each point was added, so the time was left out for the 3D scatterplots.

Figures 15a and 15b show the results of tracking the trajectory of the moving object in 3D space. Figure 15a shows that sensors 1 and 2 were inaccurate for 6 seconds each. Still, sensors 1 and 2



(a) Graph of Distance Sensors over time in 3D Localisation Experiment

(b) 3D Scatterplot of localisation over time in 3D Localisation Experiment

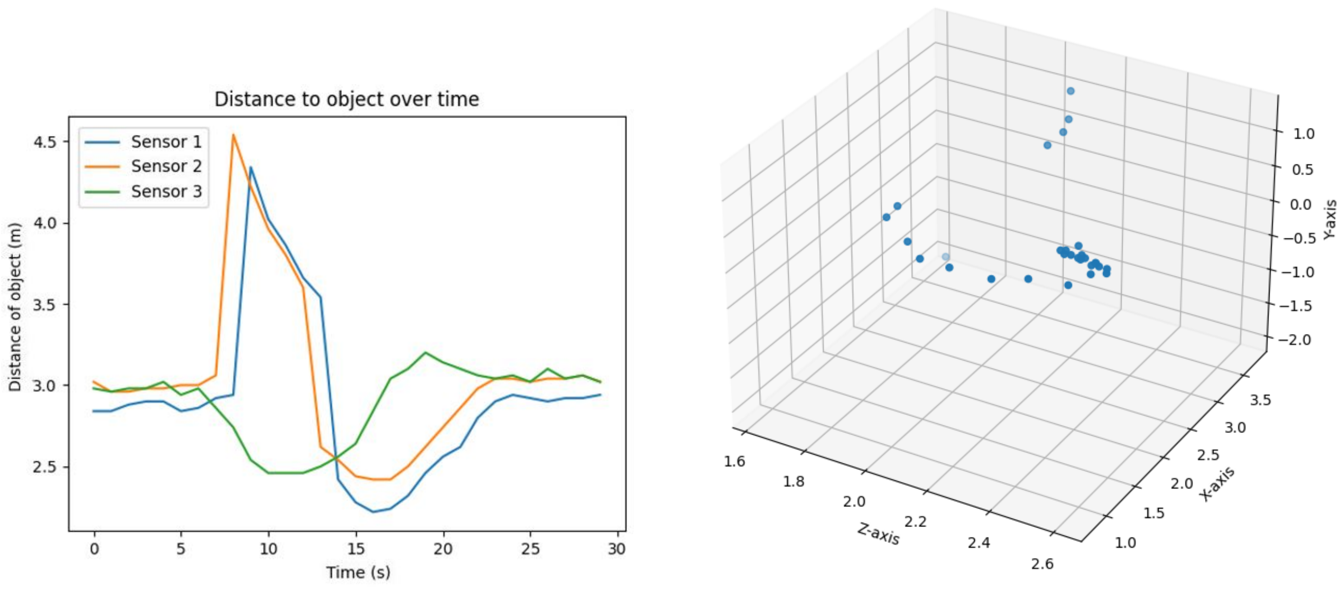
Figure 14

noticed movement in the moving object during those 6 seconds. This indicates that the signal reached the receiving sensor, but in an indirect way. Ultrasound echoes that bounce off the ceiling and walls distorted the trajectory shown in Figure 15b. We still see part of the circular motion, but because of the inaccuracies, the trajectory could not be fully tracked.

5.4 Comparison 2D and 3D Localisation

The Pros and cons of the 2D and 3D localisation experiments have been determined and are shown in Table (2. These pros and cons were determined by literary research and experiments. 2D localisation has fewer errors in the distance measurements and positions than 3D localisation. Also, 2D localisation is better at tracking trajectories than 3D localisation. This may be caused by the fact that the 2D experiments were executed on a smaller scale than the 3D experiments. 3D localisation is more susceptible to being upscaled because 3D localisation covers a larger area with the same amount of sensors.

The detection of objects behind obstacles and the detection of multiple objects are important factors to consider as well. In literary research, 3D localisation is often preferred when tasked with these problems. 2D localisation has the benefit that, for detection of objects behind obstacles, reflected signals bounce off of objects in a 2D space and not in a 3D space. Using no-line-of-sight signals to calculate the location of an object is difficult but possible as shown in [6].



(a) Graph of Distance Sensors over time in 3D Movement Experiment

(b) 3D Scatterplot of Circular Movement over time in 3D Localisation Experiment

Figure 15

5.5 Upscaling

Following from the HC-SR04 user's manual and Figure 12b, the measuring angle of 30 degrees is optimal. To implement the possible scale-up architecture, 12 sensors are needed per pole for a 360 degree angle. The optimal distance between the sensor poles depends on the method of measuring distances. Using the reflective method, the poles should be at most 2 meters apart, because the signal needs to be reflected and the range of the signal is 4 meters. Using the direct method, the signal does not need to be reflected and therefore the poles should be at most 4 meters apart.

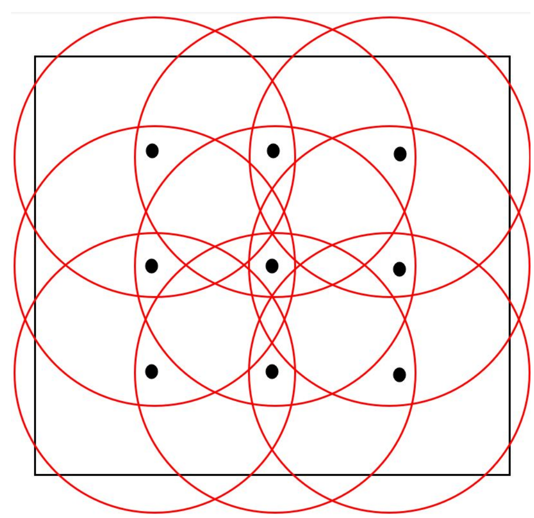


Figure 16: Possible scale-up architecture, 16 x 16 meters, each black dot is a pole at a height of 2 to 3 meters with 12 sensors.

