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MMWAVE TECHNOLOGY APPLICATIONS: COMMERCIAL MMWAVE EMBEDDED SYSTEM DESIGN CONSIDERATIONS

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ABSTRACT

Lari Karvinen: mmWave Technology Applications:
Commercial mmWave embedded system design considerations
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The objective of this thesis was to examine Texas Instruments' mmWave product line of single-chip FMCW radar sensor and their utilization potential in commercial embedded systems. This work was done for Wapice Ltd.

To achieve these goals both literary survey and experimental research were carried out. Chapter 2 of this thesis presents the theoretical foundations for different types of radar systems from simple pulsed radar to a modern FMCW radar system. Then, Chapter 3 specifically examines TI mmWave technology, presenting both the capabilities of the technology as well as important design considerations for ensuring a successful product development process. Main advantages of mmWave sensors are their high accuracy and excellent immunity to many environmental conditions.

Chapter 4 compares mmWave technology against other modern sensor technologies. While having some drawbacks, mmWave sensors compare favourably and can be considered as a valid solution for both presented example use cases.

To gain insight into the actual product development process with an mmWave sensor solution, Chapter 5 first presents an mmWave based system for monitoring both traffic patterns and road snow conditions with a single radar sensor. The tools used are presented and experiments are carried out to assess the proposed system's feasibility. Experiments demonstrated that mmWave sensors provide the performance needed for this application but further algorithm work is needed to produce a functioning system.

The most substantial challenges in utilizing mmWave technology are the need for a PCB radar antenna and the regulatory compliance aspects of a radar device. However, introduction of Antenna-on-Package technology has the potential of removing these challenges. This thesis concludes that mmWave sensors provide a versatile and strong performance sensing solution for use in commercial embedded systems.

Keywords: mmWave, FMCW radar, frequency modulated continuous wave radar, sensor, embedded systems

TIIVISTELMÄ

Lari Karvinen: mmWave teknologian käyttökohteet:
Kaupallisen mmWave-laitteen suunnittelunäkökulmat
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Tämän diplomityön tavoite oli tarkastella Texas Instrumentsin yhdelle piirille integroituja mmWave-tuoteperheen FMCW-tutkasensoreita, sekä niiden hyödyntämismahdollisuuksia kaupallisissa sulautetuissa järjestelmissä. Tämä työ on tehty Wapice Oy:lle.

Tavoitteiden saavuttamiseksi toteutettiin sekä kirjallisuuskatsaus, että kokeellista tutkimusta. Kappale 2 esittää teoreettisen pohjan erilaisille tutkajärjestelmille, aloittaen yksinkertaisesta pulssitutkasta ja päätyen moderniin taajuusmoduloituun jatkuva-aaltotutkaan. Tämän jälkeen kappale 3 keskittyy tarkastelemaan TI:n mmWave-tutkateknologiaa, esitellen sekä teknologian toiminnallista kyvykkyyttä että tärkeitä suunnittelunäkökulmia, jotka auttavat onnistuneen tuotekehitysprosessin varmistamisessa. Eräitä mmWave-teknologian vahvuuksia ovat sen tarjoama suuri tarkkuus ja erinomainen immuniteetti mittausympäristön olosuhteille.

Kappale 4 vertailee mmWave-teknologiaa muiden modernien sensoriteknologioiden kanssa. Huolimatta muutamista heikkouksista, mmWave-tuoteperheen sensorit vertautuivat suotuisasti muihin teknologioihin ja niitä voidaan pitää hyvänä vaihtoehtona molempiin esitettyihin esimerkkisovelluksiin.

Käytännön kokemusta ja näkökulmia mmWave-laitteiden kehityksestä haettiin kappaleessa 5 esitetyn sovellusprototyypin avulla. Kappaleessa esiteltiin järjestelmä, jossa yhdellä tutkasensorilla pystyttäisiin tuottamaan tietoa sekä liikennemääristä että tiellä vallitsevista lumiolosuhteista. Kappaleessa esiteltiin käytetyt kehitystyökalut ja suoritettiin mittauksia esitellyn järjestelmän toimivuuden tutkimiseksi. Kokeiden perusteella mmWave-sensorien tarjoama suorituskyky soveltuu järjestelmän toteuttamiseen mutta toimivan järjestelmän saavuttaminen vaatisi huomattavaa ohjelmisto- ja algoritmikehitystä.

