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Opportunities for Low Power Occupancy Sensor

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Title:	Opportunities for Low Power Occupancy Sensor
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Problem given by:	Disruptive Technologies, Pål Øyvind Reichelt

Task Description:

The task given by Disruptive was to survey existing possibilities for presence detection in a room. A list of objectives with regard to power consumption, detection area, sensitivity, peak current, detection time, cost, volume, memory usage and CPU/DSP demands where given.

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Summary

Disruptive Technologies have developed a low power IoT chip. To further improve their chip, the task of developing a low power occupancy sensor was given. There are several commercially available motion detectors on the marked, but real occupancy sensors, with the possibility to detect presence and not only movement, is not in widespread use. To be able to detect presence two possible technologies are in focus in this thesis, ultrasound and radar. The main goal of the thesis, has been to show if it is possible to design a occupancy sensor, within the objectives given by Disruptive, the main objective is a average power consumption of 450nA. To be able to achieve this requirement it was chosen to focus on ultrasound technology and look closer at a possible COTS transducer.

There were made no test with the selected transducer, but calculations on the power consumption where made. These calculations showed, that it is not reasonable to assume that the selected transducer, could be made to comply with the stringent power requirements. To further make this case, test where performed with a secondary ultrasound transducer to demonstrate some of the issues with employing ultrasound, in a low power system. It was shown that ultrasound are prone to large propagation losses, giving it a range shorter than wanted. Based on the research done in this thesis it is not possible to make any final conclusion on the possibilities to use ultrasound in a low power occupancy system. It is however shown that ultrasound has some challenges not present with the use of radar. These challenges are connected to wave propagation, where ultrasound have a greater propagation loss compared to radio and to much time is spent listening and processing the echo signal with the use of ultrasound. For further research into the field of low power occupancy sensing, radar is therefore recommended, rather than ultrasound.

Preface

This project started as a task given by Pål Øyvind Reichelt and Disruptive Technologies, on the possibility of a low power, battery powered occupancy sensor. This project was a great opportunity for me to explore the world of sensor technology.

I would like to thank Pål Øyvind Reichelt for all help and encouragement throughout this project period. Øystein Moldsvor was of great help with soldering of the SMD mounted transducer and help with testing the circuit. Trond Ytterdal for counselling and Mathias Tømmer for guiding me trough the finishing of the report. This thesis would never have been possible without the help, pressure, chocolate deliveries and love from my fiancée, Mia.

Håkon Mellbye

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Listings

Acronyms

AC	Air Condition
ADC	Analog-to-Digital Converter
COTS	Commercial off-the-shelf
DAC	Digital-to-Analog Converter
EM	Electromagnetic
EVM	Evaluation module
FIFO	First In First Out
FSPL	Free-space Path Loss
HVAC	Heating Ventilation and Air Conditioning
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
IR	Infra Red
LNA	Low-noise Amplifier
LSB	Least Significant Bit
MSB	Most Significant Bit
PIR	Passive Infrared
RF	Radio Frequency
SMD	Surface-mounted device

SNR	Signal-to-noise Ratio
SoC	System on Chip
ToF	Time of Flight

Chapter 1

Introduction

1.1 Motivation

Disruptive Technologies, a company focusing on IoT solutions, are developing a IOT chip capable of living of a 20mAh battery resource for at least 15 years. This chip will incorporate several sensors to be able to provide a smarter home. One of the sensor Disruptive wish to incorporate is an occupancy sensor. Occupancy monitoring features several challenges, where the most prominent is the detection of presence when the object is stationary. There are several commercially available sensors for motion detection, where the best known and widely used are Passive Infrared(PIR) and ultrasound sensors. The opportunity to detect presence in a room can then be used to control lightning, air condition, heating and much more.

1.2 Introduction

To be able to test the design of a low power occupancy sensor this thesis will cover some of the basic principles for motion and occupancy sensing. Due to the extreme low power consumption required, a system able only to detect movement will be investigated first. The proposed motion sensor is then required to be modified to an occupancy sensor, with a different mode of operation, with less stringent power requirements. The focus of this thesis will be on the motion sensor and investigate if it may be implemented with commercial of-the-shelf (COTS) parts. The main objectives of the thesis is listed below.

- Survey of existing occupancy sensing methods and map out their benefits and drawbacks in terms of sensitivity (range), accurate detection vs. false triggering, instantaneous and average power consumption, size (physical volume required) and cost. In addition compare how the various technologies complies with a prioritized requirements list given by Disruptive.

- Based on the survey to identify the best candidate for a sensor based on the set of given target requirements, where low average power consumption will be the most important factor.

- Assessment of different types of technologies based on commercial available parts (COTS) and analyse compliance towards the list of requirements from Disruptive.
- Explore the opportunities for further work on a low power occupancy sensor.

The power resource requirement to do this may be broken into two different parts, sensing and data processing unit, which may be explored separately. For this report the sensing unit will be in focus, the complexity of the data processing will be taken into account, but the power requirements will not be analysed. After reading this report, one should be able to use the information attained to understand the different disadvantages with the various sensor technologies, and be able to better select an appropriate sensor technology for other projects. Further it should be read as an requirement study for a low power occupancy sensor. Highlighting the minimum requirements for a working occupancy sensor, as well as an feasibility study of the implementation of an occupancy sensor onto the chip developed by Disruptive.

Chapter 2

Background Theory

This chapter will present some background information to better understand the most used effects employed in sensor platforms used for motion or occupancy detection. This includes pyroelectrical and piezoelectrical effect as well as some theory on wave propagation and reflection . The last section will cover some basic challenges in human occupancy monitoring

2.1 Physical Effects

Many sensing application, requires the conversion of energy in one form to another. For passive sensing, a sensor where no active signal is emitted, there are several ways of detecting human presence. Humans emit energy in the form of heat and sound is generated when moving. To sense the energy emitted in the form of heat the pyroelectric effect may be utilized, to detect sound the piezoelectric effect may be utilized to convert sound waves into electrical energy, and vice verca.

2.1.1 Pyroelectric Effect

When subjected to temperature change some crystals have the ability to generate a temporary electric polarization, this effect is know as the pyroelectric effect. Any change in temperature will then cause a change in the magnitude of the materials polarization. This change may be massured, and the resulting current generated may be found by equation 2.1, where p is the pyroelectric coeficent, A is the area of the electrode, and dT/dt is the rate of temperature change [9, p. 52-54].

$$I = pA\frac{dT}{dt} \tag{2.1}$$

To utilize the pyroelectrical effect two pyreelectrical elements may be coupled together in reversed polarization. Then when a rapid change in heat is detected the sensor will perceive this as a detection only if the element next to it is exited as well.

Due to the small changes in polarization the use of reversed polarization is also preferable to make detection off a exitation easier. When kept at a constant temperature the voltage across the crystal will dissipate due to leakage current. This makes near constant measurement important. To be able to detect larger areas a fresnel lens is often incorperated into sensors utelizing the pyroelectric efect. The fresnel lens is used to focus the infrared light from larger zones onto the pyroelectric elements. Figure 2.1 shows how a fresnel lens functions. The two elements coupled together will then have zones next to each other focused into the pyroelectric element. Since the zones widen as they get further away from the lens, it will be less sensitive to change in heat. Movement inside a single zone will not be detected.

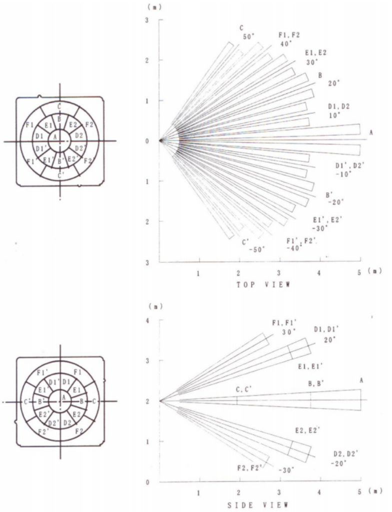


Figure 2.1: NL11NH Fresnel Lens [24]

2.1.2 Piezoelectric effect

The Piezoelectric effect is the conversion of mechanical pressure into electrical charge. Materials who are able to internally generate a electric charge when mechanical force is applied are also able to do the reverse. They are able to convert a electrical charge into mechanical force. This effect is utilized in many sensing applications, including sound, pressure and high voltage. For this report the main importance is the usage of this effect to construct ultrasonic transducers, able to convert electrical energy into sound waves and vice versa.

2.2 Electromagnetic Waves

The interest of this section is to provide some background information of attenuation of waves and the reflection of human tissue.

The Friis transmission equation [3], states that the difference between the received and transmitted power, given isotropic antennas may be may be found by the gain for each antenna, the distance between antennas and the wavelength of the transmitted signal. It's important to note that Friis equation only holds for distances, $d \geq \frac{2a^2}{\lambda}$, where a is the largest linear dimension of either of the antennas.

Friis transmission equation for isotropic antennas

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \tag{2.2}$$

The interesting factor for use in this report is the last factor $(\frac{\lambda}{4\pi R})^2$, this is also know as the free-space path loss, FSPL, when inverted. The FSPL may be seen as the loss in signal strength when the electromagnetic wave propagates trough free space. FSPL is only dependant on distance between targets and the frequency of the transmission. Where higher frequency, f, will result in higher loss as may be seen directly from equation 2.3, where $\lambda = \frac{f}{C_L}$ and $C_L$is the speed of light. Although for EM wave in the GHz range, C_L would be the driving factor and we may assume no loss when travelling trough air. The EM wave will still be dispersed.

$$FSPL = \left(\frac{4\pi df}{C_L}\right)^2 \tag{2.3}$$

Reflection When an electromagnetic wave travels trough a medium, and hits a new medium, part of the wave will be reflected. This reflection may be calculated by knowing the reflection coefficient ρ. The reflection coefficient may be found by equation 2.4, given in [20, p. 266] Where the parameter η is know as the intrinsic impedance of the medium. [20, p. 249]. This states that if the two mediums have an equal intrinsics impedance most of the energy in transmitted into the second medium. Conversely, if the intrinsic impedance differ greatly, most of the energy is reflected of the second medium back to the first. In [25, p. 42] a table showing the depth of human tissue at which power reduces to 99% is shown. This table shows that for increased frequencies the skin depth reduces, showing that more energy in reflected. This is also shown in [21], where the different layers of the body is investigated. Here it's shown that most of the signal is reflected by the layer of fat direcktly underneat the skin. For a more in depth explanation of reflection and electromagnetic waves [20, 25] is good sources for information.

$$\rho = \frac{E_1^-}{E_1^+} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \tag{2.4}$$

2.3 Ultrasound

Any sound wave above the range of human hearing (20kHz) are defined as ultrasonic [11, p. 29-30] In [6] a general rule of the effective distance of an ultrasonic transducer in air is formed:

> A useful measure of attenuation in air due to absorption is the extinction distance, or distance over which the amplitude of a signal is reduced to 1/e of its original value, which is about 1/10 or 20 dB for a round-trip doubling of the distance.

