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Solutions for presence detection in an intercom door station

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Abstract

In this work, different solutions for human presence detection in a door intercom device are examined. The study was conducted at a company in Lund, Sweden. The aspiration was to have a reliable presence detection to be able to put the device in sleep mode when not used, and the current solution is not optimal because of limiting design requirements and false triggers. In the project, several different sensor technologies and sensors were examined and evaluated. After an initial selection, four different sensor technologies were studied and six different sensors using these technologies were investigated and examined both theoretically and practically during tests. The sensor technologies explored were passive IR, active IR, ultrasonic and radar. With the knowledge gained during the investigation and experiments, the different sensors suitability for the project were discussed and evaluated.

The technology most appropriate for this project was found to be radar, due to its ability to easily be installed and integrated inside the intercom since it can function through a lot of materials, including the hardened glass found on the device. While the first radar sensor that was tested demonstrated the potential of the technology, it was found to be a bit too simple. There are a lot of sophisticated radar sensors available but after much investigation the one ultimately chosen was the 60 GHz Acconeer A121 Pulsed Coherent Radar Sensor due to its compatibility with the specific use case. This sensor allows for a much smarter presence detection than the one currently used in the intercom. After testing and learning about the sensor it was concluded that it could be integrated into the intercom's PCB and function through the hardened glass panel on the front. This makes it much easier to implement than the currently used solution by having less limiting requirements on the mechanical design of the intercom. The sensor enables more efficient presence detection because of the ability to activate only when someone approaches, and filtering out unwanted triggers with the help of the sensor's high accuracy.

Preface

This work was performed in partnership with a company during the spring of 2023 in an effort to improve the current method of presence detection in their intercom products. Authors Anton Bengtsson and Måns Andreasson worked collaboratively and equally on every part of the project. The study was conducted in Lund, Sweden.

Acknowledgement

We would like to thank the company for giving us the opportunity to conduct our master thesis with them. We would also like to thank Johan Björnstedt, our supervisor at Lund University for supervising and helping us with the project. Last but not least, we would like to express our gratitude to our company supervisor Alexander Holmström, Vasilios Spiropoulos, Hedvig Sannar and the rest of the department for welcoming us to the team and taking their time to assist us in every way possible with the project.

Contents

Abbreviations

D-PIR	Digital Passive Infrared
FOV	Field of View
GUI	Graphical User Interface
HPF	High pass filter
IR	Infrared
I2C	Inter-Integrated Circuit
LED	light-emitting diode
LPF	Low pass filter
LSB	Least significant bit
MCU	Microcontroller Unit
MSB	Most significant bit
PCB	Printed Circuit Board
PIR	Passive Infrared
RLG	Radar loop gain
SCL	Serial Clock
SDA	Serial Data
SNR	Signal-to-noise ratio
ToF	Time-of-flight

1 Introduction

This project was done in cooperation with a company in Lund, the company produces many different products but the one this project focused on was a door intercom device. This is a smart intercom device used beside front doors on the outside of commercial buildings to let people in. Today the intercom uses a dual element type pyroelectric PIR (passive infrared) sensor to detect human presence. This is done to be able to put the intercom into sleep mode when no one is close to it. There are several big advantages to this. It reduces the heat produced and power consumed in the device by shutting down functions when not needed. This can increase the life span of the product by keeping the components cooler, reduce energy costs, etc. It can also pull attention to the user by lighting up the display when their presence is detected.

The current PIR solution has a few problems. Using PIR limits the placement of the sensor because infrared light can't travel through most materials. To solve this, a special plastic material is used in front of the sensor, but this material is hard to get certified as a weatherproof material and since the intercom sits on the outside of buildings this is not desirable. The fact that the PIR cannot see through most materials also makes the implementation of the sensor limiting for the mechanical design of the intercom. Another problem common for PIR sensors is the amount of false triggers. The plastic cover currently used is not a Fresnel lens, meaning the ability to detect movement is reduced. To counteract this, the sensitivity of the sensor is turned up, which in turn leads to more false triggers. The sensor is especially sensitive to the movement of people walking past the intercom and not even approaching it. If there are too many false triggers, the purpose of the presence detection is lost.

In this project, several different sensor solutions were tested and evaluated. After the first test, it was clear that radar was a good solution for this project. The tested Microwave Doppler Radar sensor is a cheap hobby sensor but it showed promising results for the technology. In the second test, the technology was explored with a more professional sensor. For that purpose, the Acconeer A121 sensor was chosen. This radar sensor gave promising results and was therefore the sensor further explored and ultimately the one that seemed to fit best for this application.

1.1 Objectives

The objective of this project was to examine alternative sensor solutions for presence detection and how to implement them. The way this will be done is to first examine a wide range of sensor technologies and then successively narrow it down until only the best solution is left. The project will focus on how well the sensor technologies work and how feasible they are to implement in the product. The goal is to find a sensor that can improve the presence detection regarding the amount of false triggers and ease of installation. The sensor solution should provide more flexibility for the mechanical design and not come with as many limiting requirements, for example, being able to detect through the glass cover. The existing PIR solution functions as a binary sensor, providing a logical HIGH signal when triggered and a logical LOW signal when not triggered. The ambition is that the new solution will be smarter and allow for better presence detection by ignoring movement that is anything other than a person approaching the intercom.

1.2 Limitations

This project did not actually implement and build a working demo of the solution but did find a solution that seemed good by doing necessary measurements and research. There was no particular focus on the financial aspect or how the logistics around purchasing the sensors will work, but overly expensive sensor technologies were not prioritized. Regarding energy demands for the sensors, there was no extensive analysis done but only feasible solutions that actually save energy when the device is in sleep mode was considered.

1.3 Disposition

This report will begin by going through the theory for the most common presence detection technologies with detailed information on how some specific sensors work. The theory section will explain both the specific sensors used and also how the physics behind the sensors work. Equations for calculations needed when implementing some of the sensors will be presented. In the Methodology section, the way the different tests were done will be explained. How the sensors were connected and what software was used to sample the sensors will be discussed. There will also be pictures showing the test setups and how the tests were done. In the end, there will be some tables with radome calculations. In the Result, graphs from the tests will be thoroughly presented. In the Discussion, the different sensors will be discussed and evaluated based on the theory and results from the tests and lastly, a conclusion based on the whole project will be provided in the conclusion section. At the end of the conclusion, there will be a brief text about recommendations for future work and projects that build on the findings in this report.

2 Theoretical background

In this section different technologies for presence detection are presented and explained. Several sensors using different methods to detect presence are also introduced.

2.1 PIR

A **PIR** sensor is a motion detection technology. It consists of a receiver that can detect the infrared radiation from heat emitting sources. When applying this to humans the interesting wavelengths are mid- and far-infrared radiation in the range of 4-20 µm. In temperature terms this is equivalent to 26-37°C. There are three PIR sensor technologies that could work. Bolometers, thermopiles, and pyroelectrics. In practice the only one widely used in the detection of people is pyroelectrics [1, p.302]. This work will therefore not examine the other two technologies.

2.1.1 Pyroelectric sensor

A pyroelectric sensor is made up of three parts. In the middle there is a pyroelectric material with an electrode in each end. It uses the pyroelectric effect for motion detection. There are two forms of pyroelectric effect. Primary and secondary pyroelectric effect. The primary pyroelectric effect transforms heat flow into electricity. A heat flow will increase the temperature of the pyroelectric material. When the temperature changes it causes the dipoles in the material to shorten or elongate. This gives rise to an induced charge ΔQ_a that can be calculated with equation 1. µ is the dipole moment per unit volume and A is the area of the sensor. µ is dependant on both the temperature T_a and the absorbed thermal energy [1, pp.113-115].

$$\Delta Q_a = A \cdot \mu(T_a, \Delta W) \tag{1}$$

The secondary pyroelectric effect is caused by the piezoelectric capabilities of a pyroelectric. A piezoelectric turns mechanical stress into electricity in the same way that a pyroelectric does with heat. When one of the sides gets a heat flow that side starts to expand. The increase in temperature will make that side expand and cause a lot of mechanical stress. This stress will give rise to an electric charge [1, p114].

All pyroelectrics are also piezoelectric[1, p.302]. In PIR sensors the secondary pyroelectric effect is the reaction that is utilized. This means that if there is any mechanical stress on the pyroelectric sensor it may false trigger due to the piezoelectric effect. This is combated by using two pyroelectric sensors and connecting them so that mechanical disturbances are canceled out as in Figure 1. When the sensor is subjected to an increase in temperature due to IR radiation the atoms in the pyroelectric material (B in Figure 1) positions in a way that makes one of the sides more positively charged and the other more negatively charged. These charges are then picked up by the electrodes (A and C) [1, pp.105-106]. This results in a charge difference in C if the heat flow over the two sides of the sensor isn't equal. The wires to the rest of the circuit are connected to C.

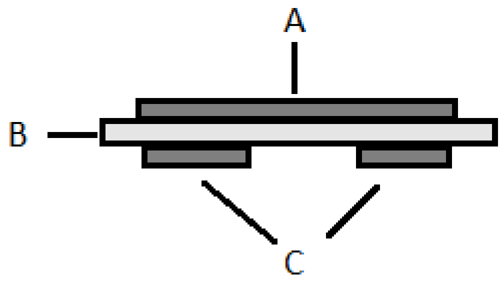


Figure 1: Dual pyroelectric sensor. Outward facing electrodes connected together (A). Pyroelectric element (B). Inward facing electrodes (C)

A lens is added so that different parts of the area visible for the sensor are only visible for one of the sensors or at least much more visible for one of them. This will result in a difference between the amount of charge the two pyroelectric elements produce. The current generated however is very low, for a person moving it is around 1 pA. This means to get a high enough voltage response a big resistor is connected between the two electrodes [1, p304].

By using Stefan-Boltzmanns law the heat radiated from an object to its surroundings can be calculated.

$$\Phi = b\epsilon_a\epsilon_b\sigma(T_b^4 - T_a^4) \tag{2}$$

ϵ is the emissivity of the object and the surroundings, σ is the Stefan-Boltzmann constant. T_a and T_b is the temperature of the surroundings and the object. The emissivity of the sensor is ϵ_s. By simplifying and assuming that both the surface of a person and air are perfect emitters the flux density ϕ of the heat emitted by a persons visible surface area A_{person} at a distance L can be calculated [1, p.306].

$$\phi = \frac{A_{person}}{2\pi L^2}\epsilon_s\sigma(T_b^4 - T_a^4) \tag{3}$$

As can be seen in Equation 3 the flux density depends heavily on the difference in temperature between the person that the sensor is trying to see and its surroundings. This means that a PIR sensor struggles both in really hot temperatures when the ambient temperatures are close to the body temperature of a person. In the same way there might be problems when the weather is colder and people dress up more which also results in a lower temperature delta between the seen surface (the outer side of the clothes) and the enviornment.

2.1.2 Analog PIR Sensor

The original PIR sensor used in the product is an analog PIR sensor. It is a dual element type pyroelectric infrared sensor. The FoV (Field of view) is 90° both horizontally and vertically. Passive infrared light isn't able to pass through glass. Due to this the sensor is currently placed behind a special plastic film that allows the sensor to detect the infrared light. The sensor is implemented in the product with some help circuitry. The analog output from the sensor is converted into either a 1 or a 0 depending on the amplitude of the signal. The now digital signal is then sent to the processor to wake the intercom from sleep mode.

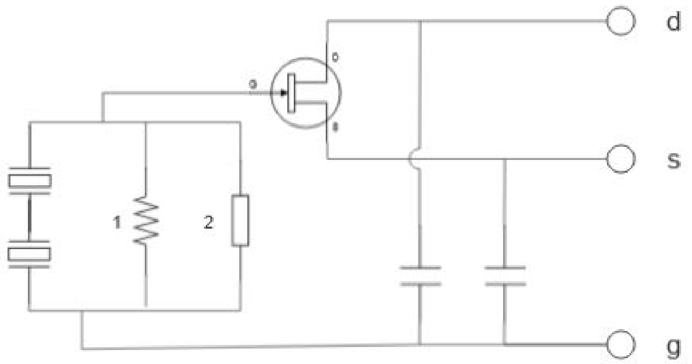
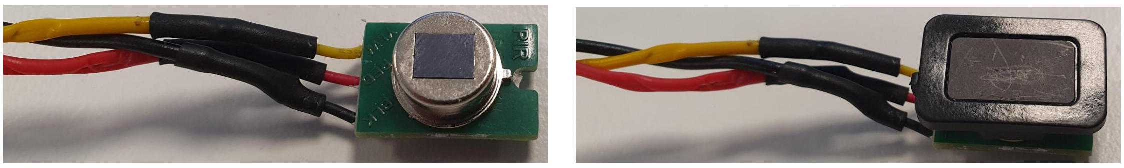


Figure 2: Equivalent circuit for the Analog PIR sensor. 1) Element resistor, 2) Gate resistor [2].



((a)) ((b))

Figure 3: (a) Picture of the Analog PIR Sensor. (b) Picture of the Analog PIR Sensor with the plastic cover used in the intercom on.

2.1.3 D4-323-AA Digital PIR Sensor

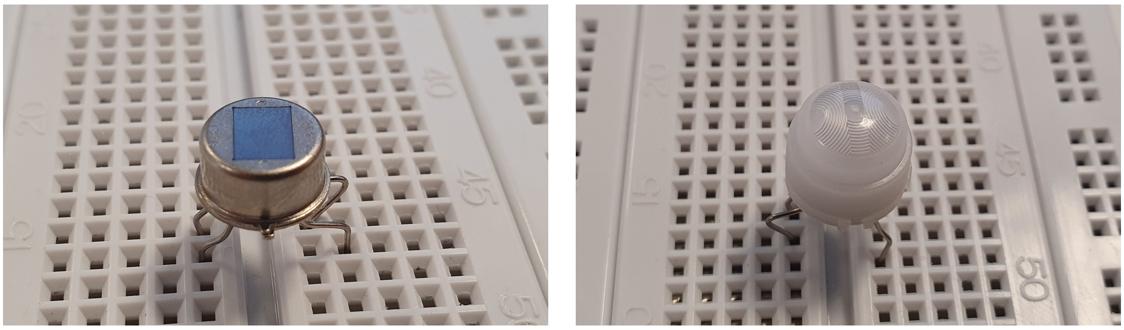
The Nippon Ceramics D4-323-AA is a digital pyroelectric PIR sensor. The FoV is horizontally 134°and vertically 120°. The supply voltage needed is 1.8 to 5.5 V. When the supply voltage is 3.0 V the supply current is typically 3.0 µA with a maximum of 5.0 µA. The sensor is a digital sensor, the conversion from analog signal to digital is done in the sensor itself. The output is a digital 12 bit signal where the MSB (most significant bit) denotes whether the signal is positive or negative. The remaining 11 bits gives a value between between zero and $2^{11} = 2048$. The communication protocol is I2C (inter-integrated circuit). It can be run in either standard mode (100 kbit/s) or fast mode (400 kbit/s). It has an individual ten bit address but it can also be called to with seven bit addressing but then general call (0x00) address has to be used. This limits the amount of other I2C devices that can be connected to it. The sensor has four pins, V_{DD}, SDA, SCL, GND. The recommended pull-up resistance between SDA and V_{DD}, and SCL and V_{DD} is 100 kΩ [3].

Table 1: Table showing HPF (High pass filter) and LPF (Low pass filter) cut-off frequency and the gain for the filters [3].

Filter type	**HPF cut-off frequency**[Hz]	**LPF cut-off frequency**[Hz]	**Typical Gain**[times] (at 1Hz)		
			Step : 1	Step : 2	Step : 3
A	0.4	2.7	104.7	642.8	3713.7
B	0.3	1.5	160.7	1521.2	9134.6
C	0.3	5.0	69.0	279.7	1067.9
D	0.01	100.0	19.7	23.6	28.1

As can be seen in Table 1 there are four different band pass filters. With these the bandwidth and sensitivity of the sensor can be decided in the software. For maximum gain filter B should be used, this also results in the lowest band width. Some balancing is needed between how much gain is needed and the available bandwidth. In practice the bandwidth should be maximized as possible as long as the necessary gain requirements are fulfilled. The threshold for the sensor can also be set. The value can be anything from negative 2040 to positive 2040. The jumps in threshold are however not possible to be smaller than eight counts. This is because only eight bits are used to set the threshold and then it gets multiplied by eight. This allows for setting of the sensors sensitivity in two different ways. Either by just changing the threshold or by changing to a different filter.

A digital output allows for the writing of scripts that makes the PIR sensor "smarter". The digital signal can be sent to an MCU and processed. In this use case, the sensor can be set so that it differentiates between someone coming towards the door and from the door. With the sensor put on a door and someone exiting the building the sensor will start to send out very large values, then as they walk further away the value will decrease. Knowing this the MCU could be programmed to only wake the device up when someone moves towards it. The main upside with a digital PIR sensor compared to an analog sensor in this case is that the conversion from analog to digital is done in the sensor. There is no need for an external analog-to-digital converter.



((a)) ((b))

Figure 4: (a) Picture showing D4-323-AA Digital PIR Sensor. (b) Picture showing D4-323-AA Digital PIR Sensor with a fresnel lens on.

2.2 Active IR

The most common active IR sensor is a light reflection sensor. These use a light source to illuminate an object and then measure the reflection of the light. Usually this is done with a near-IR LED (Light-emitting diode) [1, p.310]. The sensor measures the intensity of the reflected light.

2.2.1 940 nm or 850 nm

The visible light is in the spectrum from 380 to 700 nm [4]. The IR spectrum is in the range 780 nm up to 1 mm [5]. The near IR range is the region of the IR spectrum that is closest to the visible light. Visible light has no problem going through glass. Just like visible light, near IR light goes through glass [6]. When deciding which wavelength to use as there are upsides and downsides to both. The most prevalent is to use a 850 nm wavelength. One downside with this is that there is a red tint from the emitting diode. This isn't the case when using a 940 nm wavelength. There is however a decrease in range and sharpness when using 940 nm [7].

2.2.2 VCNL4200 Active IR Sensor

The VCNL4200 is a dual purpose sensor. It contains both a high sensitivity long distance proximity sensor and an ambient light sensor. For the use of presence detection the proximity sensor is the most interesting. Therefore it will be the part of the sensor that will be examined and the ambient light sensor will be disregarded. The proximity sensor works by sending out IR light with a wavelength of 940 nm from an IR emitting LED. The light then bounces on any objects in front of the LED. The supply voltage is 2.5 V to 3.6 V and the supply current is 350 µA without the LED. The LED supply voltage is in the range of 2.6 V to 5.5 V dependant on if an external FET is used or not, and a maximum current demand of 800 mA. The sensor has a maximum range of 1.5 m [8]. The field of view is 90° however the intensity of an object will be much higher if it is right in front of the sensor compared to if it is to the side. At 30° the amplitude for an object at the same distance will be 40% compared to at 0° [9].