This architecture does not cover the entire room, because at least three distances need to be determined to calculate the location using trilateration. Estimating the moving object's location using only 1 or 2 sensors could be possible, because of the limited spatial sensitivity of one sensor. Then, the accuracy of the locations measured by only 1 or 2 sensors will decrease. To use trilateration in the whole room, more sensors are needed in the corners.

Estimated Position and Measured Position of Moving Object (m)						
Time (s)	x (estimated)	y (estimated)	z (estimated)	x (measured)	y (measured)	z (measured)
0.0	1.40	0.80	1.44	1.818929	1.0000	1.849297
1.0	1.40	0.80	1.44	1.785500	1.0000	1.881592
2.0	1.40	0.80	1.64	1.350071	0.8656	1.648649
3.0	1.40	0.80	1.64	1.383357	1.5865	0.975572
4.0	1.40	0.80	1.64	1.296286	1.7101	0.982243
5.0	1.40	0.80	1.84	1.312500	0.7921	1.846597
6.0	1.40	0.80	1.84	1.365143	0.7903	1.835269
7.0	1.40	0.80	1.84	1.364857	0.7437	1.880871
8.0	1.40	0.80	1.84	1.330857	0.8608	1.775456
9.0	1.40	0.80	1.84	1.400000	0.7867	1.863519
10.0	1.40	0.80	2.04	1.327429	0.8299	1.949154
11.0	1.40	0.80	2.04	1.344500	0.8016	2.025675
12.0	1.40	0.80	2.04	1.344500	0.7777	2.034970
13.0	1.40	0.80	2.04	1.306786	0.8257	2.040620
14.0	1.40	0.80	2.04	1.362857	0.7759	2.048658
15.0	1.40	0.80	2.24	1.303214	0.7687	2.187769
16.0	1.40	0.80	2.24	1.341929	0.8944	2.140485
17.0	1.40	0.80	2.24	1.302500	0.9205	2.153735
18.0	1.40	0.80	2.24	1.341500	0.7904	2.205821
19.0	1.40	0.80	2.24	1.300357	0.7615	2.288403
20.0	1.40	0.80	2.44	1.400000	0.7507	2.378245
21.0	1.40	0.80	2.44	1.338929	0.8344	2.337402
22.0	1.40	0.80	2.44	1.379500	0.7776	2.381579
23.0	1.40	0.80	2.44	1.318857	0.8625	2.314457
24.0	1.40	0.80	2.44	1.316571	0.8033	2.432231
25.0	1.40	0.80	2.64	1.314286	0.7977	2.529413
26.0	1.40	0.80	2.64	1.357143	0.8248	2.521561
27.0	1.40	0.80	2.64	1.378500	0.8236	2.534052
28.0	1.40	0.80	2.64	1.335500	0.8248	2.533090
29.0	1.40	0.80	2.64	1.288929	0.8200	2.651389

Table 1: Accuracy Table

	Pros	Cons
2D Localisation	Less errors in distance measurements Better at tracking trajectories	More sensors needed Smaller area covered Harder to expand
3D Localisation	Less sensors needed Larger area covered Easier to expand	More errors in distance measurements Worse at tracking trajectories

Table 2: Pros and Cons Table

6 Conclusions

We determined the location of a moving object using 2D and 3D localisation. We used trilateration formulas based on Time-of-Flight measurements of ultrasound waves through air to calculate the location. We determined the location of the beacons using measuring tape since it was a small-scale setup.

The best object for the reflective method was cylindrical because of its capacity to reflect signals to multiple directions. The mug reflected the signal stronger than the bottle. The downside to a cylindrical object is the calibration errors. Following the sensor range profile of the reflective method, a 1.3 m^2 area was utilised as it was the largest, but still accurate 2D setup that could be created. The direct method can cover more area per sensor, because the signal only has to arrive at the moving object and does not have to be reflected back to the transmitting sensor. This makes it more suited to large-scale localisation.

2D localisation had an average error of 1.30 centimeters and 3D localisation of 10.93 centimeters. 3D localisation is preferred for locating moving children in a playground, because 3D localisation covers a way larger area with the same amount of sensors and is therefore more suited for a more large-scale project. The average error of the 3D localisation is believed to be higher, because there is more room for errors measuring longer distances. Also, 3D localisation causes reflections via the ceiling and ground since the sensors are angled down or up. Indirect signals distort the distance measurements which cause more inaccuracies. This is a downside to 3D localisation.

A possible scale-up architecture should use a measuring angle of 30 degrees per sensor and a measuring distance of at most 4 meters using the direct method. All sensors must be positioned 30 degrees relative to the other sensors. Consequently, the scale-up architecture can maximize the area this ultrasound indoor positioning system can cover.

6.1 Future Research

Future projects could scale the 2D and 3D localisation setups to a larger area. To scale this ultrasound indoor positioning system, the devices should be extended with wireless sensors. This could be achieved by buying add-ons for the Arduino that implement, for example, WiFi. A large number of USB-cables in a large-scale project could not all be connected to the same computer, so wireless sensors are necessary.

Removing miss measurements could decrease the average error and increase the accuracy of the moving object's position. Outliers in the data should be trimmed and an estimate should be made for the location based on its surrounding data points. Another way to increase the accuracy the area covered by sensors is to use sensors with larger range profiles or bigger measuring angles.

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