This may then be calculated by the absorption coefficient ρ, found in equation 2.5. where α is the root-mean-square pressure amplitude of an acoustical plane wave at a given initial location, ρ is the pressure amplitude of the wave after it has progressed a distance z in meters, and a is the absorption coefficient in inverse. Then the extinction distance, in mm, may be expressed as in equation 2.6

$$\rho = p_o e^{(-\alpha z)} \tag{2.5}$$

$$\text{Extinction distance} = \frac{5 \times 10^{13}}{f^2} \tag{2.6}$$

For a frequency of 40kHz this then gives a maximum distance of 31.25 meters, this rapidly decreases as the frequency increases. At 50kHz the range is reduced to 20 meters, and at 100kHz it's down to 5 meters.

Reflection An important factor in the calculation of acoustic waves is the acoustic impedance. For far field applications this may be treated as as a impedance R_a, which depends on the density of the medium, ρ and the speed of sound, C_S, as can be seen in equation 2.7. [27, chapter 29, p. 29-3] The speed of sound is highly dependant on the medium it travels trough, for sound travelling trough air the important factors are temperature, pressure and the chemical composition of air. For use in this report the speed of sound will be defined as 343 m/s, the typical value at 1 atm pressure and 20°c [27, chapter 29, p. 29-1]. Although this report won't take the differentiating speed of sound into account, it's an important factor to note if more precise calculations are needed. As for EM waves it's evident by equation 2.8, that an increased difference in impedance between the mediums will result in an increase in the reflected energy. The characteristic impedance of skin is given as 1.7×10^6 [11, p. 39], and the characteristic impedance of air at $20°C$ is 415Ω [10, p. 126]. Indicating that most of the energy from a sound wave will be reflected when hitting skin.

$$R_a = \rho C_S \tag{2.7}$$

$$\text{Reflection coefficient} = \frac{I_{reflected}}{I_{incident}} = \frac{(R_1 - R_2)^2}{(R_1 + R_1)^2} \tag{2.8}$$

2.4 Challenges In Occupancy Monitoring

When developing a sensor for occupancy monitoring, some challenges will arise. In the paper *A Survey of Human-Sensing: Methods for Detecting Presence, Count, Location, Track, and Identity* [22], six common challenges in human-sensing are presented. An abridged version is reproduced here.

1. **Sensing noise:** Noise generated by the irregular arrival rates of particles or waves being studied, thermal and quantization noise and aliasing. These are all sources of noise that must be taken into consideration when designing sensors. These are well studied effects with well know solutions.

2. **Environmental variations:** Unexpected or sudden changes in environmental conditions. Such as a PIR sensor being triggered by heat currents flowing from a HVAC system.

3. **Similarity to background signal:** A person must be separated from the background signal, but background signals in the real world may grow arbitrarily complex. Unwanted sources of signals with the same frequency spectrum or timing

characteristics, due to multipath or other phenomenons, may also occur, making correct detection more difficult.

4. **Appearance variability and unpredictability:** People come in all shapes and forms and walk and pose in numerous different ways. Furthermore people change there appearance with different clothes witch may change how waves reflect or make image analysis even more complex. People will also move unpredictably, making localization and tracking systems harder to implement.
5. **Similarity to other people:** A problem when tracking or identifying persons is the high degree of similarity amongst people.
6. **Active deception:** Jamming of radio systems, turning of the lights in camera covered areas or walking slowly to fool motion sensors. These are all possible ways to deliberately avoid detection.

Chapter 3

System Requirements

This chapter will introduce a prioritized list of objectives, given by Disruptive, these are all required to be taken into account when choosing a sensor technology. In the following subsections each objective will be elaborated with respect to the challenges that arises.

3.1 Objectives

There are several objectives that needs to be met to make a functioning low power occupancy sensor. Early in the process, Disruptive made a prioritized list of objectives. These objectives are shown in table 3.1 [18]. This list is not a list of absolutes, but if an objective is not met, it should be accounted for and solutions to overcome the problem should preferably exist. There is therefore not an absolute necessity to resolve all problems or design a fully operational prototype, but it should be made clear if a solution exist and that a sensor system may be developed to met these demands.

Table 3.1: List of Objectives

1.	Battery lifetime	$\geq$ 15 years from a 20mAh Li-MN02 battery
2.	Detection area	$\geq 50\text{m}^2$
3.	Sensitivity	detect a 10kg dog, given field of view
4.	Peak current,	$\leq$ 50mA/10ms
5.	Detection time	$\leq$ 1s
6.	Cost	$<$ 2USD in 100k volume
7.	Volume	$< 2\text{cm}^3$
8.	Memory usage	Low, <1kB
9.	CPU/DSP demands	modarate demands, $<$ 50MHz/50k

3.1.1 Battery Lifetime

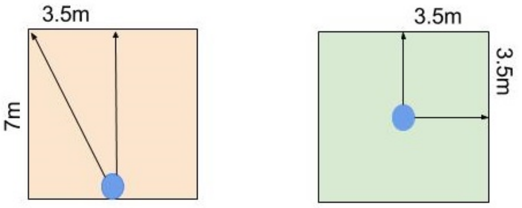
To be in line with the product Disruptive has developed, the proposed sensor system should have a battery lifetime of 15 years, given a 20mAh Li-MN02 battery. This is the total power budget of the chip developed by Disruptive, so the power consumption, should preferable be even lower than this. The power consumption will be the main objective for any proposed system, and any technologies chosen for this project will have to be able to deliver on this demand. The most important question this will ask of the technologies in question will be how much power it will require to operate as an occupancy sensor. The power required to do this may be broken into different parts, sensing and data processing unit, which may be explored separately. For this report the sensing unit will be in focus, but the complexity of the data processing will be taken into account. Since the processing unit is not a part of the design in this report, the power requirements of data processing will not be tested. When choosing technology, lifetime requirements will be a driving factor, such as how much energy is required to survey a room, and how often must this be done. The average current, given a 15 year lifetime from a 20mAh battery, could be found by equation 3.1 Giving a average current of only 150nA, or 450nW given 3V battery voltage. This does not take into account any degradation of the battery or similar effects but serves as absolute best case.

$$\frac{20\ \text{mAh}}{15\ \text{years}} = \frac{20\ \text{mAh}}{131400\ \text{h}} \approx 150\text{nA} \tag{3.1}$$

To be able to keep the power consumption as low as possible, some assumptions about the system as a whole will be made for use in this report. Firstly we will assume that when the sensor is in power down, no sensing and no data processing, there will be no leakage current. This is not a likely scenario, but the developed system from Disruptive already have a power management system that makes sure that when subsystems are turned off, the leakage current is < 1 nA. [18]. Further this report will not look at a finished system, but only subcomponents, so it will only be able to test the power consumption in these components, witch then should be well under the limit given by the battery.

3.1.2 Detection Area

To be able to compare the detection area of different technologies, two expressions will have to be clarified: range and detection angle. When used in this report, range is the maximum distance from the sensor that a target may be detected, while detection angle is the angle the sensor may detect within. For a sensor, the range and angle of detection will be greatly impacted by the placement. To calculate an estimation of the required range and angle, we will assume a square room 7 by 7 meters, giving a 49m^2 room, with a hight of 3 meters. When placing the sensor in a room, there is two different placements to look into, wall and roof, as seen in figure 3.1. Placement in a corner will not be possible due to the form of the finished product by Disruptive. This is simply a small chip placed directly on the wall. A placement in a corner would not be recommended as it would not be possible to place it so that it points towards the middle of the room. When placed on the wall we will assume that the sensor is placed in hight with the target, making the calculations easier. These calculation will be enough to give a rough estimate of the required range. For a placement in the middle of one wall the required range is close to 8 meters as seen in (3.2), this solution would require a 180° detection angle. The last possibility would be to place the sensor in the middle of the roof. This would drastically reduce the range of the sensor to 4.6 meter, as seen in 3.3, although it would increases the detection angle to a full 360° The most important aspect to note is the fact that the placement of the sensor will impact both the detection angle and the range. From the calculations it is clear that the maximum detection range is 10 meters, but that it could drop to as much as 4.6 meters with restrictions on the placement of the sensor. A full 360° may be hard to achieve. Therefore the most likely placement would be somewhere along the wall and the chosen technology would preferable provide a range of 7 to 8 meters and 180 ° angle of detection. Depending on the chosen technology some placement may also be more profitable then others.



(a) Wall placement

(b) Roof

Figure 3.1: Alternative placement of sensor

$$X^2 = 7^2 + 3.5^2 = 61.25 \ X = \sqrt{61.25} \approx 7.83m \tag{3.2}$$

$$X^2 = 3^2 + 3.5^2 = 21.25 \ X = \sqrt{21.25} \approx 4.61m \tag{3.3}$$

3.1.3 Sensitivity

The sensitivity of the system is defined as its opportunity to discover targets. In the previous section, range was discussed and it was made clear that a range of eight meter was wanted. With a demand for detection of a 10 kg dog, given a field of view, this implies that a dog should be detected at a distance of eight meters. To fully meet the objective of working as an occupancy sensor this requirement will not be sufficient. One of the main challenges with occupancy monitoring is to detect stationary targets. Everyone have experienced the bothersome light controller who turned of the light while you were still sitting in the room. Forcing you to wave your arms to turn the light back on. This is an issue since many sensors have problems with detecting small movements or stationary targets. For this system to operate in a home environment, detection of stationary targets would greatly improve the usefulness. Although this is beyond the initial demand from Disruptive, a system able to detect a stationary human, preferably also out of view, is a desired goal. To truly work as an occupancy sensor for home use, this is a goal that will have to be taken into consideration. The detection of stationary targets is the difference between a motion sensor and a true occupancy sensor. If detection of stationary targets is not possible to achieve. The goal must be that the system may detect very small movements. This also open up for a sensor who may have two modes of operation. One where its only required to function as a motion detector, to detect large moving objects and another for detecting stationary targets or targets with only small movement. This is possible since any target moving into a room is required to move over some distance before settling down. Put in other words, before laying down on the couch you first will need to walk up to it.