The on/off duty ratio is the ratio between how long the LED is on and how long it is off. It is adjustable and there are four different values it can be. If it is 1/160 it means that for every microsecond the LED is on there are 160 microseconds where it is off. The other possible duty ratios are 1/320, 1/640, and 1/1280. By allowing several (up to eight) pulses per measuring period the range can be increased.

The pulse signal of the LED is 30-270 µs where $30 = T$ and the pulse length needs to be a multiple of T. The maximum amount of pulses that can be programmed in per multi pulse is eight. The main upside with multi pulsing is that it allows for a higher detection range. There is a downside if the amount of pulses is too big and the time for a multi pulse is too long. With a larger pulse duration the maximum allowed forward current is limited [9, p.6]. This means that when using multi pulse with a high forward current the duty ratio might have to be lowered.

When implementing the active IR sensor the first thing to do is decide which current level to use to drive it. The maximum current for the LED is 800 mA. With a 800 mA current the typical forward voltage is 2.5 V [9, p.5]. By multiplying with the on/off duty ratio the average current can be calculated. If the peak current is 800 mA and the duty ratio is the biggest at 1/160 the average current is 5 mA. This is the highest average current that the LED will get since it is the highest current and largest duty ratio for a single pulse. In a case like this the total current consumption would be $5mA + 0.35mA = 5.35mA$ since the supply current without the LED is $0.35mA$.

2.3 Ultrasonic

Ultrasonic waves are sound waves with a frequency over 20 kHz. The audible range for humans is 20 to 20 000 Hz. Therefore ultrasonics are soundless for humans. Certain animals are able to hear the lower range of ultrasonic sound waves such as dogs that can hear frequencies up to 40 kHz [10]. An ultrasonic sensor works by sending out ultrasonic waves with a transmitter and measuring the returning signal with a receiver. To send out the ultrasonic sound wave and measure the returning signal a transducer is used [1, p.274].

2.3.1 Piezoelectric Transducer

A transducer is a device that converts energy from one form into a different form [11]. For an ultrasonic sensor the goal is to convert electrical signals to ultrasonic sound waves and vice versa. To achieve this an ultrasonic transducer is used. The most commonly version used in air is the piezoelectric transducer [1, p.274]. The piezoelectric effect has already been mentioned in subsubsection 2.1.1. The way it works is by transforming mechanical stress into electrical charges. This is utilised in an ultrasonic sensor is by using an oscillating electric field that the piezoelectric element converts into a vibration. This mechanical vibration is enhanced with a diaphragm [1, p.274]. The mechanical vibration is what creates the ultrasonic wave [10]. In the same way when a sound wave reaches the receiver the piezoelectric material starts to vibrate which results in an electric signal which is measured. The same physical phenomena is used just in reverse order when transmitting and receiving. This makes it possible to use a single element that does both [1, p.274].

2.3.2 Time of flight

ToF (Time-of-flight) measures the time t it takes for a sound wave to travel to an object and for the echo to come back to the receiver. It then uses this to calculate the distance L to the object. The angle Θ is the angle that the sound waves emitted from the transmitter bounce of the object before it reaches the receiver. If the transmitter and receiver are the same unit or positioned close enough to each other compared to the measured object $cos\Theta \approx 1$ [1, p.273]. v is the speed of sound in the medium that the waves travel through. Equation 4[1, p.274] can be used to calculate the distance to the object.

$$L = \frac{v\ t\ cos\Theta}{2} \tag{4}$$

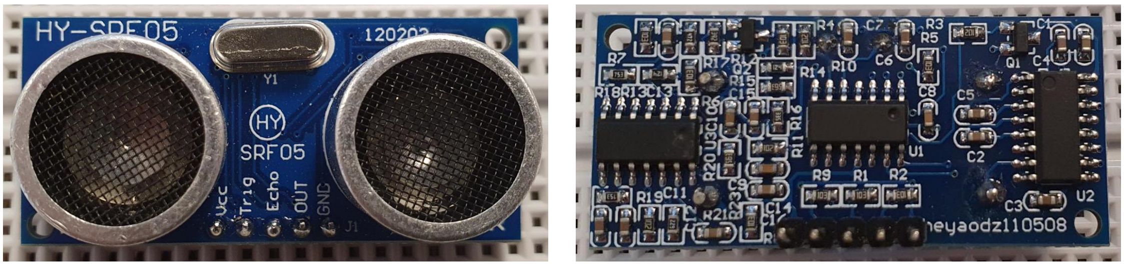
One upside of using sound waves is that the speed is relatively slow. In this project the sound waves will travel through air. The speed of sound waves in air is 343.59 m/s at 20 °C and atmospheric pressure. This however is dependant on the temperature in the air [12, p.486]. Because of the relatively low speed of sound waves the measuring doesn't have to be as precise and can be done much cheaper than for other waves [1, p.274]. A measuring inaccuracy of one millisecond in room temperature results in a 17 cm error. If the speed instead was the speed of light c this would result in an error of almost 150 km.

2.3.3 Doppler effect

Instead of measuring the time it takes for the signal to come back, the frequency of the signal can be measured. If the sound wave has bounced on a static object the frequency will be almost the same as the transmitted signal. However if it bounces on a moving object there will be a difference between the emitted signal and the echo [13]. This is due to the Doppler effect. When something moves towards the sensor the sound waves will be compressed. In the same way when something moves away from the sensor the sound waves will be stretched out. This concept is further discussed in subsection 2.4.

2.3.4 HY-SRF05 Ultrasonic Sensor (1)

The HY-SRF05 is an ultrasonic ToF sensor. The range is measured by sending out ultrasonic sound waves from a transmitter. The sensor then measures the time it takes for the sound waves to bounce from a target back to the receiver which is located next to the transmitter. This is done by sending out eight 40 kHz pulses and checking if a pulse signal bounces back. The measurement range is 2cm to 4.5 m with a measurement resolution of 0.3cm. The supply voltage is 4.5 V to 5.5 V with a supply current of 10 mA to 40 mA. The static current is less than 2 mA [14].



((a)) ((b))

Figure 5: (a) Picture of the frontside of the HY-SRF05 (Ultrasonic 1) sensor. (b) Picture of the backside of the HY-SRF05 (Ultrasonic 1) sensor.

2.3.5 TDK CH201 Ultrasonic Sensor (2)

The TDK CH201 is an ultrasonic range sensor. It utilizes ToF technology. The sensor has one piezoelectric element that it uses for both transmitting and receiving. This means that Equation 4 can be simplified. The sensor also assumes that the speed of sound is constantly 343 m/s, which as mentioned previously is the speed in room temperature. This means that the measurements will be accurate within a few percent depending on the temperature and air pressure [15, p14].

$$L = \frac{t \cdot v}{2} \tag{5}$$

The sensor works by sending out one ultrasonic pulse, and then it waits for it to come back. This measurement is then used in Equation 5 to calculate the distance to the object. When measuring if there is an incoming ultrasonic sound wave it also measures the amplitude and phase of the returning wave. The signal it gets is then sent to the internal microcontroller. The signal is a complex number on the form $(I + jQ)$. The way the amplitude is calculated is by taking the I which corresponds to the amplitude of the signal and the Q value which corresponds to the phase of the signal [15, p9].

$$A = \sqrt{I^2 + Q^2} \tag{6}$$

The values for I, Q, and A are a multiple of the LSB (least significant bit) of the internal analog to digital converter. This value is not calibrated to any standard units [15, p9].

The base settings are that the sensor communicates where the closest target is. If for some reason the target isn't the closest object to the sensor it can be solved with two software solutions.

The first one is *Static Target Rejection*. This setting makes the sensor ignore non moving targets. The way it works is that a moving average high pass filter is applied on the signal [15, pp.16-17]. This works by looking at the amplitude A at each measuring point. If there is no change in the amplitude the sensor ignores that specific point. If instead there is a change in amplitude it can be assumed that there is a moving target in that measuring point. This solution is however not free from problems. By implementing this the sensor gets a bit of latency. This is because the sensor needs to measure a couple of times to be able to see if there is a change in amplitude. If it is very windy the amplitude of a static target can vary which may result in false triggers.

The second solution is to use different thresholds for different ranges. This is a solution that works very well if the environment around the sensor is known previously. An example could be that a big metal pole is situated three meters away in the FOV of the sensor. Then the threshold for that distance could be increased so that it ignores it. There are some guidelines to follow when setting the thresholds. The minimum recommended threshold is 200 LSB and there isn't really any point in setting it higher than 40 000 LSB. It can be set as high as 65 535 but any value above 40 000 means that the sensor will ignore the target. The rest of the zones should have thresholds that are in the range of $\frac{1}{8}th$ to $\frac{1}{4}th$ of the amplitude of the returning ultrasonic wave for the target at that specific zone. The upside with this method is that there isn't the same added latency as for the static target rejection. However as mentioned earlier there is a need to set up each sensor individually depending on their environment [15, pp.25-26].

The size of the sensor is only 3.5 x 3.5 x 1.26 mm. For better signal strength a speaker is added which increases the size to 8 x 8 x 6.18 mm. The supply voltage is 1.8V while the supply current is dependent on the range and number of samples per second. The main component in calculating the power consumption comes from the number of samples. With a range of 1 m and a sample frequency of 1 sample/s the supply current is 7.5 µA. This is increased to 13.5 µA when the range is increased to 5 m. When the sampling frequency is increased to the max of 25 samples/s with a range of 1 m the current consumption increases to 63 µA. The maximal supply current needed is with 25 samples/s and 5 m max range. With these settings the needed supply current is 247 µA [16, p1].

The maximum range of the sensor is as mentioned 5 meters but the ability for it to detect is dependent on the ability of the ultrasonic waves to bounce on the target. This means that the material of the target and the targets size will impact the range. In the application of trying to detect a person the clothes, direction, and size will impact the ability to sense them. In general the maximum distance people can be sensed at is three to four meters away [16, p10]. The size of the sensor is only 3.5 x 3.5 x 1.26 mm. The speaker usually has a 45° housing that focuses the signal. This allows for better detection of smaller targets at longer ranges. [15,p.29]. It also results in the size increasing to 8 x 8 x 6.18 mm.

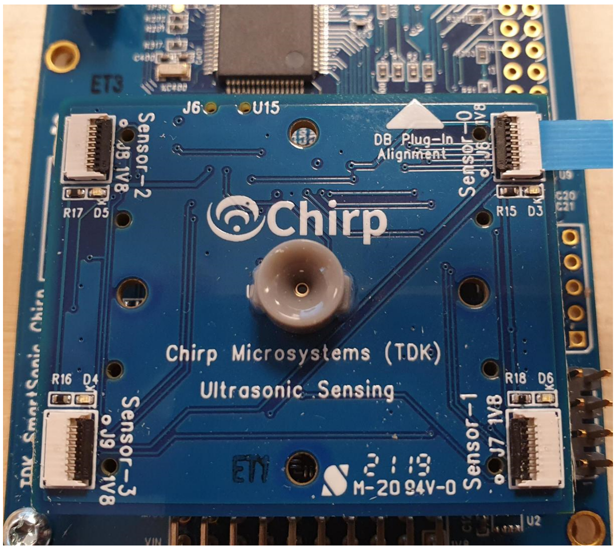


Figure 6: Picture showing the TDK CH201 (Ultrasonic 2) sensor with a speaker mounted on an evaluation board.

2.4 Radar

The word radar was originally an acronym for **Radio Detection and Ranging**. As the acronym tells, radar is an electromagnetic sensor technology that uses radio waves to detect objects in many different ways. It's used in the aviation industry, automotive industry, space industry etc. It can for example be used to locate, track, recognize, detect presence and measure speed of objects. It operates by transmitting electromagnetic radiation toward objects and then receive and observe the reflected waves, the echo, from the object. The object could be anything from insects to planets. Radar is an active sensing technology that has both a transmitter and a receiver.

A broad spectrum of frequencies can be used in radar systems, from a few Hz up to terahertz has been used. The different frequencies enables different use cases. The first radar systems were developed in the 1930s for military purposes. One of the first radars the U.S Army created was an aircraft detecting radar using a frequency of 100 MHz. Modern small presence detection radar sensors use frequencies in about the 3 Ghz to 60 Ghz range. In general, a lower frequency means longer wavelengths which gives higher range and better ability to penetrate through material while a higher frequency means shorter wavelengths and better resolution.

Radar systems typically work by radiating a beam of electromagnetic energy from an antenna towards a target, when the target is illuminated by the beam, it intercepts some of the energy and reflects a portion back to the radar system where the radar can receive it. Most radar systems do not transmit and receive at the same time, so a single antenna is often used for both transmitting and receiving. Antennas can look very different depending on the system, from sizes bigger than houses to sizes that fit on a PCB board. When the reflected wave is received, the time taken for the signal to make the round trip is used to measure the distance. The frequency of the returning signal is used to determine the radial velocity of the target by taking the Doppler effect into consideration [17].

2.4.1 Doppler equations

The Doppler effect equation

$$f_r = f_s \cdot \frac{(v \pm u_r)}{(v \pm u_s)} \tag{7}$$

shows how the reflected frequency f_r depends on the source frequency f_s, wave velocity v, velocity of reflector u_r and the velocity of the source u_s [12, p.519]. In the case of radar sensors, the sensor is using electromagnetic waves propagating at the speed of light , $v = c$. The sensor is fixed, which means that u_s is 0. Equation 7 can therefore be simplified to

$$f_r = f_s \cdot (1 \pm \frac{u_r}{c}) \tag{8}$$

The Doppler effect makes the reflected frequency higher as the reflector moves toward the source. This means that a plus sign is used in equation 8 when the reflector is approaching. The Doppler effect is used in radar systems to calculate the radial velocity of a target by knowing the transmitted frequency, received frequency and velocity of the radar system. Knowing these parameters it's easy to solve for the radial velocity of the target.

2.4.2 Radar & radome equations

The radar range equation gives the maximum range the radar can see R_{max} as

$$R_{max} = \sqrt[4]{\frac{P_s G^2 \lambda^2 \sigma}{(4\pi)^3 P_{e_{min}}}} \tag{9}$$

where $P_{e_{min}}$ is the minimum received power [W] the radar can detect, P_s is transmitted power [W], G is the gain of the antenna [unitless], λ is the wave length [m], σ is the mean radar cross section area(RCS) [m^2] [18]. This equation shows how the received power depends on several factors, for example a doubling of the frequency with all other factors the same will theoretically mean a decrease in range of about 30 % since $\sqrt[4]{0.5^2} = \sqrt{0.5} \approx 0.7$.

When an electromagnetic wave hits the interface between two mediums, some of the energy will go through and some will be reflected. In the case of linearly polarized propagation at normal incidence, the Fresnel equations express the reflection coefficient r by the ratio between the incident and transmitted fields as

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}. \tag{10}$$

When the reflector is a non-magnetic material, then $Z = 1/\sqrt{\epsilon_r}$. In the special case of normal incidence between air and non-magnetic material the reflection coefficient simplifies to

$$r = \frac{1 - \sqrt{\epsilon_r}}{1 + \sqrt{\epsilon_r}}. \tag{11}$$

Where ϵ_r is the relative permittivity of the material. Since conductors have a high relative permittivity ($\epsilon_r \to \infty$), they will give a strong reflection. Polymers typically have a ϵ_r in the range of 2-4 and therefore give a weaker reflection. In the context of radar technologies for small sized sensors, it's often necessary to protect the radar behind a housing. The word "radome" comes from radar and dome and is what the protective material of the radar is called. A radome is a dielectric material that is designed to be transparent to the radar signal while giving a layer of protection from the outside world. By tuning the radome thickness and distance from the radar, the radome can be made transparent and even in some cases enhance the range of the radar.

When there is air on both sides of the dielectric, the total reflection coefficient Γ_1 can be described as

$$\Gamma_1 = \frac{r_1(1 - e^{-2jkd_2})}{1 - r_1^2 e^{-2jkd_2}} \tag{12}$$

where d_2 is the thickness of the radome, $k = 2\pi/\lambda$ is the wave number and r_1 is the reflection coefficient when an incident wave hits the first interface. As the wave leaves the dielectric it hits a second interface and another reflection and transmission takes place but in the case there is air on both sides of the dielectric, this reflection is equal to the negative of the first reflection. Two special cases can be seen from this equation:

For $d_2 = m\frac{\lambda}{2}, m = 1, 2, ...$we have $e^{-2jkT} = 1$ or $\Gamma_1 = 0$. (13)

For $d_2 = m\frac{\lambda}{4}, m = 1, 3, 5...$we have $e^{-2jkT} = -1$ or $\Gamma_1 = 2r_1/(1 + r_1^2)$. (14)

It can be seen that the optimum radome thickness is when it's equal to a multiple of half a wavelength because then $\Gamma_1 = 0$. Similarly when the radome thickness is equal to an odd multiple of a quarter of a wavelength, Γ_1 is at a maximum, meaning there is maximum reflection. Since λ changes inside the material of the radome depending on its dielectric constant the equation for the optimum radome thickness can be written as

$$d_2 = m\frac{\lambda_0}{2\sqrt{\epsilon_r}}, m = 1, 2, 3, ... \tag{15}$$

where λ_0 is the wavelength in vacuum.

As well as the radome thickness, the distance between the sensor and radome also affects the reflection. In the case of a small radar sensor, the reflection from the radome will cause additional reflections from the sensor and PCB and result in a standing wave pattern where the amplitude varies with the distance to the radome. The amplitude will be at a minimum when the reflected wave from the radome is in-phase with the transmitted wave. That means the optimum radome distance d_1 is

$$d_1 = m\frac{\lambda_0}{2}, m = 1, 2, 3, ... \tag{16}$$

Where λ_0 is the wavelength the sensor emits in air, this is only valid if the thickness of the radome is optimum as well [19].