Suurimmat haasteet mmWave-teknologian hyödyntämiselle ovat sensorin tarvitsema piirilevyantenni, sekä tutkalaitteita koskevien säädösten mukainen sertifiointiprosessi. Antennin suoraan osaksi piirin koteloa integroivat Antenna-on-Package -ratkaisut voivat kuitenkin lievittää näitä ongelmia mahdollistamalla ulkoisesta antennista luopumisen ja mahdollisesti sertifiointiprosessin keventymisen. Tässä työssä tehtyjen löydösten ja analyysien perusteella voidaan todeta, että mmWave-teknologialla on mahdollista toteuttaa monipuolisia ja suorituskykyisiä sensoriratkaisuja kaupallisiin sulautettuihin järjestelmiin.

Avainsanat: mmWave, FMCW-tutka, taajuusmoduloitu jatkuva-aaltotutka, sensori, sulautetut järjestelmät

PREFACE

This thesis was written for Wapice Ltd while working at the Wapice Tampere office. I would like to thank Wapice for making this thesis possible. I would also like to thank all of my colleagues who have helped me in various ways during this work. Special thanks go to Mika Inkinen, who provided me guidance, suggestions and encouragement throughout this process.

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I would also like to thank my friends and family for their support. My years in Hervanta, be it inside lecture hall's or roaming in blue overalls, have been an experience that has changed me forever.

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Tampere, 18th May 2021

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LIST OF SYMBOLS AND ABBREVIATIONS

60 GHz band	60-64 GHz band
77 GHz band	76-81 GHz band
AEC-Q100	reliability standard by the Automotive Electronics Council
ASIL-B	automotive safety integrity level designation
A_e	efective area of an antenna
ADC	analog-to-digital converter
AoP	antenna-on-package
B	bandwidth
c	speed of light
CAN	controller area network
CAN-FD	controller area network flexible data-rate
CPU	central processing unit
csv	comma separated value
CW	continuous wave
d	physical distance
DSP	digital signal processing
DSS	DSP sub-system
EM	electromagnetic
EMC	ElectroMagnetic Compatibility
EU	European Union
EVM	evaluation module
f	frequency of a wave signal
FMCW	frequency modulated constant wave
FoV	Field-of-View
G	gain
GUI	graphical user interface
HARM	High Accuracy Range Measurement

IC	integrated circuit
IDE	integrated development environment
IF	intermediate frequency
IR	infrared
λ	wavelength of a signal
LRFT	local resampling Fourier transform
MSS	Master sub-system
MTI	moving target identification
ω	phase of a wave
P	power
PCB	printed circuit board
PWM	pulse-width modulation
σ	radar cross section
RAM	random access memory
RF	radio frequency
RFSS	RF sub-system
RX	receiving
SIL-2	safety integrity level designation
S	slope of the frequency change in and FMCW signal
SPI	serial peripheral interface
SRD	Short Range Devices
TI	Texas Instruments, a semiconductor manufacturer
t	time
ToF	time-of-flight
TX	transmitting
UI	user interface
USB	unversal serial bus
UV	ultra violet
v	velocity

1. INTRODUCTION

This chapter provides a primer for the ensuing exploration of radar technology, the motivation and the purpose for this work, as well as an overview on the contents of this thesis.

1.1 Evolution and state of modern radar technology

Foundations for radar technology were laid down in the 19th century when Michael Faraday and James Clerk Maxwell did their work on electromagnetism. Following that, the earliest precursors for radar emerged in the beginning of the 20th century. One of these was Dr. A. Hoyt Taylor's experiment in which a ship could be detected travelling trough a river by it blocking a radio signal sent from one shore of the river to another. [1]

While various nations were developing radar systems in yearly 1930s, radar's potential became truly evident in the first years of the Second World War as planes could be detected far beyond visual range. During the war radar development saw order's of magnitude increase on resources and radar technology saw significant advances. [1]

After the Second World War development of radar continued and radar systems started to emerge also in civilian applications such as different types of airport control and assistance radars. Radar also begun to see use in various scientific efforts including atmospheric research and weather forecasting. [1][2]

Radar has seen continuous development ever since it's first appearances in the beginning of the previous century. Today radars are used for detecting or tracking anything from ships to insects and applications range from missile defence systems to parking assistance sensors. Modern society relies on radar for countless of different applications. [1][3][4]

Radar continues to grow in deployments and shrink in size. Today radar solutions are already able to fit within a few centimeters and advent of Antenna-on-Package technology promises to reduce device foot print and manufacturing costs even further [5]. Radar technology has already been successfully fit into a smartphone [6]. Apart from performance increases to miniaturization, work is also being done on merging radar with communication technology and if the proposed systems are implemented, vehicles would be able to use the same radar hardware to both sense their surroundings as well as communicate between each other and the infrastructure [7].