3.1.4 Peak Current

Peak current should be limited to a maximum of 50mA over 10ms. This objective will influence both the sensing and the signal processing of the system. Some energy will be needed to drive the sensor, and after the sensing some sort of signal processing. As for the power consumption objective, since this thesis will focus predominantly on the transducer, it is not possible to guarantee that a finished occupancy sensor will comply to this requirement, but it will be possible to make assumptions based on the data received from the selected sensor unit. If an active sensor unit is chosen this will most likely also be the driving factor of any peak current. Further excitation of a transducer and the data processing is by necessity also separated in time. Thus making sure the transducer or antenna, for a radar solution, does not exceeds the peak current limitations, is a large step in showing that a finished system will comply with the required 50mA.

3.1.5 Detection Time

The most time critical time for the system is when a room goes from unoccupied to occupied. For the system to work as a light control unit, persons walking into a room will have to be sensed within a short time frame. This time frame is specified as $\leq$ 1s. This does not take into account that there will be a time delay between detection and lights when the lights are turned on. At this early stage, this is not of concern. If the detection time must be decreased by a factor, it should be easy to calculate the new power consumption. When the system has detected a presence, the time frame may be increased drastically, since there is little need to know the precise time when the room is emptied. This holds true even if used to control HVAC systems. This time frame may be as much as one minute or even more. An increased time frame is profitable since the system may be in sleep mode between each sensing action. This is under the presumption that an occupancy sensor, able to detect presence without continuous monitoring is employed.

3.1.6 Other Requirements

Cost will be calculated when a technology is chosen, but it will not be a driving factor in the choice of technology. The volume of any finished sensor will have to be taken into account, since any proposed sensor should fit onto the developed chip from Disruptive. Memory and CPU/DSP usage, will be important as these factors all will impact the total power consumption of the system.

Chapter 4

COTS Sensors

This chapter will present the most used types of sensor technology for occupancy monitoring as well as an introduction to how they are used. Some lesser known and used technologies will briefly be explained. The last section will explain and justify the use of ultrasound technology, chosen for testing.

4.1 Infrared Sensors

PIR sensors are in widespan use as motion detectors [23]. There are several reasons for the widespread use of PIR sensors, price, complexity and ease of use being the prevalent reasons. PIR sensors are passive sensors which works by detecting infrared radiation or more simply put the heat of objects in the room. The key component to the power usage of PIR sensors is the reqiurement to amplify the the signal received from the IR elements, and the requirement to continously monitor them. Continous monitoring is required since the voltage induced quickly disperses, due to leakage currents when kept at a constant temperature. By utilizing a fresnel lens, it is possible to divide an area into several sectors, as shown if figure 2.1. A PIR sensor will only detect a movement if it detects a rapid change in IR over two or more sectors. In effect this makes is impossible to detect stationary targets. Additionally, due to the sectors growing further apart as one moves away from the sensor, detection of movement further away is often not possible. Slow motion is also a factor to take into account, if one sector detects a temperature change, the voltage induced in the sensing element may dispersed before the targets crosses over to the next sector. To detect change in temperature the pir sensor also requires an unhinderd field of view. The problem of detection rate have been studied and a solution implementing several PIR sensors in a sensor network are proposed in [29]. Here the detection rate is given as high as 100%. Since no energy is used to actively output a signal PIR sensors are know to use little energy, down to 4-7mW [23], this is still considerable higher than the 450nW required for this project.

PIR sensor implementations with lower power consumption may be possible, or already achieved, but the power consumption is not the only important factor when choosing to not look any further into PIR sensors. The low detection rate for stand-alone sensors, the lack of detecting minor movements and field of view requirements are all reasons that PIR is not suited for the proposed system.

4.2 Radar

The usage of RF radar for occupancy monitoring is quite new, but already commercial available systems exists, such as the X2M300 from Novelda [17]. These systems uses radar to detect human movement. A simmular system is also proposed in [28]. Where a CC2530 RF transceiver is used for developing the radio, sending a continuous wave at 2.405GHz. A later paper [12] have further explored and improved the system proposed in [28], with respect to power consumption.

The proposed 24GHz system in [12], reports of a power consumption as low as 0.2mW given 20 measurements per second. It's also worth noting that since the measurements is done inside a very short time frame, there exist an almost linear relation between the number of measurements and the power consumption. Further it's also important to mention that the measurements done in this report is done at short range with a simulated target, a 120mm × 80mm metal plate, at a distance of 2 meters. It's reasonable to assume that if the range was to be increased the power consumption would also be increased. Other preferable factors with the use of radar is the fact that no transducer is needed, only two antennas for Tx and Rx respectively. These antennas is also easily integrated on chip, leading to saved energy and size.

4.3 Ultrasound

The use of ultrasound in motion detectors are quite common and several commercial systems are available. The basic principle employed to detect motion is to send a pulse of energy in the form of ultrasonic sound waves, and observe any change in the reflected waves. The two most important factors which are used for detecting change in the reflected wave is time of flight(ToF) measurement and the Doppler effect. ToF simply listens and identify the amplitudes of the reflected signal and based on the time it took before being reflected is used to calculate the distance. This makes for very simple signal processing. Most research in the field of Ultrasonic transducers are geared towards use in the medical imaging field. This is not directly compatible with the use proposed in this report. The main problems are with the freqencies used and medium. For medical imaging purposes, freaquncys in the MHz range er used, as opposed to the 40-70 KHz range mostly used for transducers designed for use in air [11]. This brings us to the second problem, the medium the ultrasonic waves are sent through. In medical imaging, the transducer must be placed in direct contact with skin, otherwise to much of the signal energy is reflected of the body, due to the different reflection coefficients of air and skin [16]. It's the same effect that is utilized in ToF measurements, where the reflected signal from the target is then reflected and perceived by an receiver circuit. This reflection coefficient may be calculated by using equation 2.8. In [19] an ultrasound-based measurement system for human motion detection is presented which uses Hough transform to analyse the returned echo signal. However, no power consumption analysis of the proposed system are presented in the paper.

4.4 Other Sensors

4.4.1 Optical

A interesting soulution where a single pixlel CMOS camera is used as an motion sensor is described in [5], with a power consumption of only 32μW at 3.3 V. The sensors works by using a CMOS image sensor to capture low resolutions images and comparing the brightness, or number of white pixels, of subsequent images. Although this solution seems promising with respect to power consumption it was not investigated closer, as any optical sensor requires a source of light, and would not work in completely dark rooms.

4.4.2 Acoustical

A possible way of reducing the time spent waking is to utilize an acoustical sensor to listen for sound generated by a human target, such as footsteps or similar. This might work as an wake up for the occupancy monitor. In that case a false positive, waking the main sensors, is not a problem, but false negatives, not waking up the sensor would not be acceptable. This might be a possibility, but no low power implementation of any such system was discovered.

4.5 Comparison of Technology

4.5.1 Propagation Loss

It is a complex task calculating the reflection and propagation loss of any type of waves. For electromagnetic waves one may calculate that almost all of the energy is reflected of a human target [21, 25]. This also holds true for ultrasonic waves [11, p. 42], with the exception of clothes. Based on this fact and the knowledge of wave propagation we further assume that the reflection of electromagnetic waves in the GHz range and ultrasonic waves in the kHz range, will behave similar, such that the reflection factor may be disregarded. This is clearly an simplification, but the will not be the driving factor for difference in loss between ultrasonic and EM waves. The more important factor will rather be the propagation loss trough air. This is may be viewed as almost non existing for EM waves. For ultrasonic waves we may calculate that the energy transmitted is has a loss upwards of 1dB/m, for a 50kHz signal, due to absorption. Higher frequency will increase the attenuation of ultrasonic waves [26].

4.6 Selecting Sensor Technology

The main criterion for the selection of sensor technology is outlined in chapter 3 *System Requirements* and table 3.1. Where power requirements, range, sensitivity, volume and CPU demands are the most important factors. A table with the most important pro and cons between the different technologies are shown in table 4.1 and in table 4.2 comparison of the COTS system are shown.

Table 4.1: Pro and Con list of PIR, Ultrasound and Radar technology

Technology	Pro	Con
PIR	Cheap Simple Widely used COTS	High false negative rates only detects large movements size due to Fresnel lens
Radar	Small Good detection rate Fast measurements	Complexity
Ultrasound	Simple COTS	Slow measurements Power consumption

Table 4.2: Comparison of different sensor technologies

Technology	Range	Detection Rate	Occupancy Sensing	Power usage
PIR	5-10 meters	Low	No	Medium
Ultrasound	5-8 meters	medium	Yes	Medium
GHz Radar	>4.5 meters	High	Yes	Low

4.6.1 Infrared

There are several drawbacks with the use of IR sensors, especially as a stand alone sensor. Problems like false triggering, field of view and detection of stationary objects, are all arguments that IR is not a viable solution as a stand alone sensor. The industry standard is therefore to use it in conjunction with another sensor. This might be a solution for this project as well. When used as a secondary sensor, it may only be used to detect first movement, when someone are entering the room. With this solution a secondary sensor may be used to remove or lessen the probability of a false trigger, and also be used to detect a stationary subject. Using it in this way would mean that placement of the sensor needs to be optimized to detect someone walking into the room. This is not wanted as it is supposed to be a general sensor, that can be used in a wide variety of rooms, with the possibility of several entrances. Further on the demands on the placement of the sensor should be kept as simple as possible since its intended use is in the mass marked. The fact that most IR sensor utilize a Fresnel lens is also a problem due to the strict area demands. In summary the use of a IR sensor for this project is deemed undesirable.

4.6.2 Radar

The use of a radar system with a frequency in the GHz range, is a tempting solution due to the possibility of detecting stationary targets, by detecting chest movement due to breathing. There is also a strong focus in the industry on SoC radio inside of the ISM band. This open the possibility for further improvements in size, range, power and signal processing in low power systems in the years to come. Another important aspect is the possibility to fit the whole sensor on a single chip, and the lack of transducer. The drawback with utilizing a radar system is complexity of such a high frequency system. The problem of interference with the existing radio system and noise from other sources of RF signals, like Wi-Fi and other wireless signals found in a home environment, is also of concern.

4.6.3 Ultrasound

Although radar is a better choice for detection of stationary targets, and less propagation loss, ultrasound have several other factors making it the preferred choice. The main factor is the fact that the complexity of the sensor system will be greatly reduced, which in turn will make the implementation of the sensor system much easier. Another important factor is signal processing. This is made easier and may be done more energy efficient with the much lower frequency of ultrasound. The fact that ultrasound is widely adopted as the sensor technology of choice, in many of the commercial available occupancy sensors, are also a fact that impacted the selection. The short timespan of the project, made it favourable to test a system based on ultrasound.