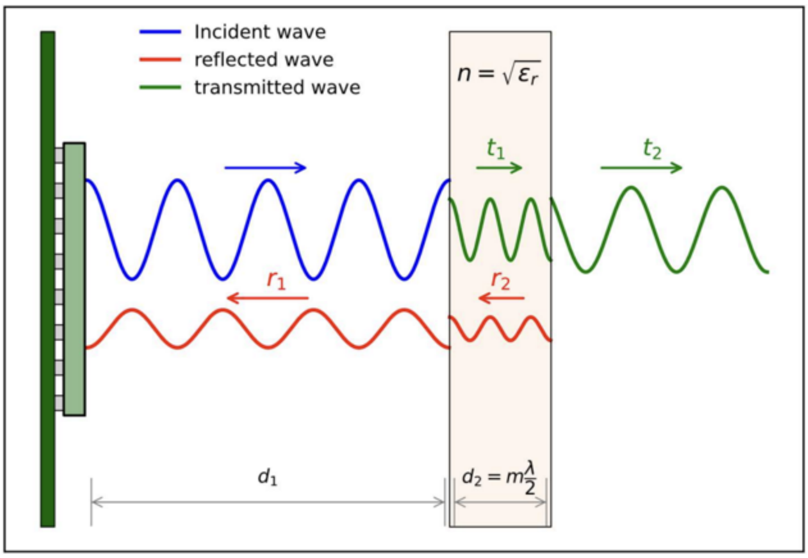


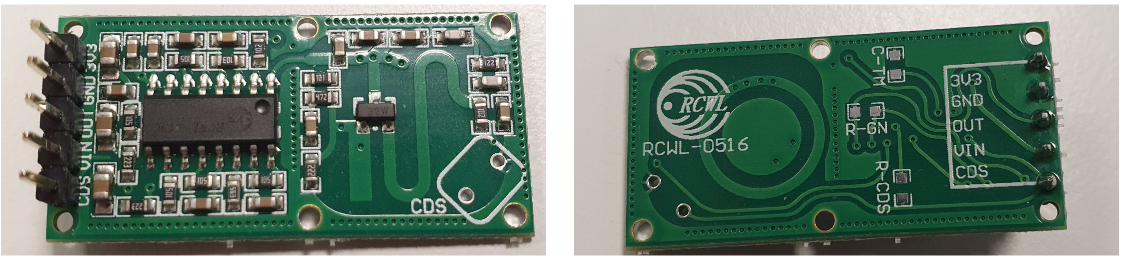
Figure 7: Transmitted and reflected signals from a half wavelength radome. Secondary reflections have been omitted for simplicity [19].

2.4.3 Pulse Radar

Pulse radar systems works by emitting short pulses of radio waves and then wait for the echo. In contrast to a continuous wave radar, the transmitter is turned off between pulses. The pulses are typically very small (typically pulse durations $\tau < 1\mu s$) and the pulse pauses much bigger $T >> \tau$ [20]. In a pulse radar system, the phase relationships between transmitted and received pulses can be either coherent or incoherent. In a coherent system the phase relationship between its oscillation and electromagnetic waves is constant. The system have a highly stable continuous oscillator that synchronizes a waveform generator that outputs the electromagnetic pulses. The pulses consists of small partial sections of the oscillator. This means that the transmitted pulses always have the same phase and frequency as the oscillator. This has several advantages, for example, very small phase shifts of the received echo signal can be detected and used to detect tiny changes in distance. The phase shifts for several pulses can be used to detect Doppler effects and thereby the radial velocity of targets. Coherent radars also have better signal-to-noise ratio than non-coherent systems [21].

2.4.4 RCWL-0516 Microwave Doppler Radar Sensor

The RCWL-0516 is a cheap hobby microwave Doppler sensor that is used to detect movement. The range is at most around 7 m and adjustable downwards by a resistor. Since this sensor uses microwaves of about 3.2 GHz, the waves are able to pass through most materials, excluding metal. The RCWL-0516 is a Doppler sensor and works by transmitting microwaves with a specific frequency and then measuring any change in frequency of the echo. If it detects a change in frequency it means that radial movement has been detected and it triggers the output pin from LOW (0V) to HIGH (3.3 V) for about 3 s. The sensor can't measure the distance, speed or amount of movement of an object, it only detects if there is enough radial movement for it to trigger. The power consumption is typically around 20 mW and maximum 30 mW [22].



((a)) ((b))

Figure 8: (a) Picture of the frontside of the RCWL-0516. (b) Picture of the backside of the RCWL-0516.

2.4.5 Acconeer A121 Pulsed Coherent Radar Sensor

The Acconeer A121 Radar sensor uses pulsed coherent radar technology with a radar frequency of 60 GHz. The range is up to 20 m with an absolute accuracy in mm and a relative accuracy of µm. The radar also works through materials such as plastic or glass [23, p.1].

The way the sensor measures is that it does so-called *sweeps*. It works by setting the start and end distance of the sweep and the distance between each measuring point. The number of points measured impacts memory usage and the time it takes to measure the sweep. This results in higher power consumption due to the longer duty cycles. There is a minimum distance of 2.5 mm. This means that when the step length Δd is 1 it is 2.5 mm. The step length needs to be a multiple of Δd. Therefore the step length is some multiple of 2.5 mm [24]. When measuring there are two values at every measuring point. One is the amplitude and the other is the phase. Using the amplitude, objects can be tracked over long distances. The phase can be used to measure finer motions [25]. This is the reason that the relative measurements are able to be so much more precise than the absolute measurements. In the *Smart Presence* app mentioned more in-depth in subsection 4.2 there is a gesture control application that showcases the sensor's ability to differentiate between different gestures such as tapping in, double tapping, and tapping out. The sensor has different profiles that can be selected. These profiles decide the characteristics of the signals. One of the things it decides is the length of the pulses. With longer pulses there is an increase in SNR (Signal-to-noise ratio). Which allows for a longer time between pulses. The precision is however also lowered and the ability to separate between objects close to each other is reduced [26].

A sweep can be split into several different sub-sweeps. These sub-sweeps can be individually configured. The settings that can be configured are things such as the range and profile. This allows using a profile with longer pulses for longer distances and shorter pulses when the target is closer to the sensor. That would give the ability to have more precise measurements when the target is closer to the sensor while still having good SNR when the target is further away.

Currently, there is legislation in the U.S. that doesn't allow for radar sensors in the 60 GHz frequency band, including the A121 sensor. There is a pending approval for the sensor depending on how the ongoing update of 47 CFR § 15.255 by the FCC goes [23, p.24]. Acconeer estimates that the regulations will be changed during the summer of 2023 which will reduce the limits on installation types and emission levels [27].

Acconeer provides some measured RLG (radar loop gain) patterns in their document *Hardware and physical integration guideline PCR Sensors A111 & A121* [19]. In Figure 9 from that document, Acconeer has measured the RLG pattern for free space (no radome) and a few different radome thickness and distance configurations. It can be seen that the field of view of the sensor is about 90 degrees. Another interesting fact is that with some configurations of radome thickness and distance, the range of the sensor is improved due to constructive interference.

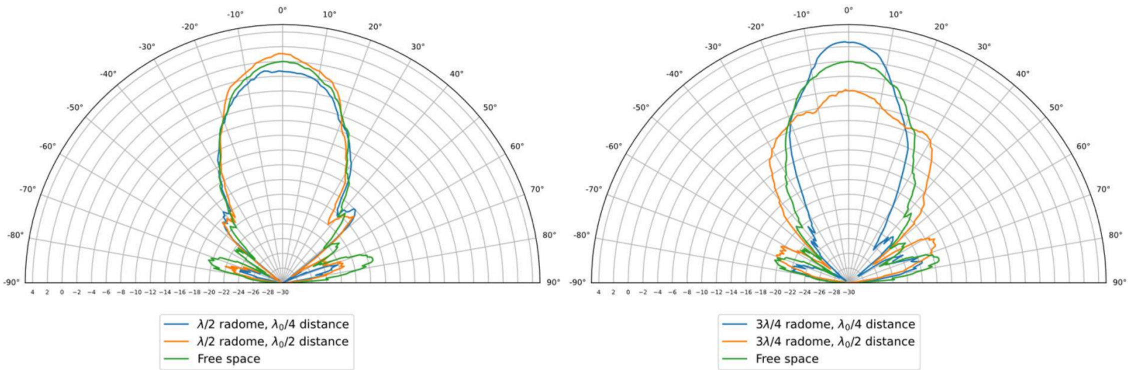
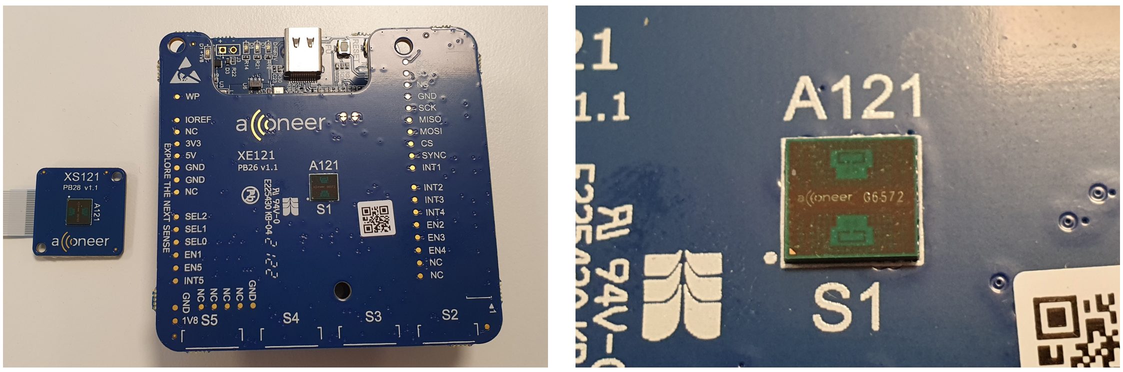


Figure 9: Figures showing the impact of radome thickness and distance to the RLG pattern of the Acconeer sensor. Free space means that there is no radome.



((a)) ((b))

Figure 10: (a) Picture of the XS121 satellite board and XE121 evaluation board for the Acconeer A121 radar sensor. (b) Close up of the Acconeer A121 radar sensor.

3 Methodology

In this chapter, a description of what tests were done and how they were done together with an explanation of how the sensors were connected and sampled is presented. Some radome calculations for the implementation of the radar sensor are also presented.

3.1 Test 1

The first necessary step was to connect each one of the sensors that were going to be examined individually to the computer. This included the following sensors:

- Analog PIR (IRA-S230S501)
- Digital PIR (D4-323-AA)
- Active IR (E207844)
- Ultrasonic 1 (HY-SRF05)
- Ultrasonic 2 (CH201)
- Microwave Doppler Radar (RCWL-0516)

To improve readability the sensors will not be referred to by their part number but instead by the technology they use, as the list above shows. Note that the HY-SRF05 sensor will be called Ultrasonic 1 and the CH201 sensor will be called Ultrasonic 2 since they both use the same technology.

3.1.1 Connecting the sensors

Analog PIR

The Analog PIR is the sensor currently used in the product, therefore it has necessary electronics on the product PCB board. These electronics convert the analog signal into a digital HIGH or a digital LOW depending on if it is above the chosen threshold. The Analog PIR sensor was connected and powered by the products PCB board in the same way as it is when used in the intercom product. A thin copper wire was then soldered to a transistor on the PCB board that was HIGH(3.3 V) when the sensor was not triggered and LOW(0 V) when triggered. This signal was then connected to the Arduino. The Arduino was programmed so that it sends out a 1 when it is triggered and otherwise it sends out a 0.

Digital PIR

The Digital PIR sensor was connected to the Arduino through the multiplexer. This equipment was initially tested with a Nicera D-pro Evaluation board. This allows for testing of four sensors at once and shows the output. Sadly this program doesn't allow saving the data onto another data processing program.

To be able to save sensor data together with the other sensors the sensor was connected to the Arduino. Some Arduino code had to be written to be able to do this. This code can be seen in Appendix A. In the setup part of the code the register setting is performed. This is where bit nr 37 to 87 are set to determine the settings of the sensor.

In the loop, 2 bytes of data is requested from the sensor. The high byte contains 4 dummy bits, therefore the data is represented by 12 bits where the MSB is a signed bit. If a negative value is measured, the sensor sends the 2-complement instead. The hardware has the ability to send a value between -2048 and 2048, where 0 means no movement detected and negative values mean a negative derivative and positive values a positive derivative of change. With the Arduino code the absolute value is shown instead. This is done because there currently is no interest if the signal is negative or positive since both means that movement has occurred. There are as mentioned in subsubsection 2.1.3 different filters that can be used. For this experiment the most sensitive filter and step combination (B3) from Table 1 was used.

A logic analyzer (Saleae Logic 8) was used to confirm that the sensor received the intended data. The logic analyzer was connected as shown in Figure 11. For further understanding of the code, one can refer to the data sheet for the sensor provided by Nippon Ceramic Co [3].

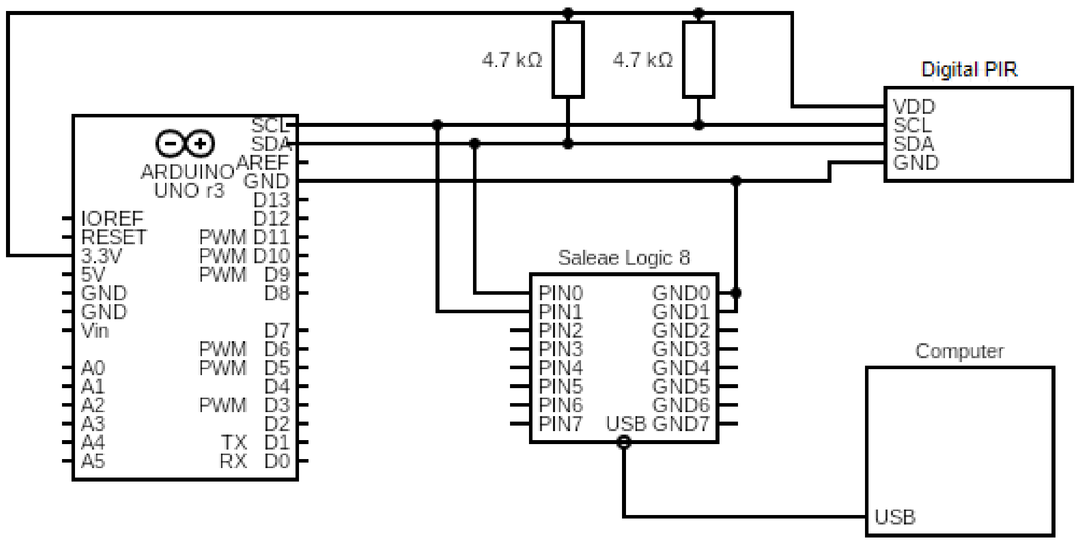


Figure 11: Schematic for the Saleae Logic 8 when analysing the I2C communication between the Arduino and the Digital PIR.

Active IR

The Active IR sensor needed a flat cable to be configured to be able to connect it to the Arduino through the breadboard. Thin copper wires were soldered on a flat cable that could connect to the sensor's PCB on one side and to a pin fitting in the breadboard on the other side. It should be noted that this sensor was connected through a multiplexer. The sensor also needed to be configured software-wise according to the data sheet.

Adafruit TCA9548A 1-to-8 I2C Multiplexer The Digital PIR sensor has no 7-bit I2C address. Because of this when communicating with it from the Arduino, the general call function needs to be used. This is a function that calls all units on the I2C bus line. Due to the Active IR sensor also using I2C communication the general call function would interact with both of them. To avoid this a multiplexer was connected. This allows the I2C communication to be directed to the right sensor. An I2C multiplexer works kind of like an old telephone exchange, up to 8 different I2C sensors can be connected to 8 different pins with individual addresses on the multiplexer. These can then be accessed individually by the Arduino by telling the multiplexer through software which one of its sensors it should establish a connection to.

Ultrasonic 1

The Ultrasonic 1 was connected and powered directly by the Arduino Uno board.

Ultrasonic 2

The Ultrasonic 2 sensors were connected to a PC through their own evaluation board and the data was extracted using their own software that was supplied with this card. Using this software it's possible to export the measured values to Excel together with timestamps. The range was set to 5 meters with a refresh rate of 3 Hz. Additionally, *Static Target Rejection* was activated. This was done to make it only measure moving targets. The developer kit that was used came with both the evaluation board and the software needed. Further information about the evaluation board can be gathered in the user guide for the developer kit provided by Chirp Microsystems [15].

Microwave Doppler Radar

The Microwave Doppler Radar was connected and powered directly by the Arduino Uno board.

Sensor Test Board

After all sensors were examined individually and the necessary code written for each sensor was verified to work, a sensor test board was constructed. The board was built out of plywood and can be seen in Figure 12. All of the sensors except the two ultrasonic 2 sensors are connected to an Arduino Uno which in turn is connected to a PC. The two ultrasonic 2 sensors were connected to another PC through their own evaluation board. The full schematic for this setup excluding the ultrasonic 2 sensors can be seen in Figure 13.

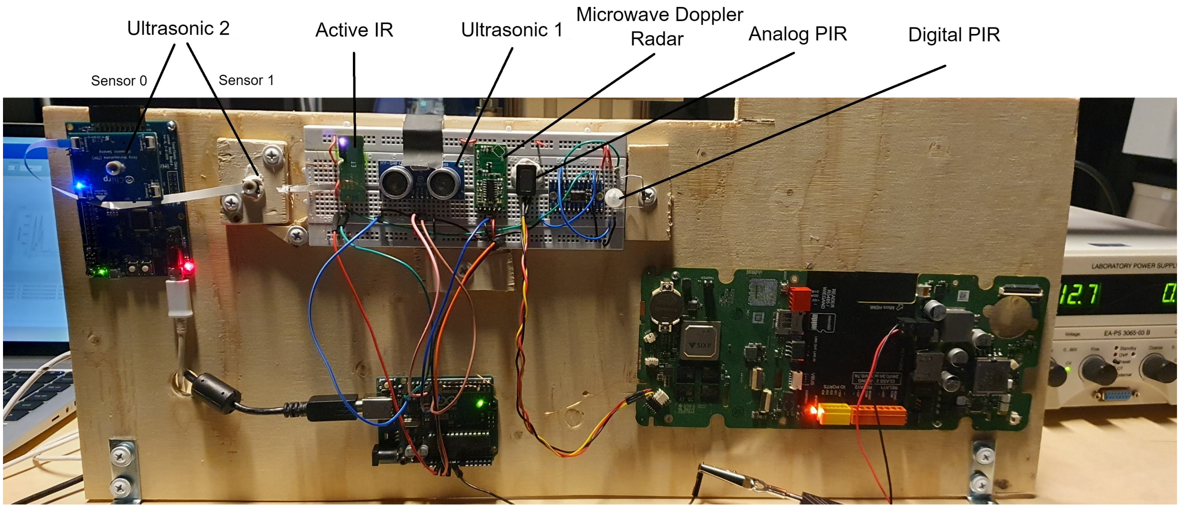


Figure 12: Close-up of sensor board. The Ultrasonic 2 sensors to the left are connected to a PC through their evaluation board. The rest of the sensors are connected to the Arduino Uno seen at the bottom through a breadboard. To the right the PCB board that the Analog PIR sensor connects to can be seen. The PCB is powered by the power supply to the right and a thin copper wire is connected directly to the Arduino Uno from it.