1.2 Objectives for the thesis

This thesis was written while working for Wapice ltd. Wapice is a Finnish software company that provides services ranging from development of machine learning and data analytics solutions to low level embedded software development and electronics design. Interest towards incorporating mmWave radar system solutions into Wapice's portfolio of expertise resulted into the subject of this thesis.

Main objects for this thesis were to gain insight into the process of developing commercial embedded systems utilizing mmWave technology and produce documentation that can be used as reference material in possible future product development processes. From the authors perspective supplementary goals were to gain experience and knowledge on the mmWave products as well as radar systems in general and produce a Master's thesis complying with the university standards for graduation.

1.3 Thesis structure

This thesis consists of four main parts, each of which is given their own chapter. While each chapter can be read on their own if a specific topic is sought, chapters do build on the previous chapters.

Chapter 2 presents some of the most common radar types as well as the theoretical foundation for their principles of operation. The examination begins with pulsed radar and ends in frequency modulated constant wave (FMCW) radar. The radar equation is discussed to gain understanding on practical design aspects of radars systems.

Next, Chapter 3 presents an actual radar system in the form of Texas Instruments' mmWave product family of FMCW radar chips. First half of Chapter 3 goes over the mmWave product family and introduces their capabilities and technical details, concentrating on one of the most advanced models, *IWR6843*. Various measures of performance are discussed, as well as external factors potentially affecting the performance. The second half of Chapter 3 goes into the design considerations for implementing an mmWave based radar system. These include requirements created by the need for an integrated antenna as well as the regulatory aspects of successfully developing a commercial mmWave radar system.

After familiarity with FMCW radar systems is established, Chapter 4 provides a base for comparing FMCW radar against other technologies with similar capabilities. Four alternative sensor technologies, laser, ultrasonic, infrared and camera, are briefly introduced and comparisons between these technologies are provided. In the end potential benefits of combining multiple sensor technologies is acknowledged.

Finally, Chapter 5 provides a look at an example of early stages of product development with an mmWave sensor solution in a form of feasibility study of monitoring road snow conditions. First the application concept is presented, followed by a look at the development tools used. Then a test plan for the study is laid out and obtained results are presented. Finally application feasibility is assessed based on the results.

Lastly, conclusions for this thesis are discussed in Chapter 6. Bibliographical information on the material referenced in this thesis is presented after the conclusions.

2. RADAR TECHNOLOGY

The term radar can be used as a shorthand to describe many systems with vastly differing principles of operation. However, all these systems described as radar share one basic concept: electromagnetic (EM) waves in the radio frequency (RF) are received with a sensor system that is able to infer information from the signal received. The book *Principles of modern radar: Basic principles* defines radar as *"an electrical system that transmits radio frequency (RF) electromagnetic (EM) waves toward a region of interest and receives and detects these EM waves when reflected from objects in that region"* [8]. However, even this definition is restrictive in the sense, that it does not include passive radar systems that have seen a lot of progress in the recent years [9]. Common technical variations between radar technologies include the frequency or frequencies of operation, range of operation, power levels and waveforms used. Different radar systems also have different purposes and capabilities; simplest systems might only measure distance to a target whereas the most advanced systems are able to produce information on target location, speed, heading, size and even shape of one or more targets. [10]

This chapter will present some common principles shared across different types of radar. In addition, basic principle of operation of three types of radar, pulsed radar, continuous wave (CW) radar and FMCW radar, will be presented.

2.1 Radar fundamentals - Pulsed radar

Similarly to the historical development path of radar systems, this examination of radar technology begins with pulsed radar systems. While pure pulse radar systems are not very common, the underlying principle is still very much in use. [1]

Before examining the physical realm, a concept for distance measurement is presented. This type of measurement concept is also used in some of the technologies presented later in Chapter 4.

2.1.1 Time of Flight measurements

One of the simplest ways of using a propagating signal for distance measurement is called a Time-of-Flight (ToF) measurement. In this type of measurement, a signal is sent at a known instance of time and then the system waits for a return signal reflected from the target of the measurement. When the return signal is received, time difference between these two events is recorded and if the propagation velocity of the signal is known, can be used to estimate distance to the target. [11] A concept level setup for a ToF measurement is described in Figure 2.1.