Chapter 5

Ultrasound Occupancy Sensor

This Chapter will focus on the outlines for a proposed low power occupancy sensor based on ultrasound, and a suggestion of the different modes it may operate in. Then the selected ultrasound transducer will be presented along with a description of the key performance details in need of testing. A section with the theoretical power consumption of the transmitted signal is also incorporated after the selection of transducer.

5.1 Ultrasound Occupancy Sensor

The most important aspect to saving energy, is to keep the occupancy sensor powered off as much as possible. The system will only need to have two main modes, occupied and empty. These two modes will be used to control the timing of the occupancy sensor. When the system is in occupied mode, there is no need to sense precisely when the room goes from occupied to empty, since there is no time sensitive action taking place after a room is emptied. There is no need to turn the lights off or change the AC the moment a room is emptied. This means that when the system first have detected a presence in the room, there is possible to sense less frequently, and by that save energy.

In empty mode there is a much higher demand on time sensitivity. For the system to work as intended, the system must be able to sense a person and react to the change in a short amount of time. This time should, as discussed earlier, be less than one second. This time sensitivity must be seen in contrast to energy consumption. Better time sensitivity will demand shorter time intervals between sensing, in extension this will demand more energy.

5.2 System Design Using Ultrasound Transducer

To drive a ultrasound transducer, the only need is an signal generator to deliver a sinusodial signal in short burst at 20kHZ or higher. For the selected transducer the nominal frequency is at 40kHz and the maximum voltage is given as 6.6V peak-to-peak. The power required for receiving the signal is not given, and would be a question of interest for testing. After receiving the signal it will need to be amplified before being sampled in an ADC when used for ToF measurements. For Doppler effect to be measured, a comperator with a copy of the original 40kHz signal would be a possible solution. Other solutions may also be available, but will not be of interest for this thesis. A small amount of memory would also be needed to store the recived measurements. If a range of 7m is wanted the memory requirements for a given FIFO RAM, could be calculated using equation 5.1, modified from an equation found in the datasheet of PGA450Q1 [7].

$$\text{FIFOsize} = \frac{2 \times \text{Range} \times \text{ADC}_{\text{Sample rate}}}{\text{Downsample} \times C_S} \tag{5.1}$$

5.3 MA40H1S-R Transducer

To be able to test the possiblities of ultrasound sensing, a suitible ultrasound transducer, where the size spesification was of most concern, had to be found. There is not many ultrasonic transducers available in the size required (<2cm) for this project. The only fit found was the MA40H1S-R from Murata, an SMD type transducer seen i figure 5.1. In table 5.1 the most important information from the MA40H1S-R datasheet [14] is gathered. When a suitable transducer was selected, some calculations regarding power consumption where made. To be able to maximize the range the maximal voltage of 6.6Vp-p is assumed, the capacitance at 1kHz is given as 4500pF and is used as a base for further calculations. With the information given it is possible to calculate the required power to generate an output signal, R_X. These calculations are made in the next section.

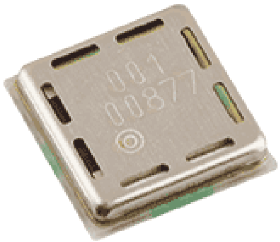


Figure 5.1: MA40H1S-R Transducer [14]

Table 5.1: Information from MA40H1S-R datasheet [14]

Rated Voltage	6.6Vp-p	at 40kHz, Square wave
Nominal frequency	40kHz	
Sound Pressure Level	40kHz 95dB min.	at 6Vp-p, Sine wave
Sensitivity	-65dB min	at 6Vp-p, Sine wave
Capacitance	4500pF ± 20%	at 1kHz

5.4 Power Consumption for MA40H1S-R Transducer

The main goal of this project is to assess the feasibility of a low power ultrasonic occupancy sensor. An important part of this, is to know the power dissipated by the transducer. This may be calculated theoretically by using the information given by the data sheet of the transducer. It may also be measured by measuring the current going trough the transducer as well as the voltage over the transducer. This may give valuable information of the power cost of sending a burst of ultrasonic sound as well as the power cost in accepting the echo produced. This information will only point to the true power cost, since loss in transforming the signal, as well as processing and storing the information will greatly impact the power usage of the system as a whole. The reasoning behind calculating and measuring the power consumption only in the transducer, is to better know where the largest savings in energy consumption may be achieved. For the purpose of this report it is also important since it is believed that the ultrasonic sensing unit will consume a large portion of the total power in a finished system. Furthermore it is important to see if the low power requirements given by disruptive is achievable for a similar system.

5.4.1 Transmitted Power

All the necessary values to calculate the theoretical power consumption is given in the data sheet of the transducer [14]. We assume that we use the proposed 6.6V p-p wave at 40KHz, with a given capacitance of 4500pF, as seen in table 5.1. The resistance X_c of the transducer is then given by equation 5.3 to be 884 Ω, at 40kHz. V_{rms} is given by equation 5.4 to be 2.33 V, which then gives the average power, p_{avg}, to be ≈ 6.1595mW, by equation 5.5, and average current to be ≈2.64 mA. A single burst is then much shorter then 1s so to calculate the power used to generate one T_X burst, we need to find the length of one burst. This is done using the information gathered from the PGA450Q1 datasheet [7]:

> The ON_A register sets the duration that OUTA is held high during one burst. To generate a square wave of a particular frequency (fburst): ON_A = dec2hex(FOSC / fburst / 2) (5) The resolution is 62.5 ns.

Given that FOSC is given at 16MHz, the equation may be given as follows:

$$ON\_A = \frac{16MHz}{\frac{40kHz}{2}} \tag{5.2}$$

Equation 5.2 then gives us the length of one burst to be 12.5 μs

$$X_c = \frac{1}{2\pi fc} \tag{5.3}$$

$$V_{rms} = \frac{\text{peak-to-peak}}{2\sqrt{2}} \tag{5.4}$$

$$P_{avg} = I_{rms}^2 \times R = \frac{V_{rms}^2}{R} \tag{5.5}$$

For the system proposed this gives $P_{T_X avg} = 77.0$nW, by equation 5.6, given one burst each second. A single burst will probably not be the case, but a linear correlation between number of burst and power dissipated by the transducer exist. This linearity may not hold for the generation of the driving signal. It is worth clarifying that the power usage calculated for T_x, is only the power dissipated in the transducer and does not include the power consumption in generating the driving signal.

$$P_{burst} = \text{Number of burst} \times ON\_A \times P_{avg} \tag{5.6}$$

To receive the echo signal we need to keep the transducer powered for the time sound uses to travel the desired range and back, given us a time frame as shown in equation 5.7. For a range of 7 meters, his gives a time frame of 40ms.

$$T_{recive} = \frac{2 \times Range}{C_S} \tag{5.7}$$

5.4.2 Complete System

The power consumption to generate the T_x signal is only one part of the power consumption for the whole system. As shown in the previous section a the time used to receive and convert the returned signal, T_x, will greatly exceed that of R_x. For a 7m range, 40ms is required to receive the echo signal. This in turn will put the power consumption requirements of the transducer, when receiving a signal, under great stress, as well as the LNA and ADC. When designing an ultrasound system an important factor is the dynamic range in the transmitted and received energy levels, and how to achieve the balance between the two. If more energy in outputted more energy will be received, and less amplification is needed. This is explored in [4], where an indication of the increased current, I_{amp} for an amplifier in a given system is compared to an increase in the excitation voltage of the transducer. Where C_0 is the capacitance of the transducer and U is the initial excitation voltage.

$$I_{amp} = \frac{C_0^K U^2 (k^2 - 1)}{2 V_{sup} T_{amp}} \tag{5.8}$$

This equation may be used to explore the possibilities in adjusting the driving signal. To use this equation an important factor to take into account is SNR. An increase in the transmitted signal will increase the SNR, but an increase in the amplification will not.

5.5 Occupancy Sensor Design

To be able to work as an occupancy sensors the proposed ultrasound transducer needs to work as more than just an motion detector. To be capable of working as an occupancy sensor this report suggest that the ultrasonic sensor will have to work in two different modes, ToF and Doppler. Firstly it will need to work as an motion sensor, utilizing ToF measurement to map the room. In this way it will need to generate a map of the returned signals amplitude peaks and timing for an empty room, to generate a basic, empty room graph of the room. To detect a presence all new measurement will be compared to the base graph, where a new presence will be detected if the new ToF measurement does not compare to the base graph. After a presence have been detected the ultrasound sensor may still utilize ToF measurement as long as any new measurements detects a change from the last. After a presence has been detected the base graph is no longer valid, this is due to the fact that by now furniture may have been moved or other persons have entered the room, such as the base graph have no longer any value. If the sensor returns a measurement identical to the base graph this is not enough to guarantee an empty room, after a presence have been detected. To make sure the room is no longer occupied the ultrasound sensor will now perform the more power intensive Doppler sensing. In this mode smaller movements should be possible to detect. The timing requirements are more relaxed in this mode, making it possible to sense less frequently. After several subsequent measurements returns an empty room the system may presume that the room is empty. When an empty room is assured, a new base graph of ToF measurements may be stored, and the system will return to ToF mode.

To further save energy it may be possible to use information from other nodes in conjunction with time of day to make some assumption. One example may be that if the exit door of the home is opened before being locked and no occupancy is present in any room, we may assume that the home is empty and therefore stop or reduce any measurements until the front door is opened again. This may be used together with time of day information to learn some routines such as when the inhabitants are at work. Many different schemes of this sort is possible, but will depend on how the system is set up, as such this report will not be able to extract any benefits from such a scheme. One possibility which may still be open for exploitation is to reduce the timing requirement at night time, such as after a given time of day and no occupancy detected it may be possible to increase the time frame of detection. Changing it from one second to two will effectively decrease the power usage by half.