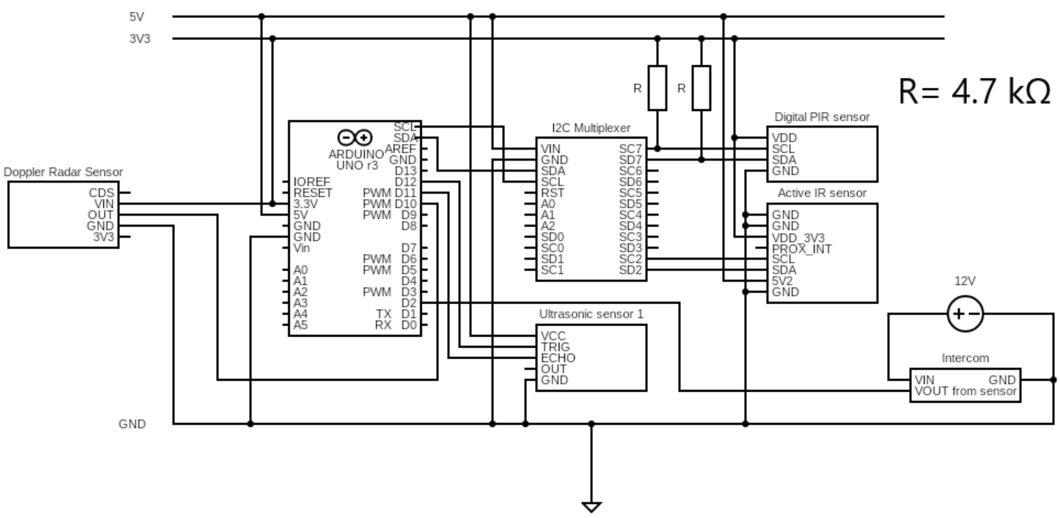


Figure 13: Schematic showing how the sensors were connected to the Arduino. The ultrasonic 2 sensors are not included in this schematic since they are not connected to the Arduino.

3.1.2 Data gathering and processing

The data from the sensor board is gathered through Excel with the help of an Arduino program. The Arduino was loaded with code that configures all the connected sensors and samples them every 333 ms. After all sensors are sampled, the Arduino sends the values over serial communication to the PC where

Excel receives and saves the values using Excel's Data Streamer add-in. The Data Streamer is an add-in that allows users to interact with real-time data in Excel. It can connect to a data source, in our case an Arduino, and stream the data in real time into a worksheet together with time stamps.

After all tests were done, there were over a hundred data recordings. These were then divided and processed into different columns in individual Excel files for the different tests. In the tests where the test person walked a determined distance, for example when walking from 12 m to 1 m from the sensors, the time stamps were interchanged with linearly distributed numbers between 12 and 1. If it took 5 seconds to walk the full distance, it was assumed that half the distance was walked after 2.5 seconds. This means that the sensor values and the real distance from the sensor might be a bit off-phase, which is why all tests were done at least three times.

The Excel files were saved as CSV-files since this makes importing the files in Python faster. The saved data was processed in Python where code was written to import the Excel files and normalize the data to values between 0 and 1 so that the sensors can easier be compared. The graphs are then all plotted and saved in a folder.

The values from the ultrasonic 2 sensors were sampled with a frequency of 3 Hz. These values were then manually added to the Excel files. This means that these data points are not measured at the exact same time but may be up to 333 ms ahead or after the other sensors at times.

3.1.3 Test 1 measurements

Six different measurements were done during this test. Each measurement was repeated three times except for measurement 3, that was repeated five times. This was done to minimize the impact of a random false trigger of a sensor. All the measurements started at a set position in the x-y plane and followed a predetermined path. The testing area was a 30 by 3.15 meters long corridor without any windows or people except for the two test persons. This means there weren't any disturbances in the data by people walking through the test area. Figure 17 shows pictures of the setup. If any sensors still triggered when they weren't supposed to they are considered to have false triggered. The sampling frequency for the Ultrasonic 2 sensors were 3 Hz and the time between samples for the other sensors were 0.333s + time to run one loop of the code. The measurements were as follows:

- Measurement 1 & 2: These measurements were conducted by running the sensors in an empty room with the lights turned on for a few minutes. Values were then taken over 200 samples to see what the baseline values were and if any of the sensors triggered. It was then done again with all the lights in the room turned off.
- Measurement 3: The third measurement was conducted by having a person walk straight towards the sensor board without any obstacles in the way. The test person walked from 12 m away and stopped 1 m from the sensor. In Figure 14 it can be seen how the person walked during the test.

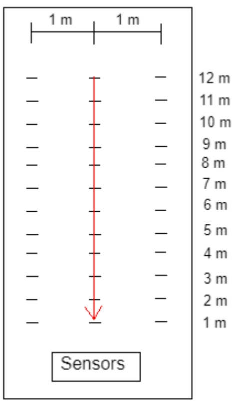


Figure 14: Sketch showing how measurement 3 was conducted.

- Measurement 4: The fourth measurement was conducted by having the test person walk parallel to the sensor board. This is done at distances from 10 m to 1 m with 1 m intervals. The distance that the test person walked is 3.15 meters. In Figure 15 it can be seen how the person walked during the test.

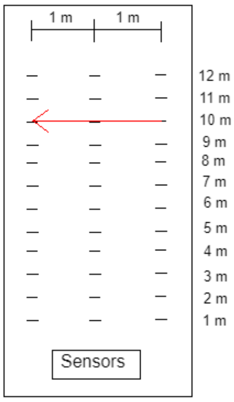


Figure 15: Sketch showing how measurement 4 was conducted.

- Measurement 5: The test person walked towards the sensors at a 45° angle. The test person started one meter to the right of the center (seen from the sensors) and walked diagonally to the other side of the corridor as shown in Figure 16.

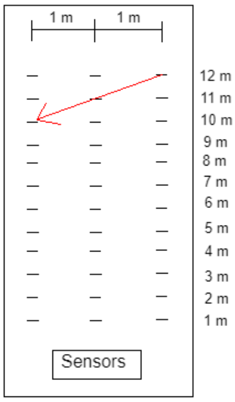
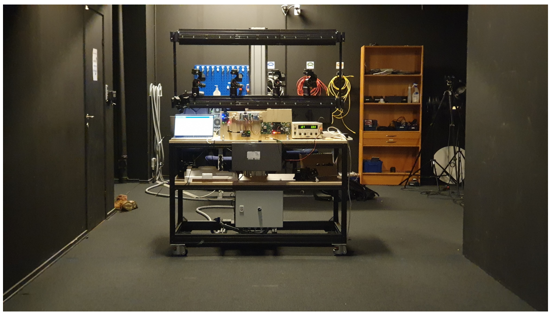


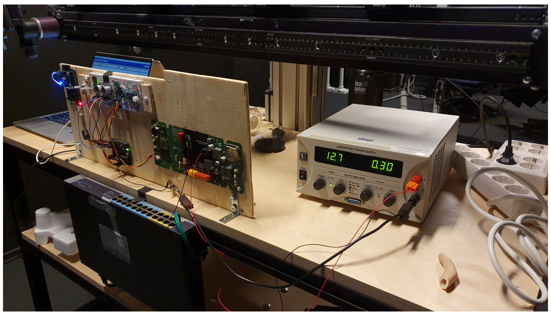
Figure 16: Sketch showing how measurement 5 was conducted.

- Measurement 6: The final measurement was to test how the sensor works behind a glass screen. This was done by taping a glass screen in front of the tested sensor and then testing if the sensor would react at all on movement by walking around in front of it. The setup can be seen in Figure 17(d).

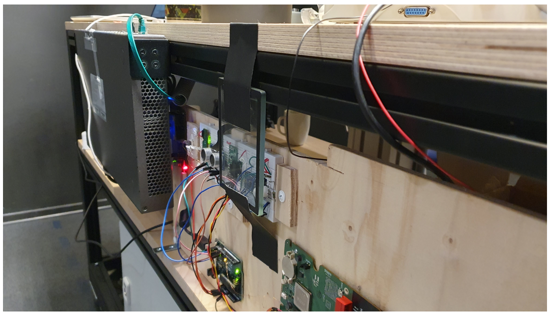


((a))

((b))



((c))



((d))

Figure 17: (a) Picture of the setup taken at the sensors from the front. (b) Picture of the test corridor taken from the sensors. The tape that marks every meter can be seen on the floor. (c) Close-up of the setup, to the right is the power supply driving the intercom PCB and to the left is the sensor board and laptop behind it. (d) Close-up of the setup when testing if the sensors could see through glass.

3.2 Test 2

To be able to test the Acconeer A121 sensor, the XE121 Acconeer development kit was used together with the XS121 satellite board. The test was done in a similar way to how test 1 was done. The main difference was that Acconeer's own software *Acconeer Exploration Tool* was used instead of an Arduino to extract the sensor data. This software made it possible to visualize and record what the sensor picks up live while performing the measurements. There are several different services in the software but the one used in this test was the *Smart Presence* app. This service lets the user determine the minimum and maximum range the sensor triggers at and also how many zones it should draw in the visualization. The software enables the user to adjust many different parameters of the sensor. The ones used in this test were the default medium range settings, with the only changes being that the range of the detection zone was set between 0.5 m and 4.5 m and split into 5 different zones where each one is 1 meter long, as seen in Figure 18. The software can thus show how far from the sensor the presence is detected by lighting up the different zones in colors when presence is detected there.

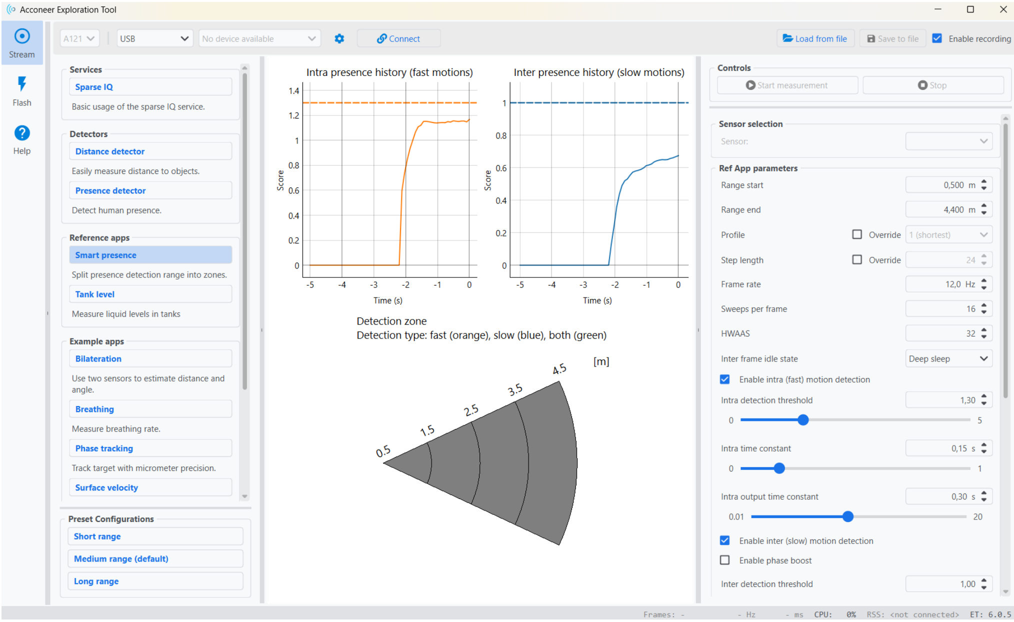


Figure 18: The GUI for *Smart Presence* in Acconeer's evaluation software *Acconeer Exploration Tool*.

The measurements with the *Smart Presence* app were done as follows. The sensor was connected to the PC through the evaluation board. The settings were set as explained above and then before each measurement the button *Start measurement* was pressed. Then there were two different types of motion that were being detected and drawn in the GUI. Fast motion is what is mostly detected when walking in front of the sensor and slow motion is detected if standing still in front of the sensor for several seconds. If only fast motion is detected in a zone, that zone becomes orange. If only slow motion is being detected, the zone becomes blue and if both are being detected it becomes green. After a measurement was done, the measurement was stopped and saved to a .h5 file which makes it possible to playback the measurement like a video in the GUI later.

The measurements done were:

- Measurement 1: Walk straight away from the sensor and back again. This was done to see how well the triggers in the different detection zones matched the movement and position in real life.

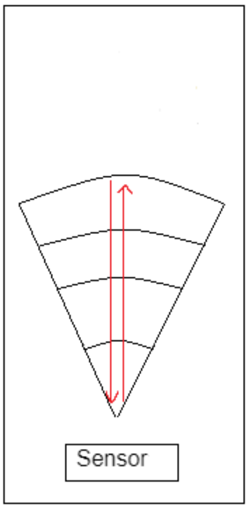


Figure 19: Sketch showing how measurement 1 was conducted.

- Measurement 2: Walk from side to side at different ranges. This was done to see how consistently it triggered in the same detection zone when walking back and forth in that zone.

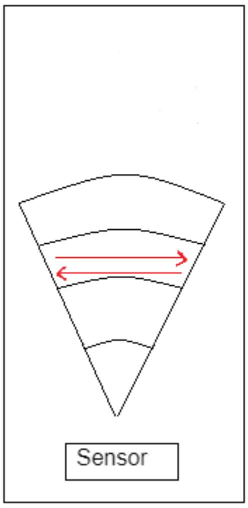


Figure 20: Sketch showing how measurement 2 was conducted.

- Measurement 3: Walking back and forth outside of the furthest detection zone. This was done to see how well it ignored movement outside the software-adjusted maximum detection range.

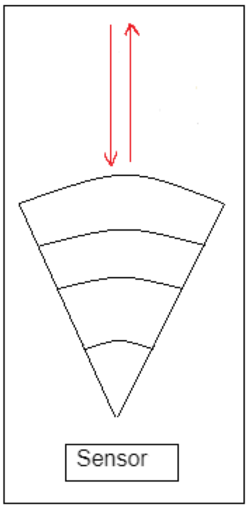


Figure 21: Sketch showing how measurement 3 was conducted.

- Measurement 4: Walking from 1 meter beside the sensor perpendicularly away until it triggers. This was done to see how wide the sensor's field of view is.

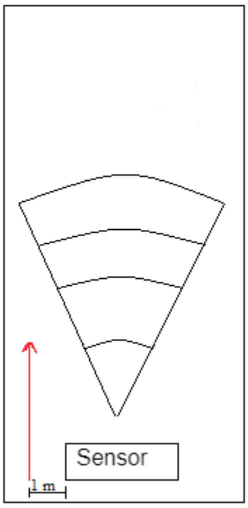
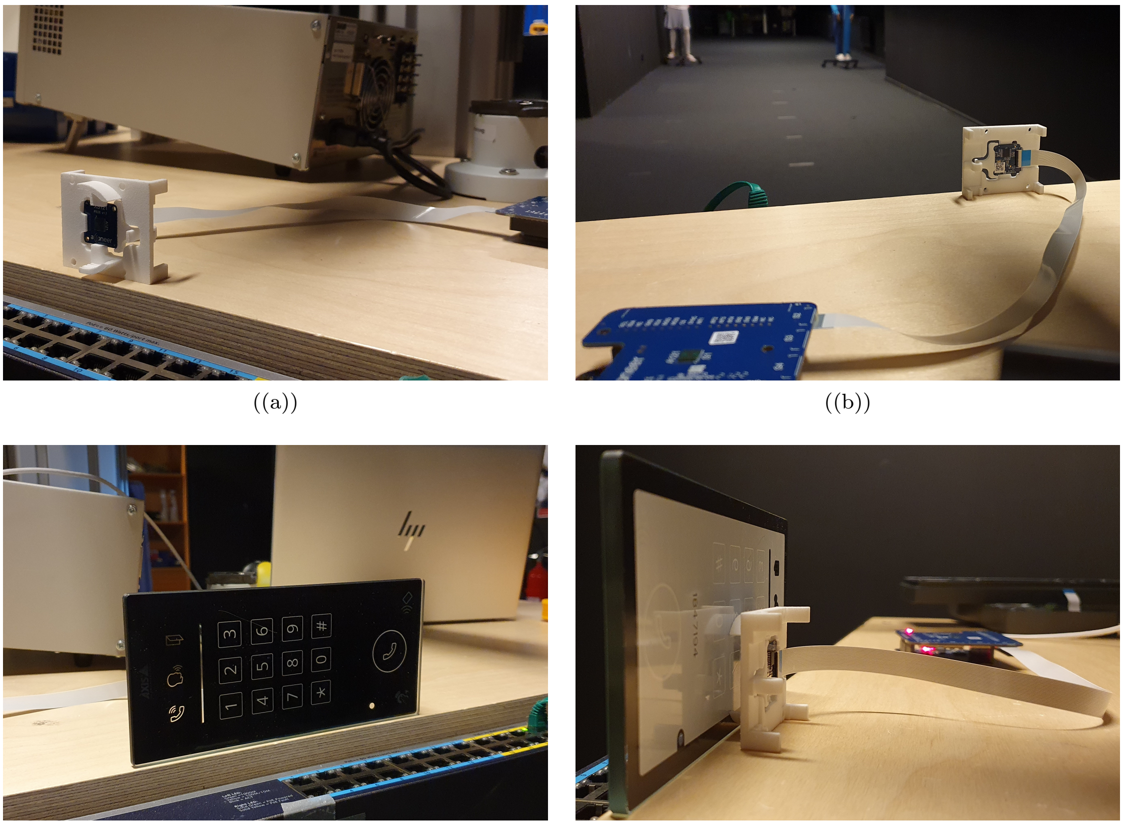


Figure 22: Sketch showing how measurement 4 was conducted.

All the measurements above were done with the sensor mounted behind a sheet of the same hardened glass that is used in the intercom. Worth mentioning is that neither the thickness of the glass nor the distance to the glass was optimized according to how the radomes should be constructed to minimize the negative impact. The sensor was simply put behind the glass as seen in Figure 23(c) and 23(d). The glass sheet is 5 mm thick and the distance from the sensor to the glass sheet is 10 mm. The dielectric constant of the glass is not known, even after contacting the supplier. This is something that can be measured so that the thickness and distance can be optimized, but is not in the scope of this project.



((a)) ((b)) ((c)) ((d))

Figure 23: (a) Picture from the front of the sensor during testing. (b) Picture from the rear of the sensor during testing. (c) The hardened glass sheet with the sensor behind it seen from the front. (d) Close-up of the setup when testing if the sensor could see through the glass. The distance from the sensor to the glass was measured to 10 mm.

3.3 Radome calculations for Acconeer Pulsed Coherent Radar Sensor

One of the big problems with the currently used PIR sensor in the product, is that the plastic cover that protects the sensor from weather and wind is hard to get certified. The material needs to be a specific type of plastic and this plastic is hard to get certified as a protecting material. A radome is a weatherproof enclosure that protects a radar and to design it in an optimal way, one must take the equations in subsubsection 2.4.2 into consideration. To begin with, using Equation 15 some optimal radome thicknesses for the Acconeer sensor can be calculated for some different material. Since the sensor uses a frequency of 60 Ghz that gives a wavelength λ_0 of about 5 mm. The calculation for the optimal radome thickness to minimize the reflection and maximize the penetration then only depends on the relative permittivity of the material. Table 2 contains both a list of different materials and their respective dielectric constant at 60 GHz, it also contains 5 different thicknesses for the materials that is calculated using Equation 15 with λ_0 as 5 mm.

Table 2: Table showing the dielectric constant for some different materials together with some calculated optimal thicknesses for these materials. The list of materials and their respective dielectic constant at 60 GHz are sourced from [19].