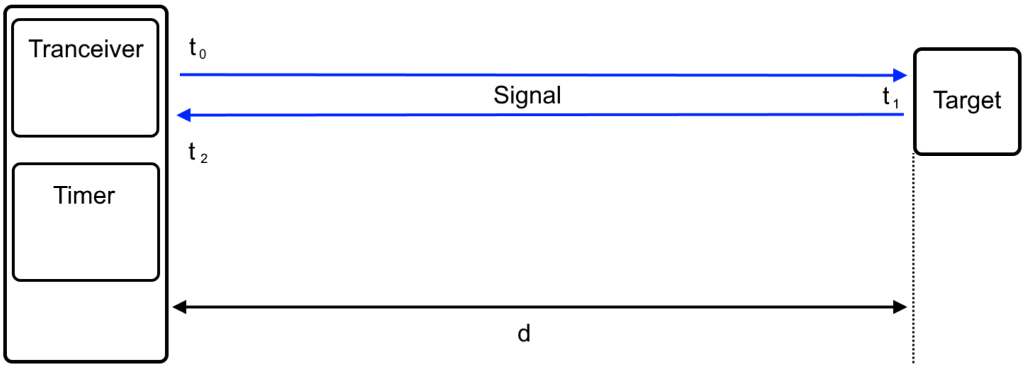

Figure 2.1. *Time-of-Flight measurement.*

A measurement system transmits a signal at time t_0, the signal then travels until it reaches the target at time t_1 and is then reflected back towards the measurement system. Finally the signal reaches back to the measurement system at time t_2, which is recorded by the system. With this procedure, the system is able to measure the total time it took for the signal to travel to the target and back. Assuming we know the speed at which the signal travels, we can derive the distance travelled by the signal, which in turn can be used to find the distance between the measurement system and the target. The physical definition for speed in it's simplest form is.

$$v = \frac{d}{t} \tag{2.1}$$

where *v* is speed, *d* is distance travelled and *t* is the time it took to travel distance *d*. Assuming we know the speed of the signal traveling in Figure 2.1, we can derive an equation for the distance between the measurement system and the target. Given that in this setup, the signal actually travels the distance *d* twice, we must add a 1/2 term to the equation, leading to

$$d = \frac{v(t_2 - t_0)}{2} = \frac{vt}{2} \tag{2.2}$$

where *d* is the distance to target, *v* is the speed of the signal and *t* is the time measured between the beginning of the transmission and the moment the reflected signal is received.

2.1.2 Time-of-Flight with Electromagnetic Waves - Pulsed Radar

When the generic signal presented in Figure 2.1 is replaced with a pulse of EM waves, the system becomes a simple form of pulsed radar, demonstrated by the measurement system presented in Figure 2.2.

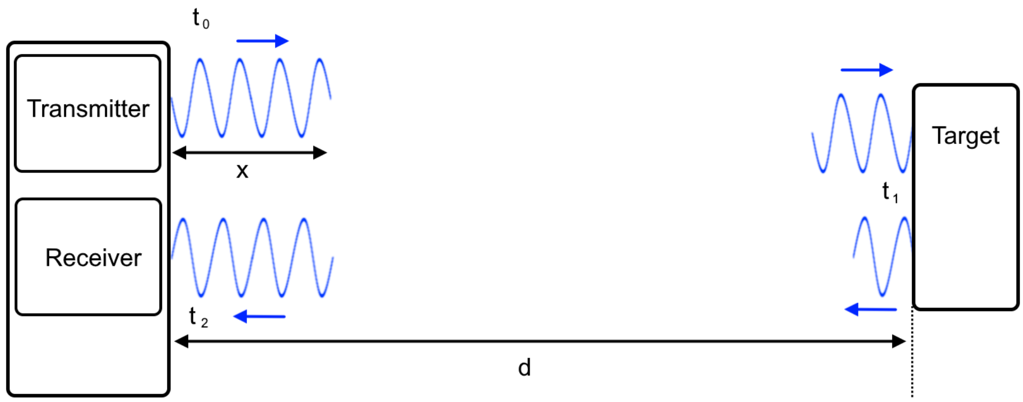

Figure 2.2. *Pulsed radar measurement. The return path of the signal is separated to a different level in order to improve visual clarity.*

Where as Figure 2.1 presented a purely theoretical system with a generic signal, the measurement system in 2.2 could actually be implemented using a radio transceiver. Although in this setup, we have an additional variable *x* representing the length of the EM pulse, it will not affect the math used for distance measurement. This is due to the fact that assuming the length of the pulse is less than *2d*, meaning the pulse is not being transmitted any more when the leading edge of the pulse returns to the system, using only t_0, the start of transmission, and t_2, the leading edge arriving back, pulse length x becomes irrelevant.