Chapter 6

Experimental Hardware and Test Setup

In this chapter the different tests and test platform used are described. As well as the reasoning behind performing the specified tests. This is followed by the setup of the tests

6.1 Evaluation Kit

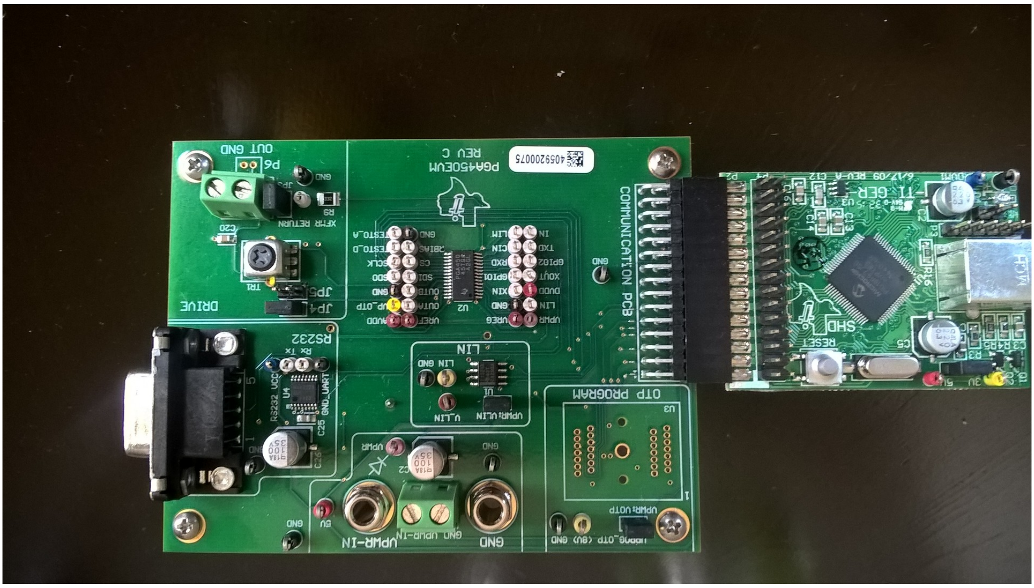


Figure 6.1: The PGA450Q1 Evaluation Kit

To be able to conduct a performance test of the chosen transducer, it was selected to try to find an existing analogue front end for ultrasonic sensing. By using an existing device to both drive the transducer and evaluate the received echo signal, the time consuming task of designing a signal processing unit, and a signal generator is eliminated. Due to time constrains and ease of testing this was a desirable solution. By using a evaluation kit, it is possible to evaluate the transducer performance, in respect to range, detection rate and false triggering. By analysing these performance criterion, it should be possible to come to an conclusion of the feasibility of using the chosen transducer in a low power occupancy sensor. Power consumption test are harder to achive, and less valuable with the proposed analogue front end, since this is not designed for low power use or power consumption testing. The chosen analog front end, PGA405-Q1 is described as following by Texas Instruments [7]:

> "The PGA450-Q1 device is a fully integrated system-on-a-chip analog front-end for ultrasonic sensing in automotive park-assist, object-detection through air, ...
>
> ... The PGA450-Q1 device can measure distances ranging from less than 1 meter up to 7 meters, at a resolution of 1 cm depending on the transducer-transformer sensor pair used in the system.
>
> The PGA450-Q1 device has an integrated 8051 8-bit microcontroller and OTP memory for program storage to process the echo signal and calculate the distance between the transducer and targeted object. Full programmability is available for optimization of specific end applications, and to accommodate a wide-range of closed-top or open-top transducers. Configurable variables include the number of transmit pulses, driving frequency, LNA gain, and comparison signal thresholds."

To make testing easier it was chosen to use the evaluation module (EVM) for the PGA450-Q1. Although the PGA450-Q1 is designed for automotive use, it is still applicable to this project due to the possibility to process the echo signal, the block diagram of the PGA450-Q1 may be viewed in figure 6.2. Further on it gives the possibility to easily change the transducer/transformer pair so that different transducer may be tested against each other. Due to time constraint this will not be done in this thesis, but if another transducer is made available with better specifications later on, the tests described in this report may easily be reproduced. To be able to determine the distance, between any targets returning an echo signal and the sensor, the time is given by the placement in the FIFO memory. The distance may then be calculated by the following equation, given in the PGA450Q1-EVM data sheet [7].

$$\text{Distance} = \frac{\text{Blanking Time} + (\text{FIFO Sample Number} \times \text{Downsample} \times \text{ADC Sample Rate})] \times C_S}{2} \tag{6.1}$$

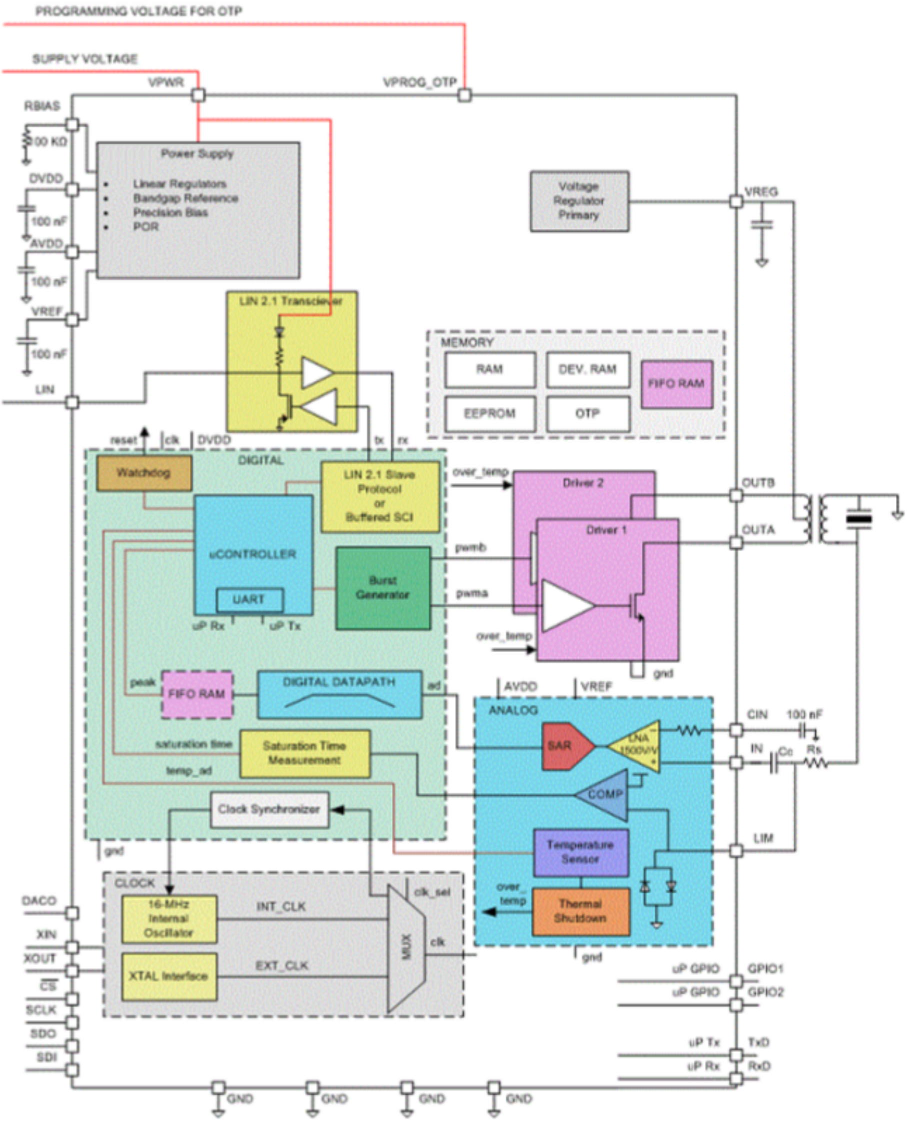


Figure 6.2: Functional Block Diagram for PGA450-Q1, [7]

6.1.1 Transformer Transducer Pair

PGA450 includes an transformer to scale up the driving voltage of the transducer, given by OUTA and OUTB, as high as 40 V. This scaling of the driving signal was not detected before testing, and due to time constraint there was no time to find a new transformer to decrease this signal. Due to this the selected transducer was driven at a higher voltage then it is regulated for.

The PGA450 is delivered for use with a transduer with 58kHz center freqvency, as such the transformer had to be calibrated. This procedure is described in the PGA450 data sheet [7, p. 118], where the main concern is to find the value of the tuning capacitor C$_{TUNE}$. This capasitor may be found by equation (11) in the data sheet, reproduced as equation 6.2, in this report. Here we use that C$_{PT}$ is know to be 4500pF, and L$_T$ and C$_T$ is given by $L_T \times C_T = \frac{1}{(2\pi \times F_{res})^2}$. Then the only unknown factor is the inductance of the transformer, L_{SEC}. This in turn is given by the data sheet of the K5-R4 transformer datasheet [15], to be tunable between 0.1 5.6mH. For the MA40H1S-R this gives us a value of the transformer, L_{SEC}, to be 2.4mH. To be able to test that the transformer is correctly set, it was chosen to measure the induction over the capacitor C20, which is in parallel with the transducer. C20 was chosen since is was possible to measure over it, unlike the transducer itself. The measurement was made with an induction measurer while the transformer induction was adjusted.

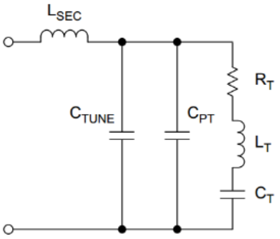


Figure 6.3: Equivalent Circuit of Transformer-Transducer Sensor Pair [8]

$$C_{TUNE} = \frac{C_{T \times L_T}}{L_{SEC}} - C_{PT} \tag{6.2}$$

The electrical model of the transducer-transformer pair taken from [7]. The driving signal may be viewed in figure 6.4. As seen the driving voltage is 50Vp-p, much higher than the 6.6Vp-p wanted. This made power consumption testing irrelevant, as well as making the ToF measurement impossible with the selected MA40H1S-R transducer. Some echo signal was returned, but it was difficult to distinguish it from the noise generated. Due to the difficulties with the selected transducer, it was chosen to reinstall the transducer who originally followed the EVM, the Murata MA58MF14-7N [13]. All results shown in chapter 7 Measurements, are done with the MA58MF14-7N transducer, with the settings on the EVM board reset to match this transducer, working at 58kHz.

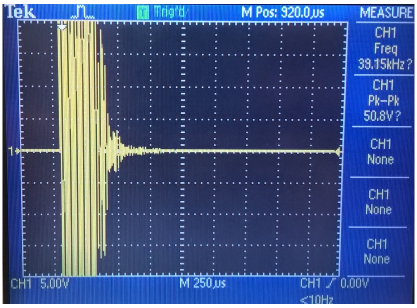


Figure 6.4: Driving signal tuned for use with the MA40H1S-R transducer, at 40kHz

6.2 Test Setup

6.2.1 ToF Measurement

To test the selected transducer firstly a simple test to determine that ToF measurements are possible to achieve, in a real world situation and that the required frequency for the driving signal is achieved. A comparison of measurements made within a small time frame, a few seconds, with no movement is also proposed. This is to be able to determine the noise level of the system. The sensor is placed at location 2, as seen i 3.1, and after the noise level is determined a target is placed directly in front of the sensor at increasing distance. To determine the distance between the sensor and any target given of an echo, one needs to know the time between the transmitted and returned signal.