Material	**Dielectric constant (60 GHz)**	d_2 **[mm], m=1**	d_2 **[mm], m=2**	d_2 **[mm], m=3**	d_2 **[mm], m=4**	d_2 **[mm], m=5**
ABS-M30 (three-dimensional printed)	2.48	1.59	3.18	4.76	6.35	7.94
Acrylic glass	2.5	1.58	3.16	4.74	6.32	7.91
Alumina	9.3	0.82	1.64	2.46	3.28	4.10
Fused quartz	3.8	1.28	2.56	3.85	5.13	6.41
Macor	5.5	1.07	2.13	3.20	4.26	5.33
PLA (three-dimensional printed)	2.85	1.48	2.96	4.44	5.92	7.40
Polyethylene	2.3	1.65	3.30	4.95	6.59	8.24
Polypropylene	2.2	1.69	3.37	5.06	6.74	8.43
Polystyrene (Rexolite)	2.5	1.58	3.16	4.74	6.32	7.91
Teflon	2.2	1.69	3.37	5.06	6.74	8.43

The optimal radome distance can be calculated in a similar way using Equation 16, Table 3 shows five different distances for a 60 GHz radar. These distances are only the optimum distances when the thickness of the radome is also optimum [19].

Table 3: Table showing the optimum distances to put the radome from the radar for a 60 GHz radar that has an optimum radome thickness.

d_1, **m=1 [mm]**	d_1, **m=2 [mm]**	d_1, **m=3 [mm]**	d_1, **m=4 [mm]**	d_1, **m=5 [mm]**
2.5 mm	**5 mm**	**7.5 mm**	**10 mm**	**12.5 mm**

4 Results

This section presents the results from the tests done on the different sensors. The results includes explanations of measurement procedures.

4.1 Test 1

The results of test 1 will be presented here. As shown previously in Figure 13 all sensors are connected to the same Arduino except for the two ultrasonic 2 sensors. These two were connected to a separate computer. This means that they are out of phase. Both of them are running on 3 Hz with a time delay of about 0.1 s between each other. The Arduino-connected sensors are not running a set frequency, instead, there is a 0.333 s delay after each time they sample. With the time it takes for the code to process, it results in a frequency that's a little lower than 3Hz. One important disclaimer for these tests is that the X values in all graphs are liable to some error. This is due to an assumption in the graphs that the speed of the tester is constant while in reality, the speed might be varying.

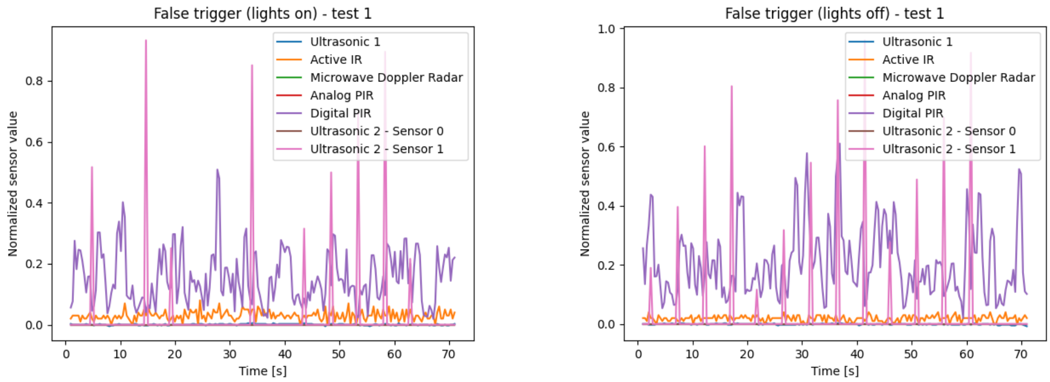
The Y values are normalized around the maximum value for each sensor. This means that for the digital PIR sensor that has a maximum value of 2048, a value of 1 is equal to 2048. For the ultrasonic sensors that measure distance a value of 1 is equal to the furthest distance they can measure. The result of this is that when someone moves closer to a sensor the ultrasonic sensors will go from higher values to lower while the opposite will happen for the other sensors. Therefore the ultrasonic sensor values are mirrored in the graphs, to easier compare them with the other sensors. When the data was analyzed the ultrasonic 1 was constantly seeing something at a distance of about 390 cm. This was assumed to be the roof/floor due to the sensor board not being perfectly perpendicular to the floor. The consequence of this is that the range for the sensor goes from 450 to 390 cm. To not pollute the graph and allow for an easier viewing of the data this value has been normalized to a 0 in the graphs.

4.1.1 Measurement 1 & 2: False triggers

The measurement was run three times with the lights turned on and three times with the lights off. Some of the sensors like the Analog PIR only sends out a 1 or a 0 depending on if it has triggered or not. The Ultrasonic 2 however sends out the distance it has measured. This means that for the sensors that are sending out a more complex signal the definition of a trigger has to be decided by the user. In this case there is an assumption of no movement and any change from "standard operation" is unwanted.

In Figure 24(a) neither the Microwave Doppler Radar, the Analog PIR, or the Ultrasonic 1 are false triggering. The Active IR sensor is not getting any noteworthy measurements either and is bouncing around 0-0.05 of it's max value. The Digital PIR has some constant noise at around 0.1-0.4. The filter used in the test is the most sensitive filter of all the available filters this sensor has. The two Ultrasonic 2 sensors are acting very differently in that one of them didn't false trigger at all and the other one is triggering several times. With only one of these identical sensors reacting it is assumed that sensor is broken. The other one that seems to be working doesn't see anything at all. This is because of the sensors being set to *Static target rejection* that makes the sensor ignore any non moving targets that is in it's range. Otherwise they should also see the previously mentioned wall that Ultrasonic 1 also sees. Due to Ultrasonic 2 - Sensor 1 false triggering randomly it will not be used in the further measurements and only the results from Ultrasonic 2 - Sensor 0 will be examined.

By examining Figure 24(b) there isn't any differences in how the sensors reacted. This isn't very surprising because most of the sensors aren't impacted by the lack of light. The only one that this seems to impact is the active IR sensor. With lower light pollution in the room the value is somewhat lower.



((a)) ((b))

Figure 24: (a) Graph of the falsetrigger test with the lights on. (b) Graph of the falsetrigger test with the lights off.

4.1.2 Measurement 3: Walking towards the sensors from 12m to 1m

This measurement was repeated five times. As can be seen in Figure 25 the first sensor that reacts to a person walking towards it is the Microwave Doppler Radar. This is followed by the digital PIR sensor. After this the Ultrasonic sensors react and finally the Active IR reacts. In this case the Analog PIR didn't trigger. This seems to be a reoccurring pattern because during the five tests the old PIR sensor didn't trigger once. The order in which the sensors reacted was also constant. The reason that the PIR sensors don't trigger easily on movement straight towards them has to do with the fact that they consist of two elements sitting next to each other that heat up and generates a current depending on their temperature difference. When walking straight toward the sensor, both elements get heated similarly.

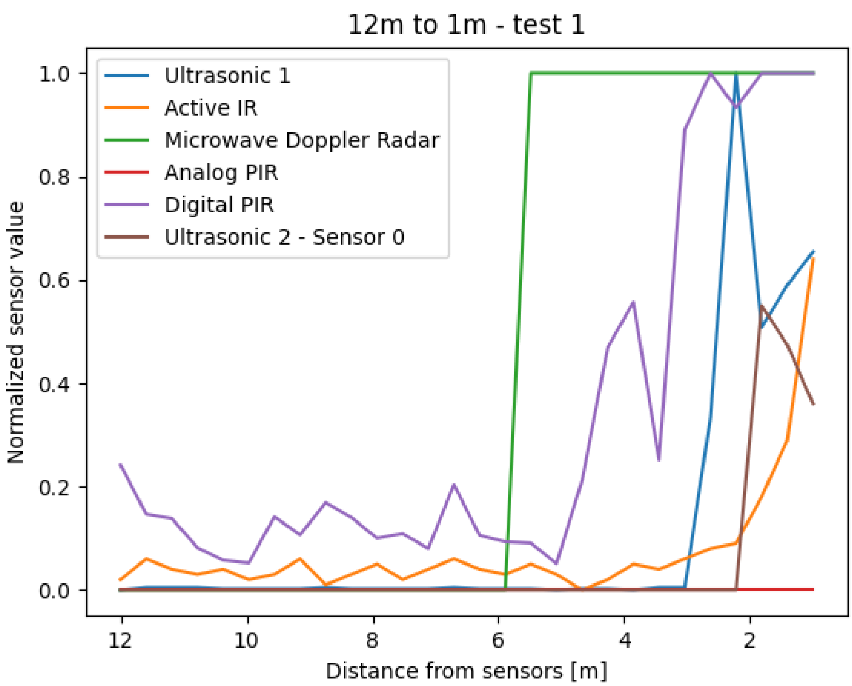


Figure 25: The line diagram is showing the change in amplitude for the different sensors when a human walks towards them. The Y axis is normalized around 1 and shows the amplitude of the sensor output.

4.1.3 Measurement 4: Walking perpendicular to the sensors from 10m to 1m

The measurement was run three times at each distance. The measurement was conducted at 1 meter intervals from 10 m down to 1 m. Not all the graphs will be presented here. Instead the distances where things changed will be shown. These are 10, 8, 3, 2, and 1 meter.

In Figure 25 The Digital PIR sensor notices the movement at a range of 10 meters when it is moving perpendicular to it's field of view. No other sensor seems to react. It is the same for the other two tests at this distance. Figure 26(b) shows that the Microwave Doppler Radar starts to trigger at 8 m. After this nothing new happens until the distance is lowered to three meters. At this distance the Ultrasonic 2 sensors notices the tester walking past them. What is interesting is that the sensor is set up to notice people at a distance of 5 m and it doesn't notice people before they are at a distance of 3 meters. For some reason the Ultrasonic 1 sensor doesn't notice the person at all. This sensor has as is mentioned earlier a range of up to 390 centimeters, still it doesn't see a person walking past at 3 meters.

The Analog PIR sensor starts to work at a range of two meters. The Active IR also reacts, however it isn't a very large reaction. The Ultrasonic 1 sometimes triggers at this range. By comparing 26(d) it doesn't trigger but in 26(e) it does. Both of these tests were done at the same range of 2 meters. As can be seen at 1 meter in Figure 26(f) all sensors react and very noticeably. Especially when looking at the active IR sensor there is a noticeable increase in the maximum amplitude at this distance.

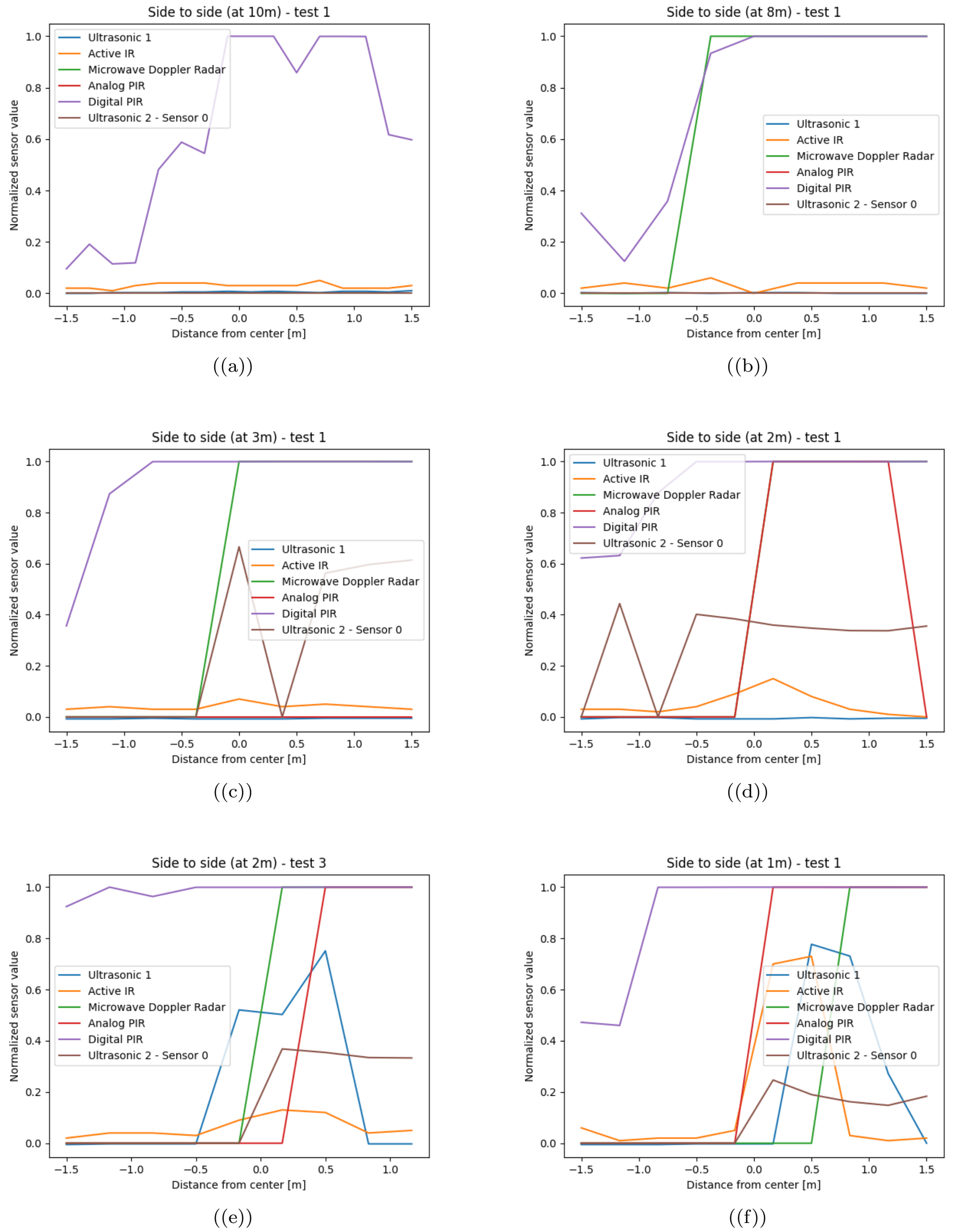


Figure 26: Graphs showing how the sensors triggered when walking side to side in front of them at different distances. The distances are: (a) 10 m, (b) 8 m, (c) 3 m, (d) & (e) 2 m, (f) 1 m.

4.1.4 Measurement 5: Walking towards the sensors with a 45° angle

In this measurement the person walked towards the sensor with a 45 degree angle. In each measurement the person walked 2 meter towards the sensor and 2 meter tangentially across the room. This makes it a combination of measurement 3 and 4.

In Figure 27(a) it can be seen that the Digital PIR sensor triggers first at around 10 m and then the Microwave Doppler Radar triggers at around 7-8 m which can be seen in Figure 27(b). In Figure 27(c) all sensors except the Active IR triggers. The Analog PIR and all the Ultrasonic sensors triggers have triggered at 2.5 m. In Figure 27(d) and Figure 27(e) the Active IR also triggers, very clearly in Figure 27(e).

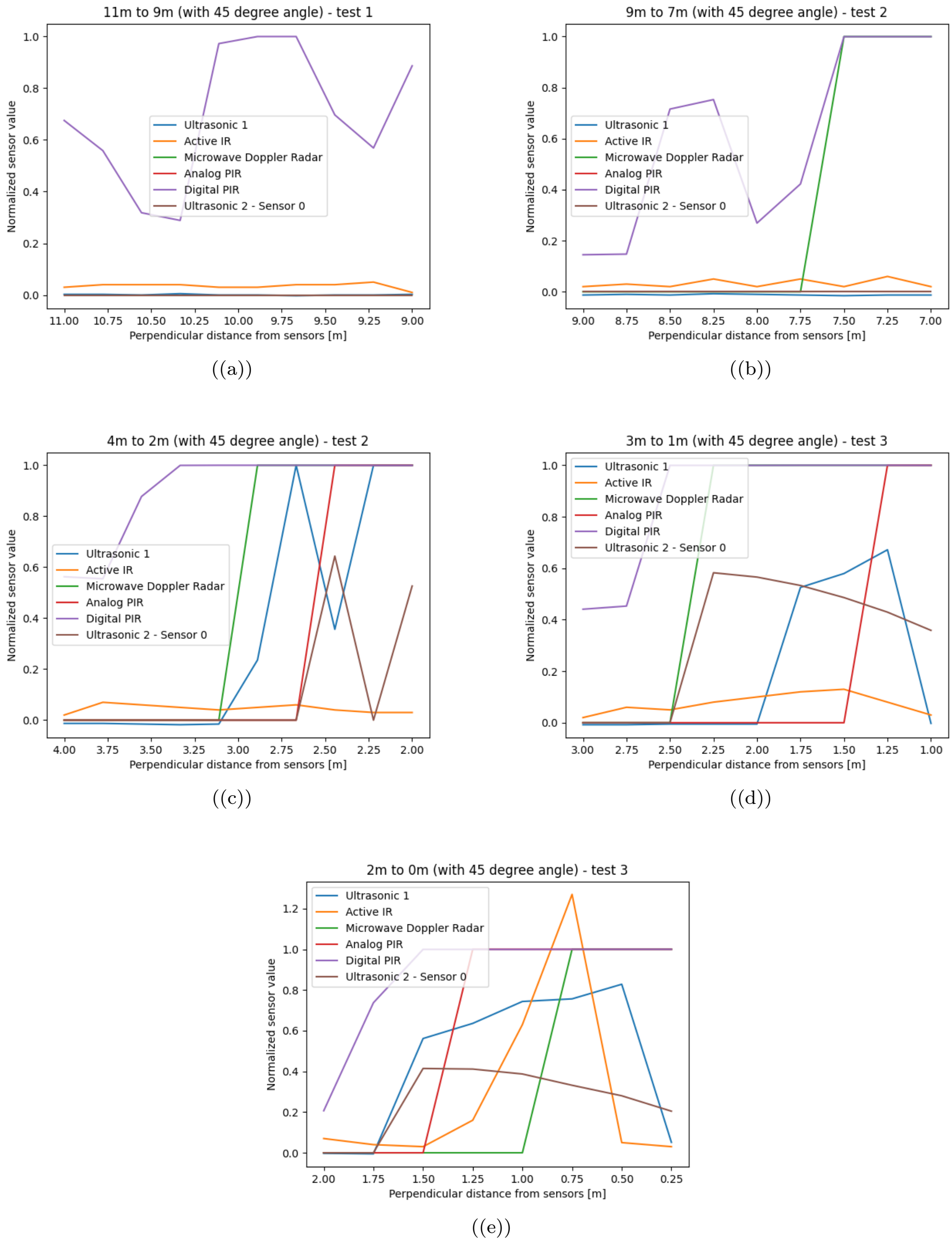


Figure 27: Graphs showing how the sensors triggered when walking towards them with a 45 degree angle at different distances. The distances are: (a) 11 m to 9 m. (b) 9 m to 7 m. (c) 4 m to 2 m. (d) 3 m to 1 m. (e) 2 m to 0 m.

4.1.5 Measurement 6: The permeability of glass for the sensor

The final experiment was to see how well the sensors worked through hardened glass. It was the same 5 mm thick hardened glass used in the intercom.

The only sensor that worked through the glass was the Microwave Doppler Radar. The test seen in Figure 25 was done behind the glass three times and performed no different from when there was no glass. This can be seen in Figure 28.

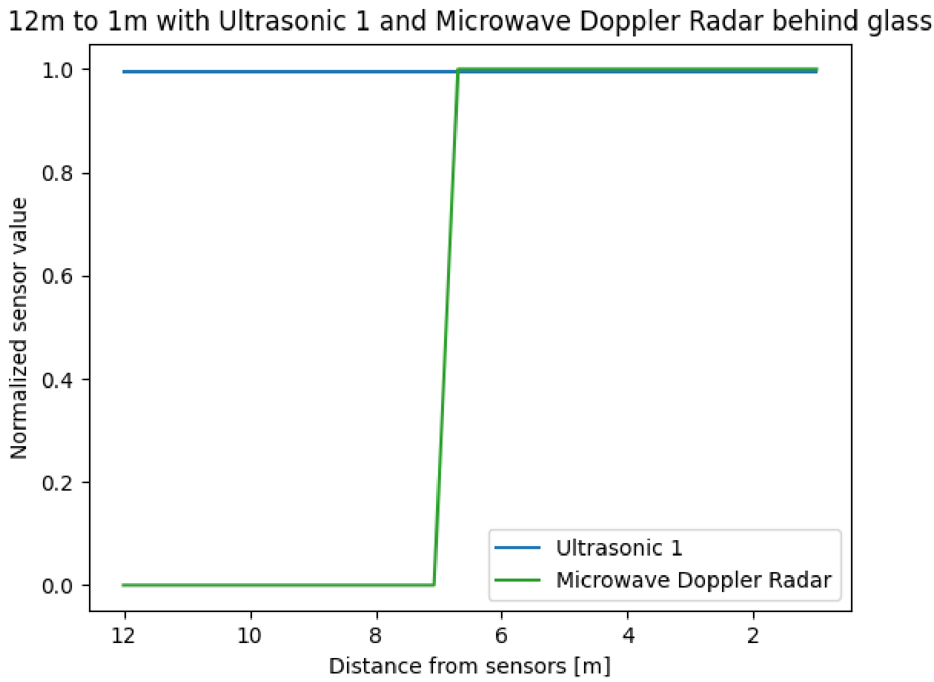


Figure 28: The line diagram is showing the change in amplitude for the Microwave Doppler Radar and the Ultrasonic 1 sensor when a human walks towards the sensor from a distance of 12 m to a distance of 1 m. In this graph the sensors are placed behind 5 mm thick hardened glass. The Y axis is normalized around 1 and shows the amplitude of the sensor output

4.2 Test 2

All the measurements in this test were done with the *smart presence* reference app from the Acconeer's evaluation software. The output from the sensor is the amplitude and the phase at each measured point. Using the raw data from the sensor a program can be developed that processes the data that checks for movement.

In the *smart presence* reference app this is done with two presence detection algorithms. The first one that is shown as an orange line is the intra presence detection which looks at fast movements. This is movement such as a walking person or other large movements. The software also tracks slow movement, this is the inter presence detection which is shown as a blue line. Slow movements are slight movements in the body such as breathing. The application analyzes the signal for both these algorithms and gives it a score. The scores are then compared to their respective thresholds.

As mentioned in subsection 3.2 the presence detection area is split into four 1 meter long areas. These will be referred to as zones. Zone 0 is any zone outside the FOV of the sensor. This is both when the object is further away from the sensor than 4.5 m and when they are too far to the sides so that the sensor can no longer see them. Zone 1 is the area closest to the sensor in the range of 0.5 m to 1.5 m away. The next zone is zone 2, then zone 3 and the outermost area is zone 4.

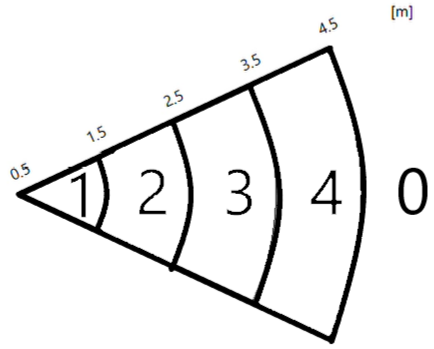
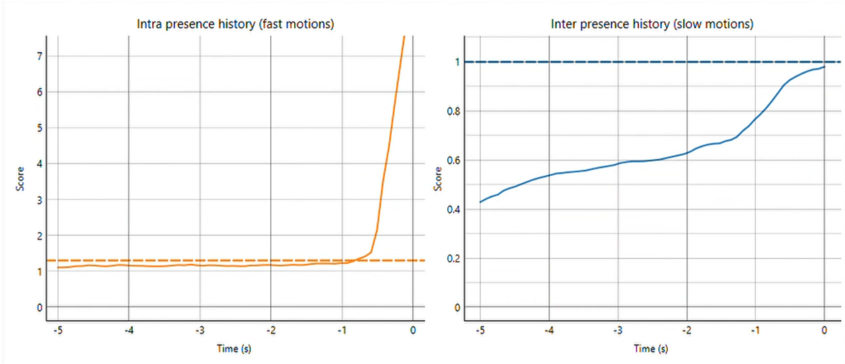


Figure 29: Picture showing the sensors four zones and their respective numbering.

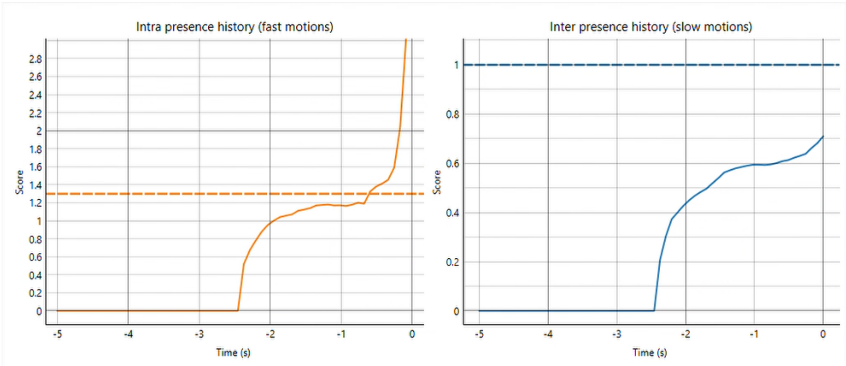
4.2.1 Measurement 1: Moving away from and towards the sensor

The first test was conducted by walking away from the sensor through all the sensors until the sensor no longer can see the tester. The tester then turned around and walked back through the sensors from the outermost zone to the zone closest to the sensor. This was then repeated with glass in front of it. The shown results will be the value upon entry into each zone. They will be presented in pairs with both the result with an unobscured view and with the glass cover in front of the sensor. For better clarity, only the inter (slow) presence and intra (fast) presence will be shown and which zone the target was in will be mentioned.

While walking into zone 1 from outside the sensor field of view the fast presence detection score quickly goes up. This is true for both Figure 30(a) and Figure 30(b). The amplitude is not increasing as much for the sensor behind the glass, but they are both far over the threshold of 1.3. The slow presence is not above the threshold for either of the two sensor setups but is much closer for the one without any obstructions. When entering zone 2 the amplitude is lower for the sensors. In Figure 31(b) the fast presence score increased all the way up to 7 before starting to decrease, meaning that the amplitude difference wasn't as big as previously shown. Both the sensor configurations are well over the threshold for slow presence meaning they are both detecting the target. The main difference between the two sensor setups is that the slow presence detection for the unobscured sensor is over it's threshold and the one behind glass isn't. Walking from zone 2 to zone 3 the slow presence detection in Figure 32(a) once again dips below it's threshold of 1 and both the fast presence detection graphs in Figure 32 are dipping below a score of 2. What can be seen is that the fast presence score is decreasing with range but not linearly. It is more of a logarithmic decrease with the range, which is not surprising if one remembers the radar range equation (Equation 9). In zone 4 the sensor score for the fast presence detection in Figure 33 continues to drop, but as mentioned above the curve continues to flatten. During all the measurements the fast presence is above the threshold. While examining the slow presence detection for the entire walk away from the sensor the sensor behind the glass has a much lower value than the one that only has air in front of it. This is also the case for the fast presence so it seems that the glass panel dampens the signal a bit.

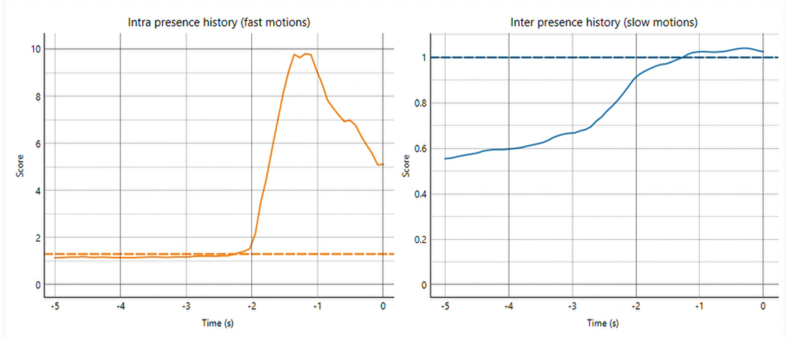


((a))

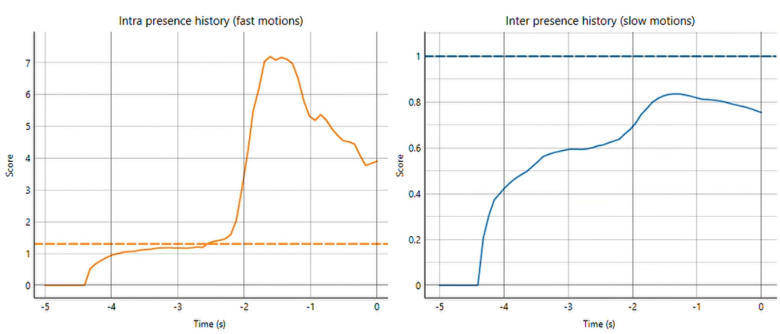


((b))

Figure 30: The response from the sensor when walking into zone 1 from outside the sensor field of view. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.

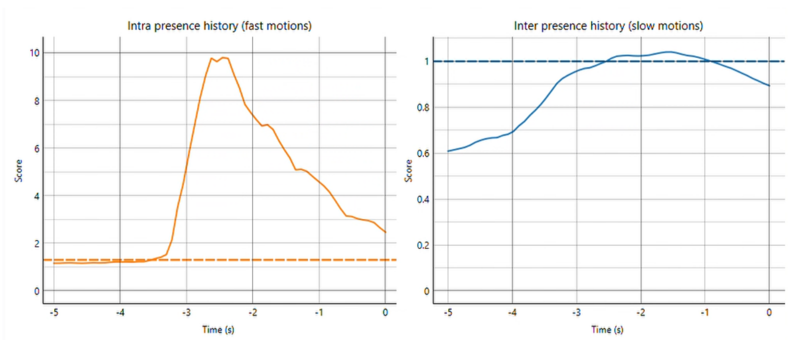


((a))

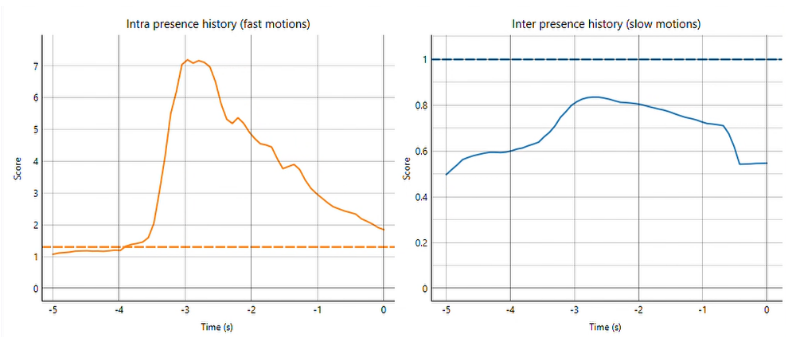


((b))

Figure 31: The response from the sensor when walking into zone 2 from zone 1. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.

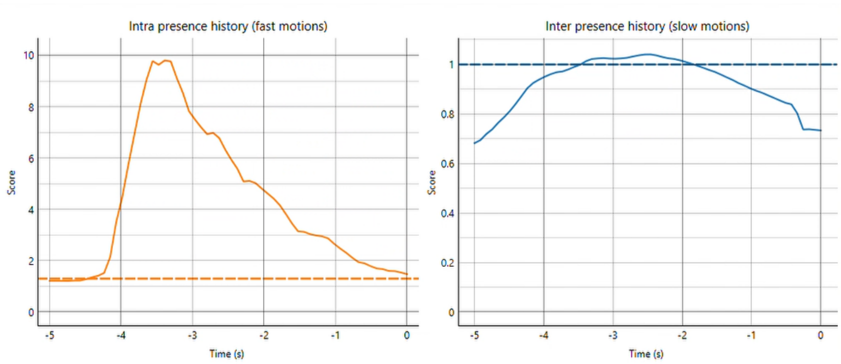


((a))



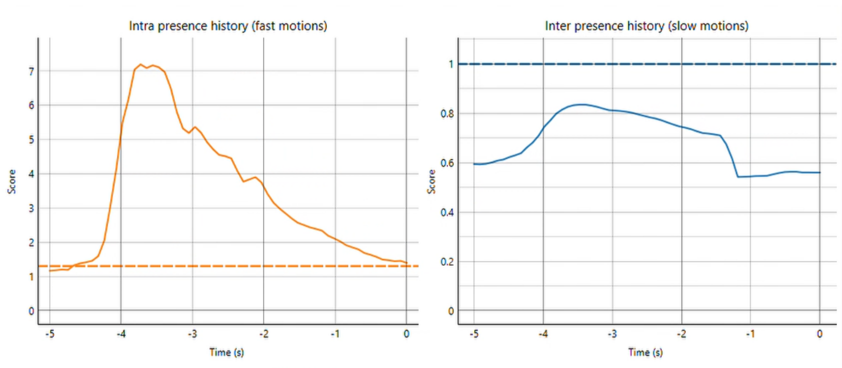
((b))

Figure 32: The response from the sensor when walking into zone 3 from zone 2. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.



.

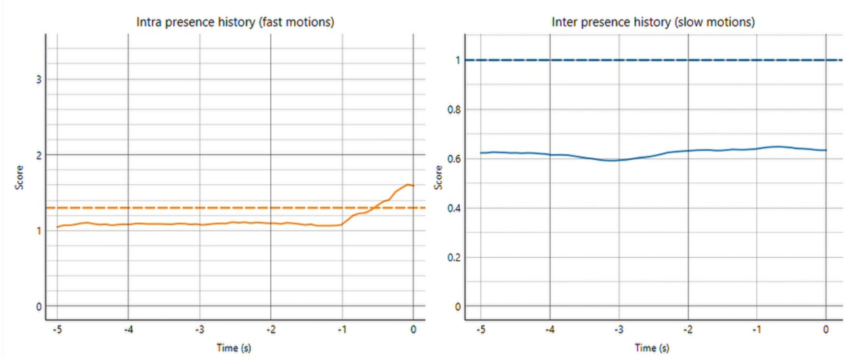
((a))



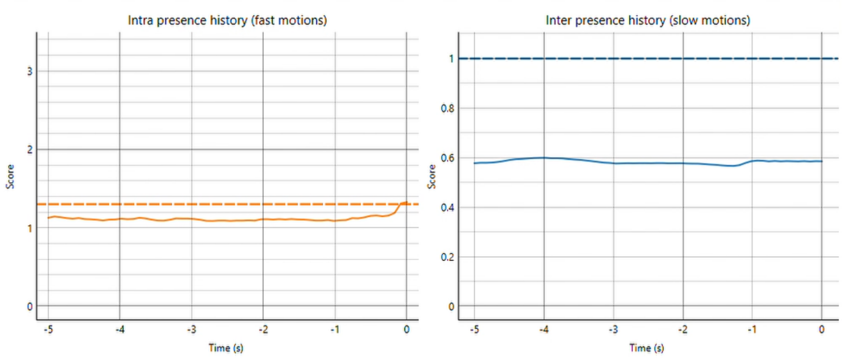
((b))

Figure 33: The response from the sensor when walking into zone 4 from zone 3. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.

When walking towards the sensor from outside zone 4 there are some differences between the two graphs in Figure 34. Both of them start to rise at a time of -1 but the increase is much slower for the one obstructed by glass. In Figure 35 when walking into zone 3 it is more obvious how the sensor is impacted by the glass cover. Between -2 and -1 the value of the fast presence score actually dips back down below the threshold for the glass covered sensor before the amplitude starts to rise again. The same behaviour appears in Figure 36 but due to a higher amplitude the decrease in amplitude doesn't put the value below the threshold. The slow presence detection doesn't seem to react much when walking towards the sensor, but in Figure 37(a) it starts to rise when the target enters zone 1.

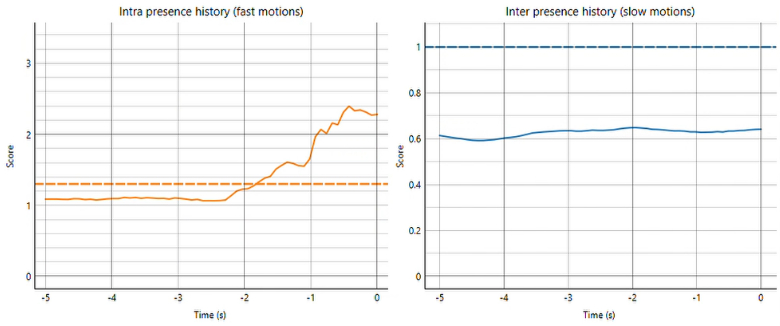


((a))

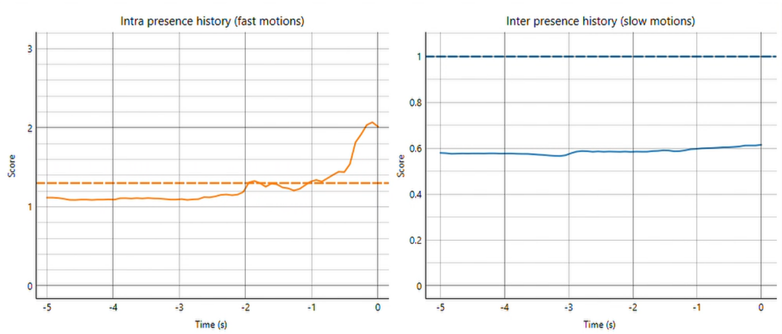


((b))

Figure 34: The response from the sensor when walking into zone 4 from zone 0. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.