6.2.2 Sensor Position

This section will cover the question of the detection area requirement and the effect of location of the sensor. As discussed in section 3.1.2 Detection Area, several different position's are interesting to explore. To do so it is proposed to place the transducer two different positions, roof and middle of the different walls. To be able to compare the different placements both the mapping of an empty room as well as motion detection capabilities are compared. To do so the room with furnitures will be kept the same, and only the transducer will be moved. Then measurements will be compared with an empty room and a person moving away from the sensor. To make the test as realistic as possible the test is performed in a furnished room, a simple sketch may be seen in figure 6.5. The room is a bit smaller then maximum required size of 50m^2, with a size of 5m by $6\text{m}(30\text{m}^2$, but it is large enough to give a good indication of how important location of the sensor is. Due to the fact that we are using ToF measurements, movement and stationary targets, close to walls may be hard to detect, due to reflections from the wall. Any movement at the same distance as the distance between the sensor and the floor may be disguised by reflections from the floor.

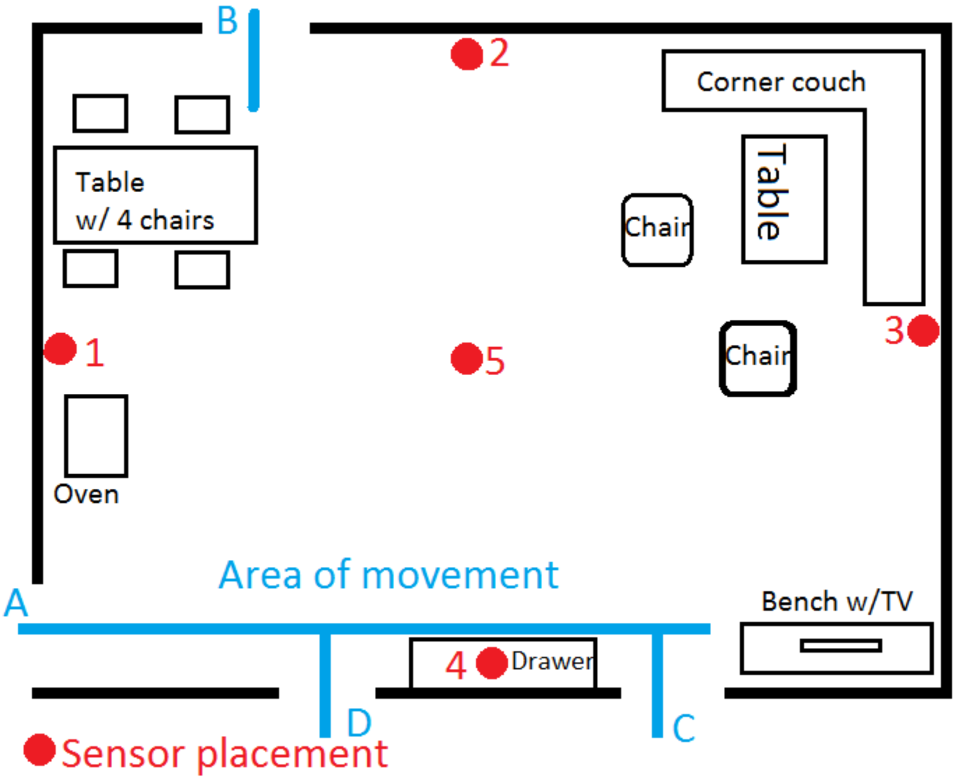


Figure 6.5: Overview room and sensor placement

Chapter 7

Measurements

This chapter will present important results from testing. Due to the problems with the transformer and driving voltage, no power consumption measurements will be included. The focus will be on detection rate and the implementation of the motion sensing part of the system. All tests are performed with MA58MF14-7N transducer at 58kHz, with 12 burst.

The first test was performed outdoors in an open space avoiding unwanted interference. A simple test to show the sensitivity of the system at a range of 1-2 meters, was performed with a target placed directly in front of the transducer. The EVM was then moved inside to perform test with more possibilities of cluttering due to furnitures and other obstacles. Here the same test as the one carried out in open space, was performed as well as some test at greater range and with movement. For the test with stationary targets 5 loops where completed and the average as well as the standard deviation is shown in most of the graphs. The standard deviation is included to show that there is little difference between each loop, it was calculated by using the STDEV.P function in Excel. The test with targets in front are shown with the difference from empty space to easier show the influence of a target. The difference is shown as an absolute value between the different measurements. For the test done outdoors the 8 middle bits of the data stream was selected to minimize noise. For the indoor test the 8 LSB was selected to maximize the range. Avery FIFO sample number is followed by a distance in meter in parenthesis. The distance is calculated by equation 6.1, and rounded to the nearest cm.

7.1 Outdoor Test Results

The test performed outdoor was made with the sensor placed atop of a table, 0.76 m from the ground and 1.68 m from the roof of a balcony with open space above the railing on 2 sides, the railing with a hight of 0.98 m is placed 2.01 m directly in front of the sensor.

7.1.1 Empty Space

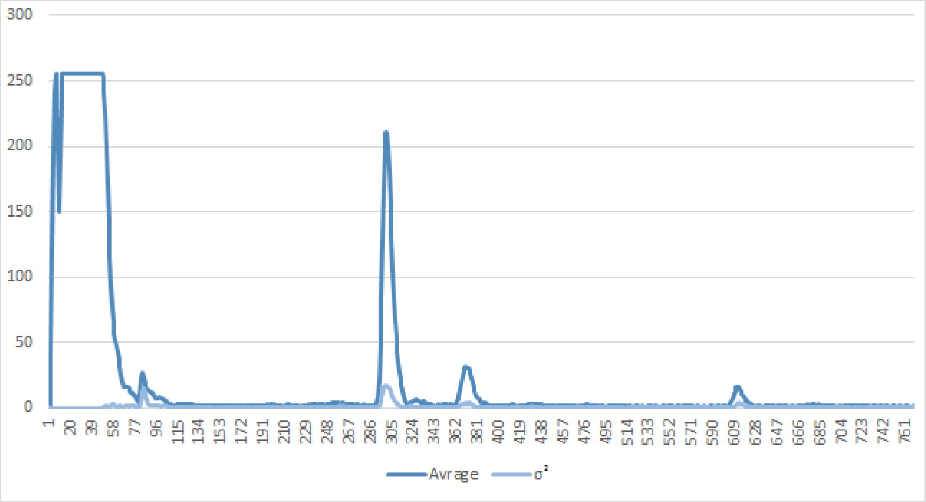


Figure 7.1: Averaged sensor output as a function of FIFO que placement (time delay), for empty space, and the corresponding σ^2

Figure 7.1 shows the resulting average echo signal, after five loops without a target in front. The standard error, σ^2, between the different loops, is also included. The average will be used as the reference measurement for the later test with a target in front. The σ^2 values is included to show that the different loops gave similar results. After the initial ringing has subsided, at around FIFO placement 100, there is very little noise. The signal spike at FIFO sample 289(1.98m) coincides with the railing on the balcony. The spike at 361(2.48m) is not as easily placed, but it is most likely a reflection from the roof or floor. The smaller spike at 601(4.12m) is most likely a result of an signal reflected from the railing and the roof or floor.

7.1.2 Target at 1 meter

A person was placed 1 meter directly in front of the sensor, and five loops of measurement was completed. Figure 7.2 shows the results from the five different loops. After the initial ringing a clear spike beginning at around FIFO sample 130(0.89m), is evident in all five loops. A smaller spike may be seen at around FIFO sample 180(1.23m), and might be a reflection off the target and the roof or floor. Note that the echo from the railing is completely blocked by the target. Figure 7.3 shows the average of the five loops together with the standard deviation, of the 5 different loops. Lastly the absolute difference between the measurements done with and without a target in front is shown. It is the difference between the two measurements which are the most important, clearly indicates that a target is detected at FIFO sample 130(0.89m) and a missing echo signals from the railing or roof at FIFO sample 289, 361 and 601. The standard deviation indicates that the returned echo signal from the human target is not identical. This might be due to the target moving or simply breathing.

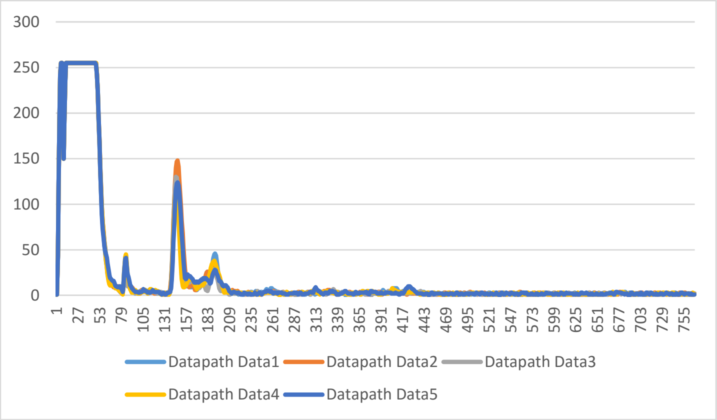


Figure 7.2: Averaged sensor output as a function of FIFO que placement (time delay), target 1m from sensor

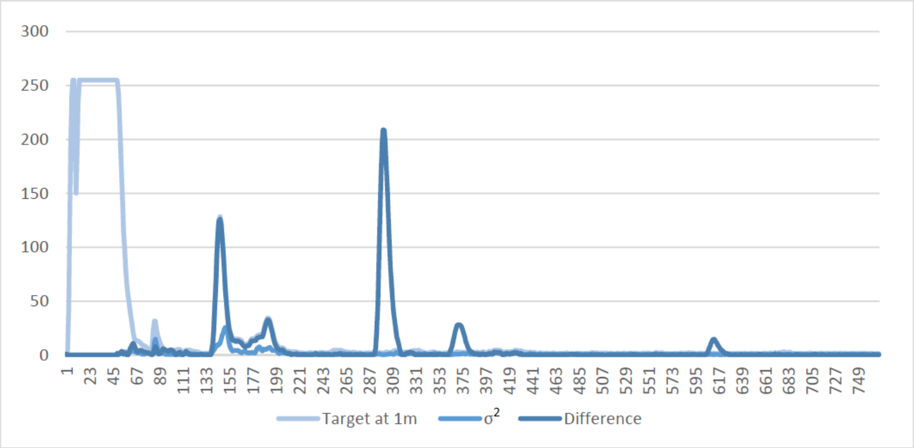


Figure 7.3: The difference between sensor output with the target at 1m and empty space. σ^2 is given for the averaged sensor output for the target at 1m.