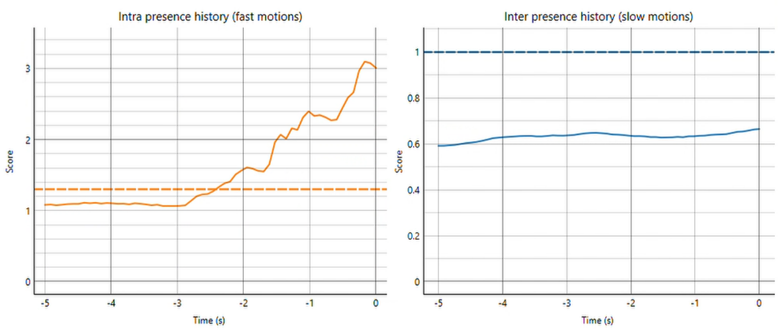


((a))

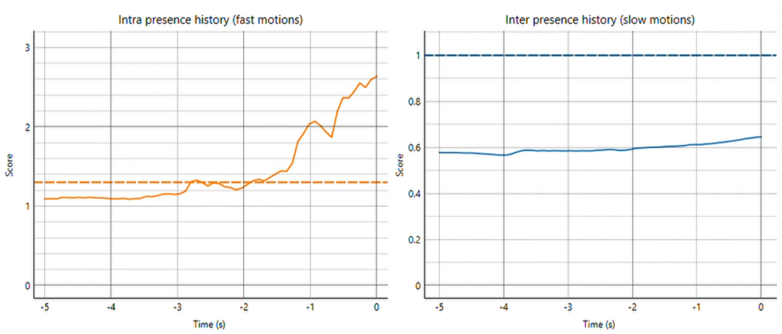


((b))

Figure 35: The response from the sensor when walking into zone 3 from zone 4. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.

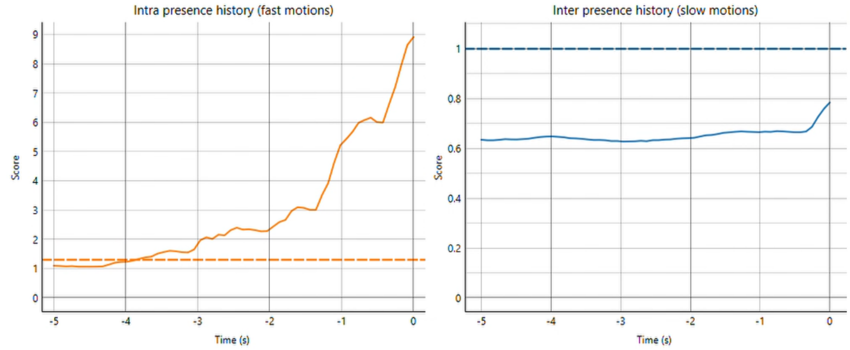


((a))

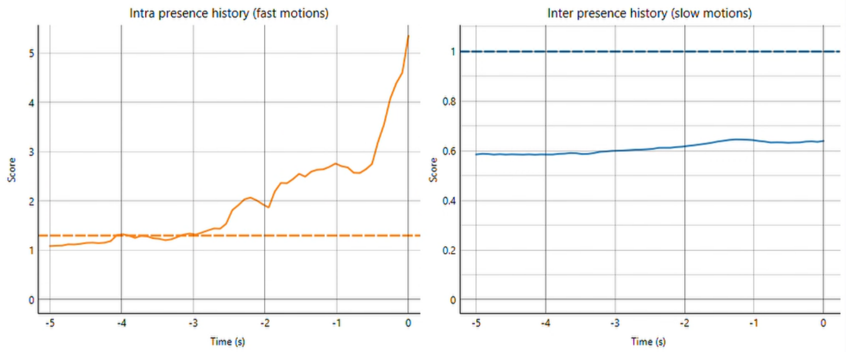


((b))

Figure 36: The response from the sensor when walking into zone 2 from zone 3. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.



((a))



((b))

Figure 37: The response from the sensor when walking into zone 1 from zone 1. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.

4.3 Measurement 2: Walking side to side

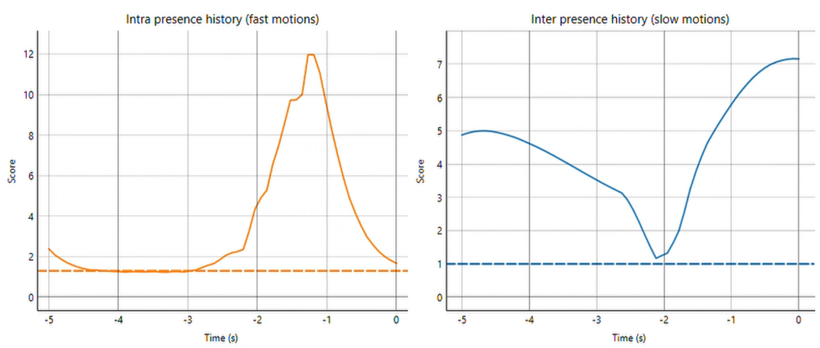
This measurement was done by walking side to side at set distances. These distances were at a distance of 1, 2, 3, and 4 meters. For all of the distances this should keep the tester in the same test area. The width of the room was 3.15 m. With the sensor placed in the middle of the room the actual distance that the target is from the sensor can be calculated using Pythagorean theorem. When the distance from the sensor is 1 meter, the actual distance while at the outer point is longer than the maximum distance for zone 1 (1.5 m). For the later zones this becomes a smaller problem. What zones were triggered for each distance is presented in Table 4. Without glass in front of it the sensor triggered at all the distances. It also falsely triggered once but this might be that the distance away actually was over 1.5 meters. When the sensor was covered with the glass panel it worked well in the first two distances however when the distance got longer the weakened signal couldn't continuously detect the target. It still managed to detect the target for all the distances however the detection in zone 4 was only with the slow detection. This can be compared to without the glass which managed to trigger the fast presence detection in all the zones. It also falsely indicated for a short while that the target was in zone 4 when the distance from the sensor was 3 meters.

Table 4: Table showing which zones were triggered for each distance. BOTH means that both the sensor setups triggered that zone for that specific distance. NO GLASS means that the sensor without glass in front of it triggered it and GLASS means that the sensor with the glass panel in front of it triggered that zone.

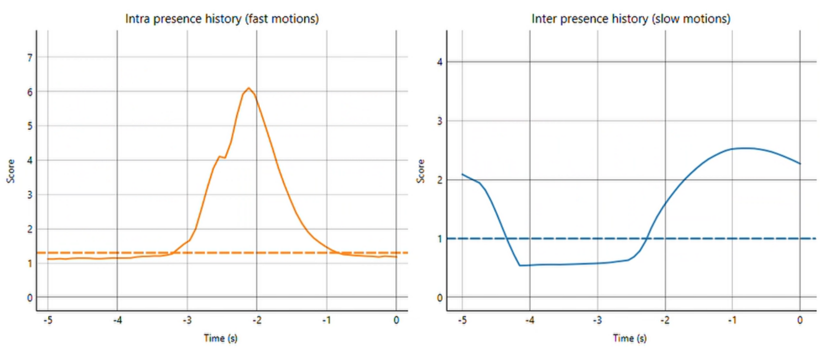
Distance [m]	Zone 1 Triggered	Zone 2 Triggered	Zone 3 Triggered	Zone 4 Triggered
1	BOTH	NO GLASS	NO	NO
2	NO	BOTH	NO	NO
3	NO	NO	BOTH	GLASS
4	NO	NO	NO	BOTH

The first distance from the sensor that was measured was the 1 meter distance. While walking past the sensor the fast presence score is increasing and while stopping and turning the slow presence stays high for a longer time. In Figure 38 the amplitude of the fast presence score even goes below it's threshold while the target is turning. This can be seen more clearly in Figure 38(b). There it can also be seen that for a short while it lost vision of the target. This happened one time out of the four times the tester walked past the sensor.

When the target gets further away the amplitude decrease behind the glass is quite noticeable on the sensors ability to pick up the target. At a distance of 2 meters both the sensors still work. However, the lower amplitude in Figure 39 is quite noticeable. At the 3 m measurements the sensor starts to struggle behind the glass. In Figure 40(b) the amplitude of the fast presence detection barely makes it above the threshold for a trigger. The duration of when the sensor sees the target also starts to increase significantly. At 4 meters the fast presence detection for both of the sensor setups starts to struggle. Especially in Figure 41(b) the fast presence score never crosses the threshold. The slow presence detection however manages to cross it from time to time. For the unobstructed sensor the slow presence detection is constantly above the threshold while the fast presence fluctuates around the threshold.

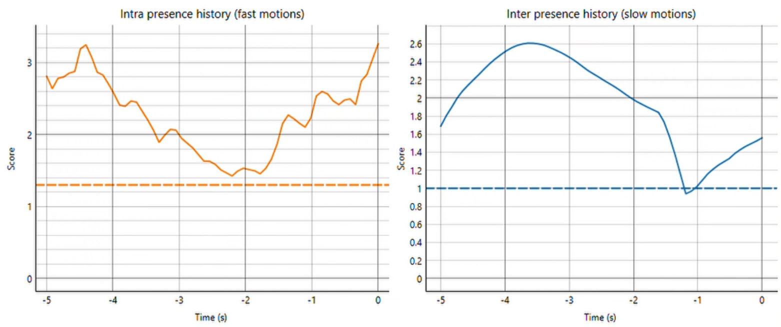


((a))

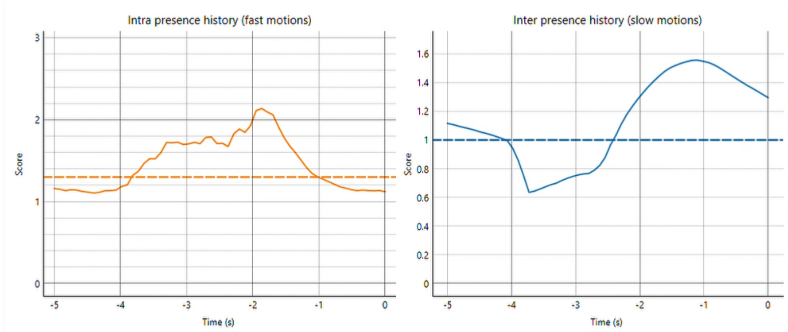


((b))

Figure 38: The response from the sensor when walking side to side at a distance of 1 meter. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.

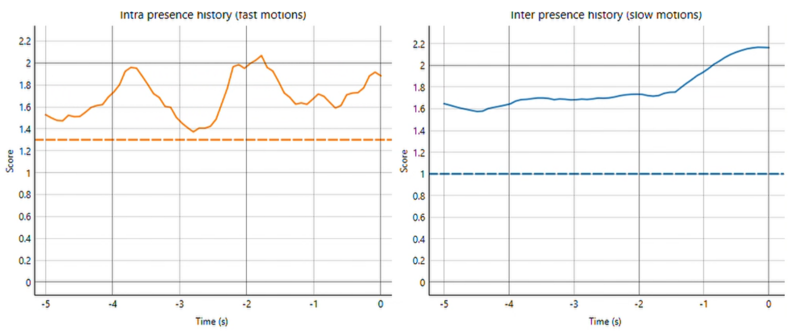


((a))

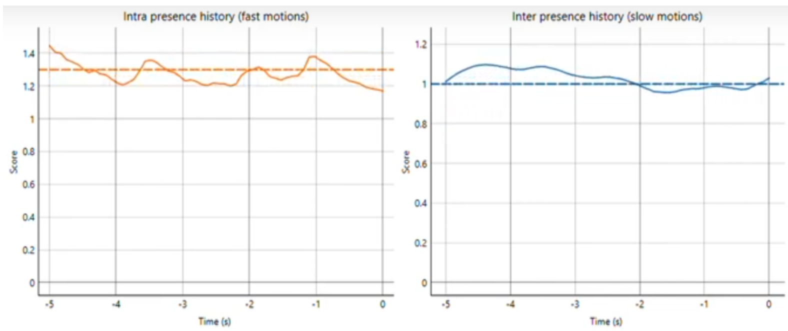


((b))

Figure 39: The response from the sensor when walking side to side at a distance of 2 meter. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.

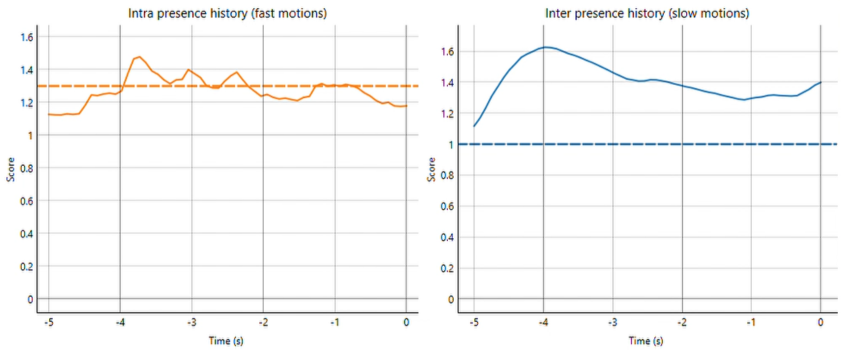


((a))

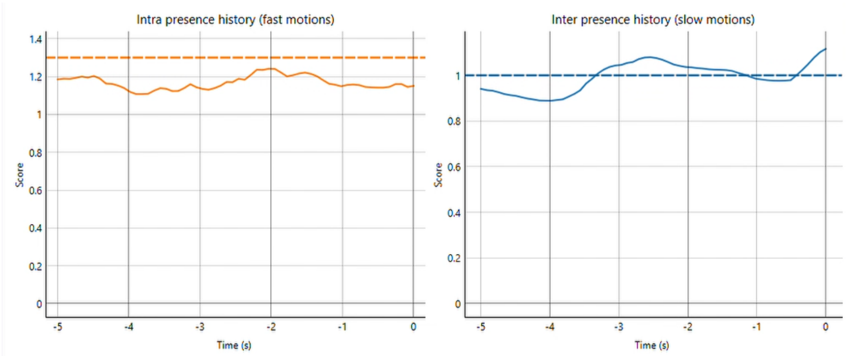


((b))

Figure 40: The response from the sensor when walking side to side at a distance of 3 meter. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.



((a))



((b))

Figure 41: The response from the sensor when walking side to side at a distance of 4 meter. (a) Without glass in front of the sensor. (b) With glass in front of the sensor. Each picture contains one graph of the history for fast presence and slow presence detection.

Interested in how much weaker the signal got from the glass panel in front of it, a measurement at a distance of 3.25 meters was done with the glass panel in front of it. As can be seen in Figure 42, the behavior is the same as in Figure 41(a), with the fast presence score hovering around the threshold and the slow presence with a higher average score. The slow presence amplitude isn't as high but is almost constantly above the threshold.

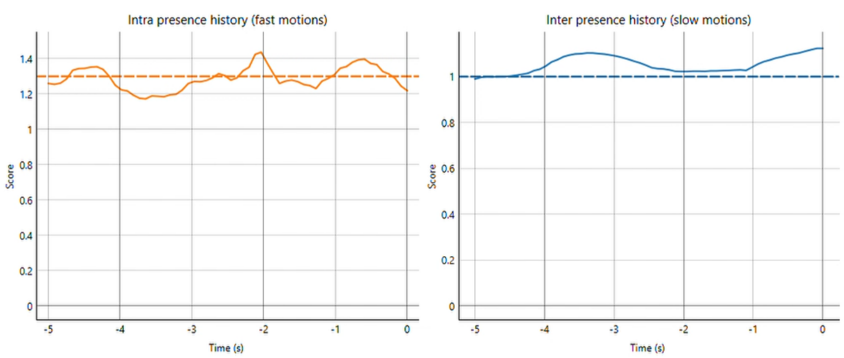


Figure 42: The response from the sensor behind a glass panel when walking side to side at a distance of 3.25 meters.

4.4 Measurement 3 & 4

These two measurements were more rudimentary than the previous two. For measurement 3 when a tester walked around outside the range of the sensor nothing happened on the sensors. The sensor respected the set range limits and didn't trigger at objects moving outside it's range.

In measurement 4, while walking away from the sensor 1 meter beside the sensor it started to notice the person at a distance of 1 meter. That would mean that the field of view is 90°. At distances closer than this while standing the score for the slow movement sometimes rose. If this was due to a person being in the field of view or if it was due to the field of view varying at closer ranges couldn't be determined. For all distances at a longer distance the field of view was big enough to see the tester at all times.

5 Discussion

This section discusses the results from the tests on the different sensors. Each sensor is individually discussed, providing reasons for its suitability or unsuitability for this particular use case.

5.1 Analog and Digital PIR Sensor

The Analog PIR Sensor is the sensor currently in use in the intercom product. The sensor is very simple to implement and uses the fact that human bodies emit IR radiation that heats the pyroelectric elements in the sensor. The sensor consists of two of these elements and when they are heated different amounts they produce a voltage between them that is then measured. In other words the sensor detects temperature differences in it's field of view. The Analog PIR Sensor then outputs a voltage corresponding to how big the temperature difference between it's pyroelectric elements is. The Digital PIR Sensor is essentially an improved version of the Analog PIR Sensor. The sensor works with the same physical principles as the analog one but can be more flexible since it outputs a digital signal that can be treated in software. The sensor gives a negative value if the derivative of the temperature difference is negative and positive if the derivative is positive. This could be useful in some cases. Since the sensor outputs a value between -2040 and 2040 depending on how much presence (or temperature difference) it sees, it could be used to program a smarter presence detection. For example if someone exits a building where the intercom is installed, they will probably first get in front of the presence detection and then walk away from the intercom. It might be possible to detect that this is a person walking away from the intercom and not wake it up. Since in this case the Digital PIR sensor should first register a big presence value but then it should decrease as the person walks away. If a person comes towards the sensor it would be the opposite way, just as seen in the result when performing the tests of a person approaching from 12 meters in Figure 25. The sensor has some base noise but as can also be seen in the figure, it's easy to differentiate when it triggers since the noise is relatively low at around 0.3 of the maximum trigger value. There are some spikes at higher amplitudes with the highest ones reaching about 0.5 of the maximum value. The high noise is because of the step response and filter combination that is in use. The combination used in the measurements was the most sensitive one. This resulted in a higher noise compared to other step response and filter combinations. Other combinations will give less noise, but also lower range.

There are some cons regarding this sensor for this use case. The first problem with the sensor is that it needs a special plastic piece in front of it to be able to see through. This plastic piece is as declared in the introduction hard to get certified as a weather proofing material. The sensor should also preferably have a Fresnel lens that focuses the IR radiation onto the sensor to improve the performance. This is hard to have while simultaneously protect it from weather and wind. Another problem with the sensor for outdoor use cases is that since it works by detecting temperature differences in front of it, the performance is worse when it's very warm outside or if it's in direct sunlight. If it's warm outside the human body temperature will be camouflaged in the hot air and if there is a lot of sunshine there is a greater risk of false triggers because there will be temperature differences even if there are no humans.

Another unfortunate property that impacts the viability of the PIR sensors is that they detect movement side to side much better than movement towards them. It could be seen in the result that when walking towards the sensor in Figure 25 the Digital PIR Sensor triggered at around 4 meters and the Analog PIR did not even trigger, but when walking side to side the Digital PIR triggered already at 10 meters as seen in Figure 26(a) and the Analog PIR triggered at 2 meters as seen in Figure 26(d). In this projects use case the most important movement to detect is movement towards the sensor, since the purpose is to wake up the intercom device when someone is approaching. Sideways movement should preferably be ignored since this means someone is just passing by and not approaching the door. This reversed nature of the PIR technology makes it unsuitable for this project. If the sensor would be implemented into the product the way it is now the sensor would wake up the intercom every time someone walked past it.

The reason that the Digital PIR Sensor triggers much earlier than the Analog PIR Sensor has to do with two things. Firstly, the Digital PIR Sensor had a Fresnel lens that came with it while the Analog PIR Sensor had not. Secondly, the Digital PIR Sensor was configured to use it's most sensitive filter. This was configured as seen in the Arduino code in Appendix A. The Analog PIR Sensor cannot be programmed with different filters. Given more time the PIR sensors could have been further tested with different lenses and different digital filters to see if range and consistency could be improved but the fact that they triggered much more on movement side to side than movement towards them made this project continue with other sensor technologies.

5.2 Active IR Sensor

The Active IR sensor had according to the data sheets a maximum range of 1.5 m. During the measurements done in test 1 in this project, the maximum range of the sensor was around 2 m. This can be seen in Figures 25, 26(d) and 26(e). It's possible the manufacturer has a different definition of when the sensor is considered to have triggered, but in this project, the sensor is considered to start trigging at around 2 m. The graphs show a couple of important things relevant for the usability of the sensor in this project. As can be seen in Figures 26(d), 26(e) and 26(f) the Active IR sensor triggers only when the person is walking directly in front of it, meaning the sensor seems to have a narrow field of view. Another thing that can be seen is that while the sensor can be considered to start trigging at 2 m distance, the difference in how distinctly the sensor triggers between the test on 2 meters distance and 1 meter is large. The sensor triggers much more clearly on short distances, preferably even smaller distances than 1 meter. The sensor was not tested in outside environment in this project, but there is a clear risk that the sensor would be affected by sunlight since it uses IR light to detect distances. If comparing the two graphs in Figure 24 it can actually be seen that the noise of the Active IR sensor is a bit higher when the lights are on in the room. This suggests that ambient does affect it, and that might be an even bigger problem in sunlight. Even if the sensor uses IR light in different wave lengths than the PIR sensors, it still has problem with seeing through material that can weather proof it. In subsubsection 2.2.2 it was mentioned that near IR light would go through glass however from the tests done that didn't seem to be the case. That would mean that the same solution that is currently in place for the analog PIR sensor would have to be used with an active IR by putting a plastic cover that is translucent for IR light to weather proof it. This sensor is made for close distance proximity sensing in an inside environment and therefore this project continued without it after the first test.

5.3 Ultrasonic 1

The ultrasonic 1 sensor is a cheap hobby sensor that is popular in hobby use cases since it's simple to use with an Arduino. It's supposed to have a measurement range between 2-450 cm and a resolution of 0.3 cm. During the tests done in this project the maximum range measured was about 3 m. The consistency at this range was very low and often it didn't trigger until around 2 m. In Figure 25 it triggers at around 3 m but at for example the 45 degree measurements in Figure 27(d) and Figure 27(e) it does not trigger until its closer than 2 meters away. This could be because of a very narrow field of view. The inconsistency and low range is not the only problems with this sensor, it is also big compared to the other solutions and would be hard to implement in the intercom. The main problem however was that even if it could fit inside the intercom there would still be the problem of implementing it behind some type of cover so that it is weather proof. Because of these reasons this project continued without this sensor as well after the first test.

5.4 Ultrasonic 2

The Ultrasonic 2 sensor is a more professional sensor made for commercial use cases. It's much smaller and uses the same element for transmitting and receiving the signals compared to the Ultrasonic 1 that has one transceiver and one receiver. The sensor was tested with it's own evaluation kit and software. The software comes with some additional smart functions, like static target rejection. This function is perfect for this project since the intercom should only wake up at movement. In the graphs from test 1, two Ultrasonic 2 sensors were tested. During the false trigger tests it was seen that one of them, the sensor called *Ultrasonic 2 - Sensor 1* in Figure 24 seemed to be damaged because it was getting high false readings regularly. Therefore, since there was two sensors of the same kind, this sensor was not considered during the other tests.

The range of the Ultrasonic 2 sensor is supposed to be around 5 m according to the data sheets. However, this depends on the material the sensor's signals reflects upon. Humans and clothes do not provide as strong of a reflection as many other materials. This could be the reason that the sensor when tested only got around 3.5 m of range. It also seemed to easy loose sight of the human, as for example seen in Figure 40 the sensor detects the human at around 3 m, but then instantly loses sight of the target. This could be because it's hard for the sensor to get reliable readings from the clothes of the target. Overall when walking side to side in front of the sensor it can be seen that the sensor often loses sight of the human.

This sensor has housings that makes it waterproof, which maybe would make it possible to implement in a good way into the intercom (if the housing is able to get certified). But the results of the measurements of this project did not look very promising. For future work it would be interesting to test the sensor more with different software settings, it might be able to perform better and since it is very small to the size and can be made waterproof, it can be a possible presence detection solution. It is also a very energy efficient solution as mentioned in 2.3.5 with a maximal supply current of 247 µA and a voltage of 1.8 V the power consumption is less than 0.5 mW. In this project, it was decided to not continue pursuing this technology though due to the downsides previously mentioned.

5.5 Microwave Doppler Radar Sensor

The Microwave Doppler Radar Sensor used in this project was the RCWL-0516 sensor. This is a cheap hobby radar sensor that uses microwaves in the 3 GHz range to detect movement. The sensor is binary and only outputs a 1 or a 0 depending on if it has detected any movement or not. When testing this sensor it performed really well. It did not once falsetrigger and it did not once miss to trigger when it was supposed to. It also seemed to be unaffected by the hardened glass. This can all be seen clearly in the graphs from test 1. There was a couple of problems with the sensor though. Since the sensor uses a relatively low frequency of 3 GHz, the range and ability to penetrate material is very good, but it also means that the field of view for the sensor is basically 360 degrees. The sensor detects movement on all sides and this can lead to false triggers in a real use case. This could maybe be solved with encapsulating the back side of the sensor in metal but its not optimal. The sensor is also very simple, the fact that it only outputs a 1 or 0 seems like a lost opportunity since then no smart functions can be implemented, like for example ignoring people passing by on the street.

It's also very hard to find reliable information about the sensor online, most data sheets found online is made by ordinary people and not the manufacturer. There is very little information about who manufactures the sensor and this makes it hard to implement because if this was going to be implemented. The company would probably integrate the chip on to the PCB board inside the intercom and design the antenna by themselves. This is very hard if there is no information to be found. This sensor did however show that radar technology is a good solution for this project but this particular sensor is not the best choice.

5.6 Pulsed Coherent Radar Sensor

After seeing that radar technology had good potential for this project, the search for a more professional sensor began. The goal was to find a sensor that was small, possible to implement inside the intercom, power efficient and smart. Acconeer's A121 Pulsed Coherent Radar Sensor seemed like a good choice and is the last sensor that was tried in this project. The sensor uses pulsed coherent radar technology and has a frequency of 60 GHz. The range is up to 20 m. This is far above the needed range for this application. However with such a long range and due to the high precision that is possible there is a good possibility to track the target very well.

First the performance of the sensor without the glass cover will be discussed. Without the glass cover it performed well. In Figure 37(a) the entire history of the amplitude when walking towards the sensor is shown. When walking away from it it also tracks the target very well. Table 4 shows that the sensor tracks the target in all the zones when walking in them. There was a false trigger of zone 2 when at a distance of 1 meter but this could be explained by the fact that the distance to the sensor was probably at the threshold of 1.5 meters when turning. In theory it would be about 1.8 meters away but with the size of a person it is probably rather at a distance of 1.5.

In subsection 3.3 the optimum thickness and distance to the sensor of a glass cover is discussed. The glass cover used for the experiments was the glass panel that is currently in the product and was not optimized at all. Neither the range nor the thickness could be optimized due to not having data on what the dielectric constant of the glass panel was. This impacted the amplitude of the signal quite a lot. This is visible in Figure 37 where the amplitude is much lower. However as mentioned in subsection 4.2 When walking both away from and towards the sensor it triggered in all zones. The lower amplitude wasn't that impacting in this case. It did affect the results when walking side to side in the zones however. At the further distances it had trouble to see the target. This isn't as big of a problem though. Most of the time when someone is walking through the sensors field of view sideways they are not on their way to the intercom. Therefore losing view of the target won't impact the ability of it to do it's job of waking up the intercom when someone is approaching it.

Something that happened for both the sensors and was briefly mentioned in subsection 4.3 was that when walking side to side the slow presence detection performed a lot better than the fast presence detection. Because when walking side to side in a zone the distance from the sensor doesn't change that much and the sensor sees the movement of someone walking in front of it as a person slowly moving a couple of centimeters or decimeters. With this in mind it should be possible to rewrite the code in a way that it ignores slow movement and only checks for fast movement. This however could create problems and might make it inaccessible to people that are moving very slowly. The walking speed tested was a "normal" walking speed and for someone that is much slower the slow presence detection might be the presence detection that triggers. It wouldn't really help with blocking side to side movement. Only in the four meter test with glass Figure 41(b) would it block out the side to side movement completely. The zone detection when walking side to side presented in Table 4 was also exact enough that using them instead to see if a person is approaching or passing by would work in most cases.

Unlike for the previous sensors tested the maximum range was not tested. The reason for this is that when simulating walking towards the sensor it was decided that a good distance to start up the device was at a distance of three meters. Therefore there was no reason to see a very long distance from that. It was decided to use four zones positioned at one meter intervals from 0.5 meters to 4.5 meters away. This allows for software optimization to decide which zone combinations start the system. An example could be to only start the intercom when the approaching person walks from a zone into a lower zone, for example from zone 4 into zone 3. If the person walks into a higher zone or stays in the same zone, that means he or she is either walking away from the intercom or just passing by, then the intercom does not need to wake up.

An interesting future experiment would be to test the field of view at longer distances in order to see if the field of view varies with range or if the 90° FOV that was measured is constant for all distances. In Figure 9 it can be seen that the angle the sensor can see is dependant on the distance from the sensor in a sort of balloon shape. It is also impacted by the lens that is used. Therefore it can be assumed that the glass cover in front of it would impact the field of view in some way.

It would also be interesting to build a setup with optimal radome thickness and distance according to the calculations made in subsection 3.3, or if the dielectric constant of the hardened glass is measured, optimize the thickness of that to see how much of an improvement that does. There is also the possibility of designing and testing different lenses for the sensor. In Figure 43 some pictures of the intercom with the sensor mounted inside where the PCB usually is installed can be seen. This is a proof of concept that shows that it's possible to install the sensor on the PCB and have it detect through the hardened glass, and this works even without any optimization at all.

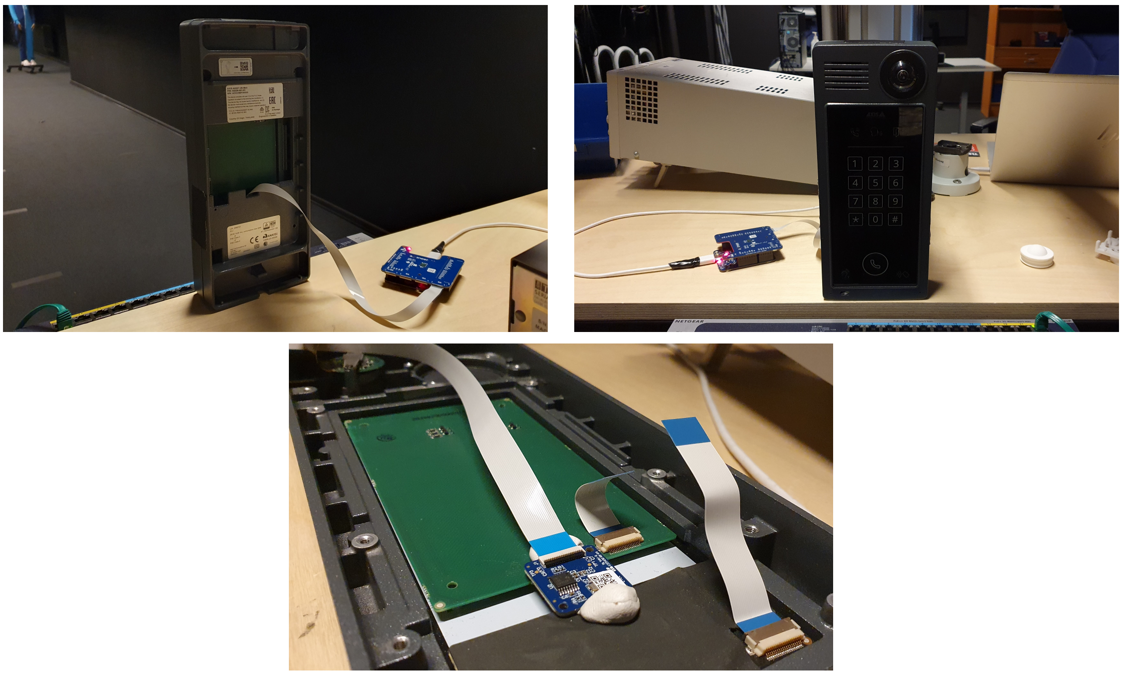


Figure 43: Pictures of the intercom with the Acconeer sensor mounted inside.

5.7 Final selection

It is necessary to take several parameters into account when deciding on which sensor to implement into the intercom. There were five parameters that were of interest in this project. They were weighed against each other to see which sensor performed best.

- Mechanical design freedom - The difficulty of integrating the sensor into the product. This takes into account the size of the sensor and if there was a need for specific protective materials to protect the sensor.
- Reliability - How well the sensors managed to react to a movement that they were supposed to react to. This includes the ability of the sensor to spot movement towards it and how well it was able to continuously detect the movement.
- Range - How far the sensors were able to detect movement.
- Resistant to false triggers - The ability for the sensors to ignore movement that was not towards them.
- Data quantity - The amount of data that the sensor gives out. The baseline is that the sensor sends out the amplitude of what it measured. One example of this is ultrasonic 1 which sends out the measured range. The sensors that performed better here sent out additional information, such as the pulsed coherent radar that also measured the amplitude and phase at each of the measuring points. The lower-performing sensors only sent out a binary signal showing if there was movement detected or not.

Table 5: Comparison table for the tested sensors.

	Mechanical design freedom	Reliability	Range	Resistant to false triggers	Data quantity
Analog PIR	0	-	-	-	-
Digital PIR	0	+	+	-	0
Active IR	-	0	-	0	0
Ultrasonic 1	-	-	0	-	0
Ultrasonic 2	+	-	0	+	+
Microwave Doppler Radar	+	+	+	-	-
Pulsed Coherent Radar	+	+	+	+	+

As seen in Table 5 the Pulsed Coherent Radar sensor was found to outperform the other sensors in all parameters investigated. The radar technology enables higher mechanical design freedom, reliability, and range than the other methods. Since the Pulsed Coherent Radar sensor was a professional and high-frequency sensor it also provided better resistance to false triggers than the Microwave Doppler Radar. The Pulsed Coherent Radar sensor provides more data than the other sensors which makes smarter presence detection algorithms possible.

6 Conclusion

This project's goal was to find a new solution for presence detection that reduced the problems with the old PIR sensor. These problems were the amount of false triggers and the dependence on a special plastic cover for the PIR to work. The result of this study conclude that radar sensors is the best way forward because they make it possible to place the sensor behind a wide range of materials, and with good design choices the sensor would not be affected by the cover. There are many different manufacturers of radar sensors but the one evaluated in this project was the Acconeer A121 Pulsed Coherent Radar Sensor. This sensor can reduce the amount of false- and unnecessary triggers significantly with its accuracy that makes it possible to implement smart algorithms to only wake the device up when a person is approaching it. This in combination with the possibility to install the sensor on the intercom's PCB behind the hardened glass cover makes it a good solution and a great improvement to the currently used PIR sensor. The amount of mechanical design freedom the radar sensor provides compared to the PIR sensor is of great value to the company.

6.1 Future work

There are several different companies developing presence detection radars with different frequencies, sizes and functions with each. The one tried in this study was a 60 GHz Pulsed Coherent Radar Sensor and just with this sensor there are a lot of different settings and set ups that would be interesting to test. With optimized settings, radome distance and thickness and maybe even a lens the sensor would probably perform a lot better than shown in this study and also be more power efficient. It would be interesting to see a study focused on one or two radar sensors where they are optimized and installed in the product to see how well they can perform. Another thing would be to write and test the algorithms to differentiate between a person walking away, past or approaching the intercom and only wake the device up when someone is approaching. With the Acconeer radar sensor, it is allegedly possible to implement gesture control using machine learning thanks to the sensors high accuracy. This is something that would be interesting to see further explored.

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A Appendix

Arduino code for the Digital PIR Sensor

```
#include <Wire.h>

#define PIR_ADDRESS 0x00

void setup() {

  Serial.begin(9600);
  Wire.begin();
  Wire.beginTransmission(PIR_ADDRESS);
  Wire.write(0x0);
  Wire.write(B00000000);          // 87-80
  Wire.write(B00000000);          // 79-72
  Wire.write(B00000000);          // 71-64
  //Wire.write(B00001001);          //63-56  / D step 1
  Wire.write(B00000100);          //63-56    /B step 3
  Wire.write(B00001111);          //55-48
  Wire.write(B00000000);          //47-40
  Wire.write(B00000000);          //39-32
  Wire.endTransmission();

}

void loop() {
  byte highByte, lowByte;

  Wire.beginTransmission(PIR_ADDRESS);

  Wire.requestFrom(PIR_ADDRESS, 2); // Request 2 bytes of data
  if (Wire.available() ≥ 2) {
    highByte = Wire.read(); // Read the first byte (MSB)
    lowByte = Wire.read(); // Read the second byte (LSB)
    Serial.print("highbyte pre and func:");
    Serial.println(highByte);
    highByte = (highByte & 0b00001111); //Take away the 4 dummy bits
    int16_t value = (highByte << 8) | lowByte; // Combine the two bytes into a single int value

    if (value & 0x800){
      value = value - 0x1000;
    }

    Serial.print("Motion value: ");
    Serial.println(value);
    Serial.print("highbyte:");
    Serial.println(highByte);
    Serial.print("lowbyte:");
    Serial.println(lowByte);
  }

  delay(400); // Wait a second before checking again

}
```