7.1.3 Target at 1.7 meter

The target was then moved to a distance of 1.7 meters. The corresponding average echo signals from five loops are shown in figure 7.4. Here it is possible to see that the human target has a much smaller reflection than the railings and only a small spike might be detected around FIFO sample 220(1.50m) through 260(1.78m). This spike is very small and the σ^2 is quite large for these samples, making the measurements quite uncertain. The echo from the railing, the spike at sample 189, is again completely blocked by the target. This is quite clear in the figure 7.4, where the spike that is seen at sample 289, is the difference between the empty space measurement and this measurement with a target at 1.7 meter. The spike at 361 on the other hand is not blocked by the target at 1.7 meter as it was when the target was at 1 meter.

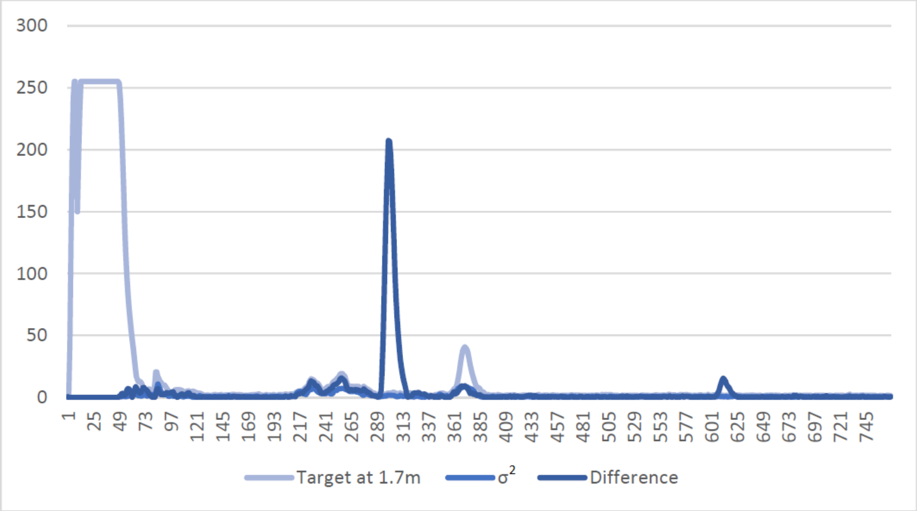


Figure 7.4: The difference between sensor output with the target at 1.7m and empty space. σ^2 is given for the averaged sensor output for the target at 1.7m.

7.2 Indoor test

The test performed indoor was made with the sensor placed at sensor placement 2 in figure 6.5, 0.50 m of the ground, 2.00 m from the roof and 4.30 m to the wall directly in front.

7.2.1 Empty Room

In figure 7.5, the σ^2 is somewhat larger than for the measurements done outside, but are not as bad as expected when moving inside with more possibility of unwanted echoes and measurements done with the 8 LSB. It is worth noting that there is very concise

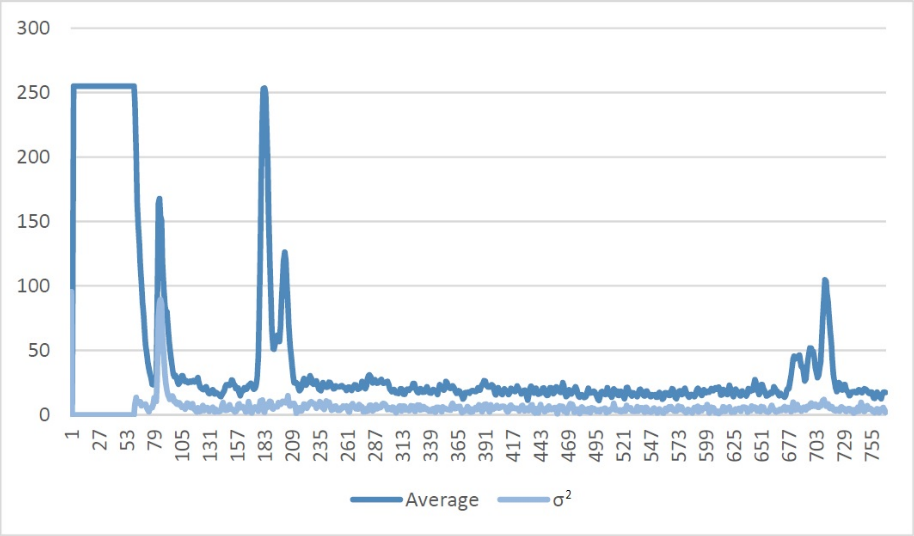


Figure 7.5: Averaged sensor output as a function of FIFO que placement (time delay), for a empty room, and the corresponding σ^2

measurements, also for the spike beginning at sample 183(1,26m). This spike is due to a chair witch was removed for the measurement done with the target at longer range. The spike beginning at sample 677(4.64m) is the wall 4.30 meter in front of the sensor. The larger spike following at sample 710(4.87m) is also worth noting.

7.2.2 Target at 1 meter

As with the test done outdoors, a target was placed at a distance of 1 meter from the sensor. The corresponding echo signal may be viewed in figure 7.6. Here a spike is observed beginning at sample 130 (0.89m), which is close to the 1 meter of the target. The large spike in the difference beginning at sample 180 is due to the echo signal from the chair being blocked by the target. Two smaller spikes in the echo signal may be seen around sample 680(4.66m) and 700(4.80m), this is most likely two returning echoes from the wall. The larger spike at sample 710 is missing in the returned echo signal, this is believed to be blocked by the target.

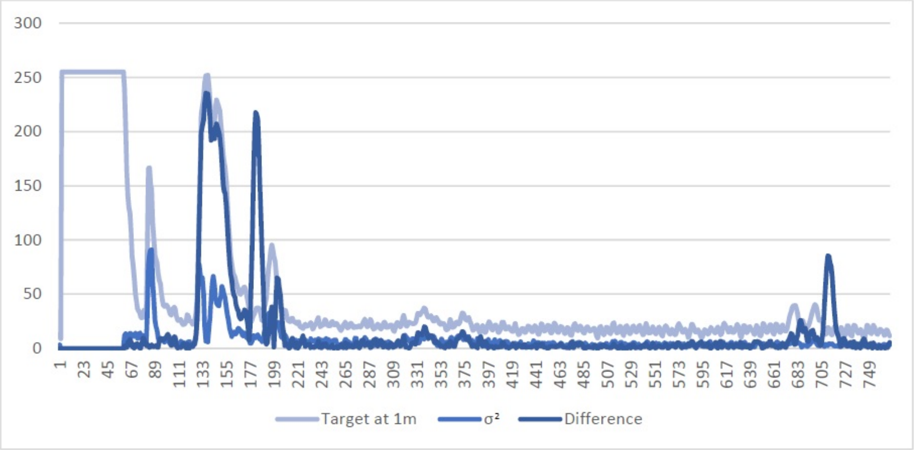


Figure 7.6: The difference between sensor output with the target at 1m and a empty room. σ^2 is given for the averaged sensor output for the target at 1m.

7.2.3 Target at 3 meter

The target was placed at 3 meters and 5 loops of measurements where done. The chair evident in the first measurements was removed before conduction the test, and a new empty room average measurement, seen in figure 7.7, was completed before using this to compare with the target placed at 3 meters. With the chair removed two new spikes at sample 420(2.88m) and 595(4.08m) is evident. These reflection was most likely blocked by the chair. The reflection at sample 420 is believed to be from some of the furniture still placed in the room, while the one at sample 595 is believed to be the drawer placed along the wall in front of the sensor. The resulting sensor measurements, with the target at 3 meters, is shown in figure 7.8. No spike in the resulting echo signal matches a target at 3 meters. Some clear spikes might be observed at sample 595, 650 and 705. The first two is due to a blockade of an returning echo, while the last on is a small increase in the echo also observed in the empty room. This result points to a problem with absorption of ultrasonic waves in clothes or less reflection expected, as well as lower sensitivity than wanted.

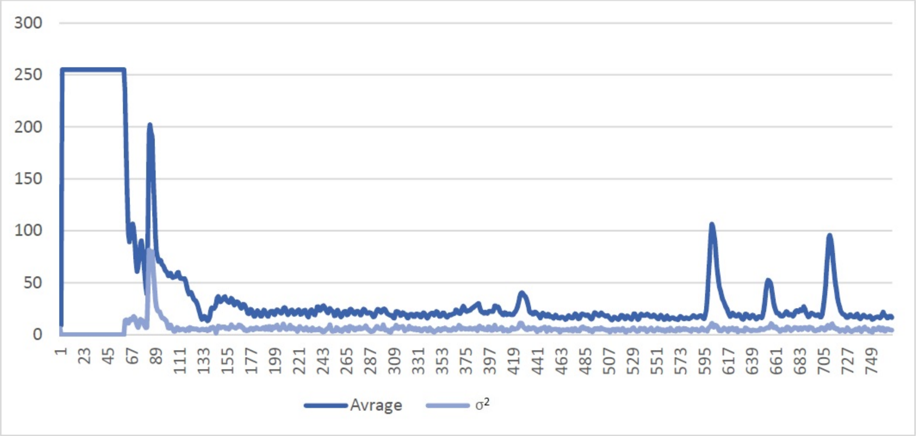


Figure 7.7: Averaged sensor output as a function of FIFO que placement (time delay), for a empty room with the chair removed, and the corresponding σ^2.

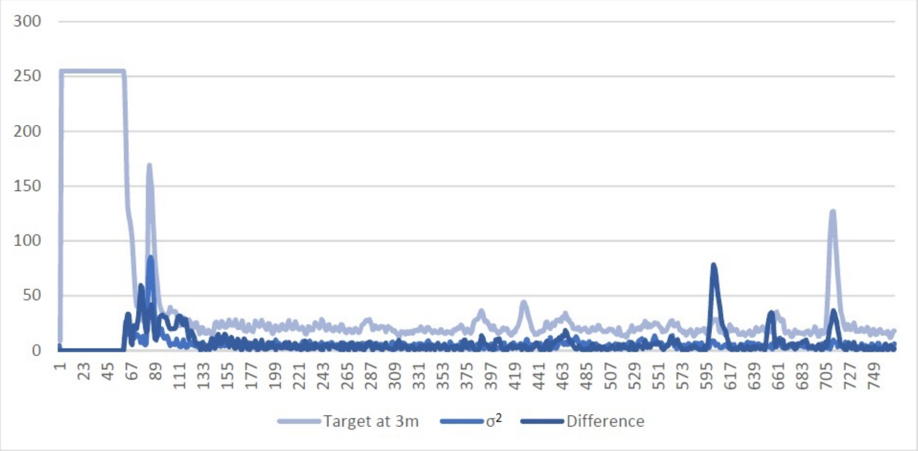


Figure 7.8: The difference between sensor output with the target at 3m and a empty room. σ^2 is given for the averaged sensor output for the target at 3m.

7.2.4 Moving Target

Measurements where the target moved away the sensor in a straight line, starting 1 meter away from the sensor and ending at the far wall, was also conducted. This measurement was also done within 5 loops, where the target tried to move between measurements and stand still for a small amount of time before moving further away. The resulting echo signal may be viewed in figure 7.9 and the difference between the recorded echo signal for an empty room and the moving target may be viewed in figure 7.10. In both figures it is clear that after the initial ringing, which subsides around sample 100, there is a clear spike in Datapath Data1 from sample 110(0.75m) to 130(0.89m). At the second loop, Datapath Data2, the target have moved backwards and a clear first spike may be seen at sample 200(1.37m). Clear spikes may be seen for the third and fourth loop as well, respectively at sample 290(1.99m) and sample 400(2,74m). For the fifth loop no spike in the echo signal is evident. The spike at 596 in figure 7.10 is evident in all 5 loops and is due to the transmitted signal or the reflected signal from the drawer being blocked.

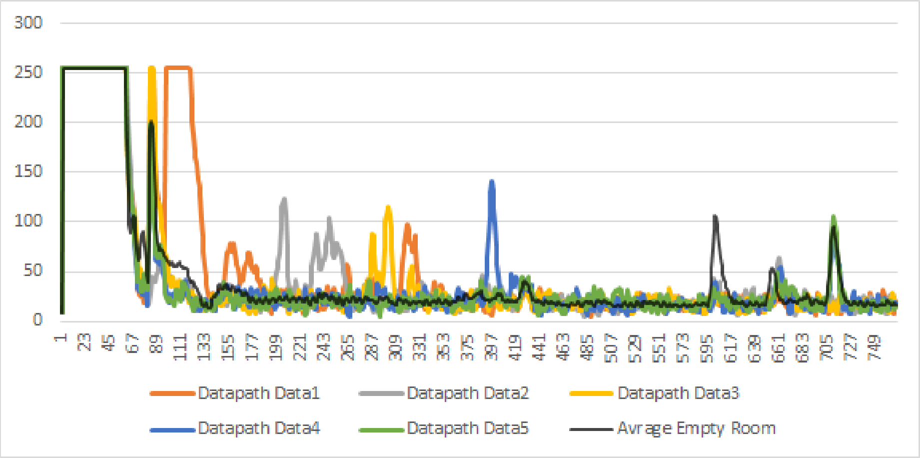


Figure 7.9: Echo signal from a target moving away from the sensor, the echo from a empty room is included as a reference.

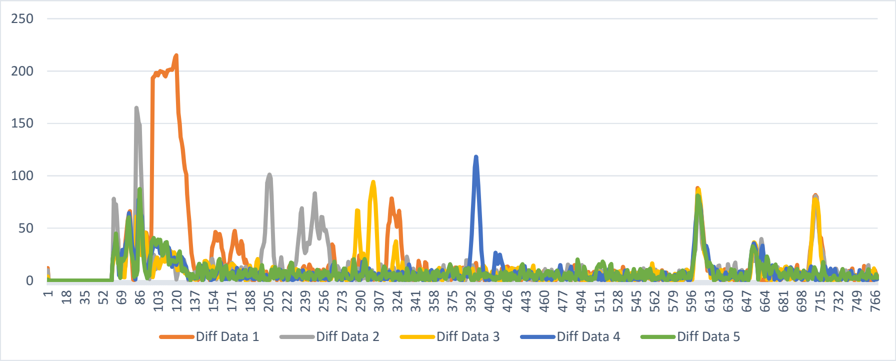


Figure 7.10: The difference between sensor output with a target moving away from the sensor and a empty room.

Chapter 8

Discussion

In this chapter the results from testing as well as the choice of technology will be discussed.

8.1 Performed Tests

The performed test is not sufficient to conclude with certainty, that it is unwanted to design a low power occupancy sensor, based on ultrasonic technology. It did however, showcase the problem with high propagation loss, leading to reduces range, and the problems with the time it takes to receive the returned echo. The reduced range is evident in both test with the target at 3 meters, 7.8, as well as with tests with a moving target, 7.10. In the first of these test no target was detected at a range of 3 meters, in the second figure a target is clearly detected at a range of 2.7 meters to then not be detected at a longer range. The high amplitude for datapath 4 in figure 7.10, may point to a longer range is possible. An important factor to note is that all test have been performed with the target directly in front of the sensor, the returned signal would be greatly reduced if the target is shifted of center. A possible solution to the range is to increase the energy transmitted. By equation 5.6, the power consumption for 12 burst with the MA58MF14-7N transducer equals to 2.385mW, which would be unacceptable for a low power sensor. An increasing number of burst would also make the ringing after excitation of the transducer worse, making it impossible to detect targets at closer range. This problem of ringing, could be solved by having separated transmitter and receiver transducer, but this would require more space. It is also worth noting that the problem only holds for the ringing, the first FIFO samples that are in saturation is the transducer Tx signal, it is possible to not store the Tx signal in the FIFO memory.

A test of the actual power consumption on the originally intended transducer together with an test of range would be preferable, the tests that was performed does however strongly indicate that a low power (nW), solution based on ultrasound would be hard to achieve. There was little support for low power soulutions in the literature, where the only system found [1], Designed and tested a ultrasonic radar system with a current draw of 30-219 mA of a 5VDC power supply, witch still are several order of magnitude from the 150nA required from disruptive. In hindsight it is easy to see that a solution with lower propagation loss, radar, might have been the better choice, but due to the strict time line of the project, a technology had to be chosen early in the process.

8.2 Compliance With the Objectives

Table 3.1 shows the objectives for the low power occupancy sensor wanted by Disruptive. The tests and calculations which is shown in this thesis shows that a sensor which utilize ultrasound would be difficult to design in compliance with the objectives given. For the objective of power consumption ultrasound have a large propagation loss and demands a long sensing time, which both increases the power consumption. The large propagation loss also makes it is hard to achieve the objective of a 50m^2 detection area and the sensitivity required. Another problem with utilizing ultrasound is the narrow band of frequency, and if any noise in the used frequency band is present any detection would be close to impossible. An ultrasound transducer have no large peaks in current consumption, such that any system in compliance with the power requirement would easily comply with a peak current of 50mA. For the detection time, there is nothing that indicates that it should not be possible to achieve a detection time of under one second with the use of ultrasound, if one disregards the power consumption. A higher detection time would increase the average power consumption, due to the necessity of sensing more often. As for cost the proposed COTS transducer, MA40H1S-R, it has a cost of $3.47 in a volume of 2500 [2]. Making it possible for a self designed transducer, to be close to or under the wanted cost of $2.

8.3 Issues With Implementation of an Ultrasound Occupancy Sensor

Ultrasound have several disadvantages with respect to low power implementations. Firstly the propagation loss are substantial, if the absorption of sound waves in clothes is also taken into account, it points to EM waves as a better choice of technology. Further the narrow frequency band makes ultrasound vulnerable to noise at the frequency it operates at. Another important source of noise is the dependency of humidity, pressure and temperature for the speed of sound. This makes ultrasound vulnerable to change in any of these factors. The need of a transformer for the driving signal, also increases the power consumption of ultrasound implementations. Where a loss of 30% or more must be expected. The relative slow speed of sound in comparison with EM waves, makes ultrasound a less desirable solution. The time to listen for a returned signal for a range of 7 meters are 40ms, when listening both the ADC and LNA would be active, which would be a large contributor to the total power consumption. This could be reduced somewhat by only listening at specific ranges, such as close to doorways when in motion detection mode.

8.4 Further Work

With the extreme low power budget given by Disruptive designing an occupancy sensor in compliance with the power requirement is the main challenge. To be able to design the wanted occupancy sensor this thesis shows that ultrasound have severe problems which is not easy to overcome. Further work with a low power sensor should rather look into the opportunities and limitations of a radar system. The proposed system in [12] shows a system with average power consumption of 0.2mW, which shows much better promise than ultrasound. Better calculations for reflection and propagation of EM waves should be made to investigate the lowest amount of power transmitted and still be able to detect the reflected signal, to show the possibilities within radar. Further it is important to make system considerations such as the least amount of sensing is possible. Looking into options to use information from other sensors to be able to be kept in a sleep mode for the maximum amount of time. The possibility of operating with two different modes should also be explored in more detail. Where a low power mode only needs to detect larger motion or is used as a wake up sensor for a more precise occupancy mode with a higher power consumption.

Chapter 9

Conclusion

This thesis set out to explore the possible sensing technologies for use in a low power occupancy sensor, with a average power consumption of 450nW. Ultrasound was chosen as the best fit for early assessment technology and a COTS transducer, the MA40H1S-R, was selected as the best fit with respect to size, cost and power consumption. No power consumption measurements where done, but the theoretical power consumption the Tx signal of the COTS transducer showed an absolute minimum average power consumption of 77nW, with no other loss. Not including losses such as loss in the transformer. Receiving and processing an echo from a distance of 7 meters take 40ms, thus being the driving factor for the power consumption, even compared with the transmit signal. This would be the driving factor of the power consumption, rather than the Tx signal. This makes the usage of the COTS transducer unrealistic. With no real power consumption measurements done it is difficult to conclude with any certainty that ultrasound is not suitable for low power occupancy sensing. However, with the test completed in this thesis it is shown that ultrasound have large challenges with range and sensitivity. A range of only 2.7 meter directly in front of the sensor was achieved with a theoretical energy consumption of 2.375mW, from the generation of the Tx signal alone. It is not possible with the information gathered in this thesis to conclude if a occupancy sensor with the proposed power consumption of 450nW is possible or not, but it's shown that a solution employing EM waves, would have several benefits over the use of ultrasound.

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