Another difference to the theoretical ToF measurement is that using EM waves sets our *v* term to the speed of light *c*, the speed EM radiation travels at [12]. Therefore with pulsed radar, the equation for distance between the measurement system and the target can be expressed as

$$d = \frac{c(t_2 - t_0)}{2} = \frac{ct}{2} \tag{2.3}$$

where *d* is the distance to target, *c* is the speed of light and *t* is the time measured between beginning of the transmission and the moment signal is received back.

2.1.3 Practicality considerations - The Radar equation

When designing real radar systems, choosing and understanding the working principle of the system is merely the first step of the process. After a type of radar has been chosen, the system must be carefully dimensioned in order to ensure intended functionality and optimal use of resources available. This section briefly presents some of the most fundamental variables of the initial dimensioning process.

In real world applications, electronic equipment will always have practical limits on it's measurement accuracy. When considering a radar system, it is clear that the EM wave pulse returning to the measurement system at time t_2 in Figure 2.2 must have high enough power to be registered by the receiver. This returned power, P_r, is dependant on both the original transmitted power, P_t, and the channel from the transmitter to the receiver.

EM waves radiate omni-directionally from the point of their origin [12]. As one pulse of EM waves consists of a finite amount of energy, the transmit power is spread thinner the further the pulse advances from the transmitter. Therefore the distance or range to the target, *R*, is a factor on the return power level.

While in practise, EM waves will always radiate omni-directionally, it is possible to concentrate some of the transmitted power to a specific direction or area using an antenna with gain [13]. An antenna with gain can be used to increase the power transmitted in the desired direction, therefore also increasing the power returned from the target. An antenna with gain will also make a difference when receiving as when correctly positioned, the antenna will also receive more power from the targets direction.

Returned power is also affected by the target reflecting the energy back to the measurement system. This factor is called the radar cross section of the target. It is affected by several parameters, including the shape, size and material of the target. [8]

All these factors can be combined into the Radar equation (2.4)

$$P_r = \frac{P_t G_t}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \times A_e \tag{2.4}$$

where P_r power received from target,P_t is the power transmitted, G_t is the transmitter antenna gain, R is the distance between the measurement system and the target, sigma is the targets radar cross section and A_e is the effective area of the receiving antenna. [10]

The radar equation almost always needs to be modified with applications specific parameters to be useful in the actual design process but this basic form provides the common base for understanding and estimating system requirements. [10]

2.2 Continuous wave radar

Another type of radar is the CW radar. Contrary to the pulsed radar presented in Figure 2.2, CW radar transmits a continuous EM wave at a specific frequency [10]. This type of radar measurement system is presented in Figure 2.3

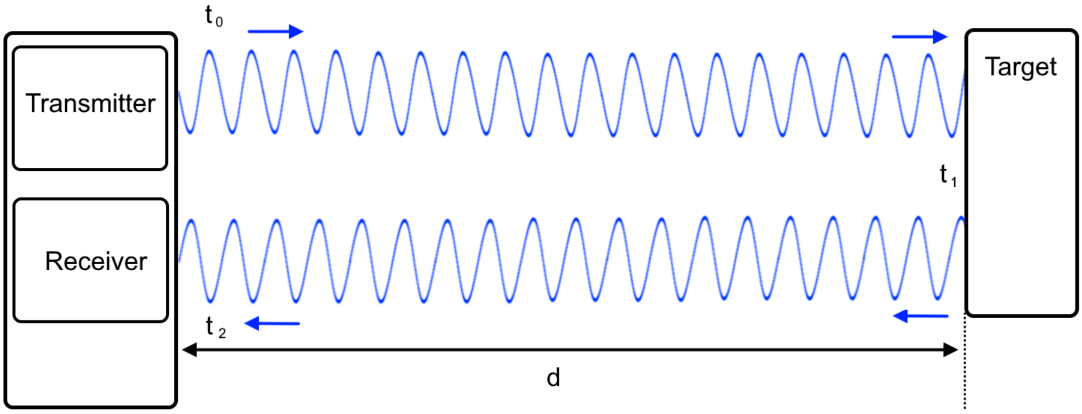

Figure 2.3. *Continuous wave radar system. The return path of the signal is separated to a different level in order to improve visual clarity.*

As the system is continuously transmitting, after the initial leading edge of the wave reaches the receiver, time markers t_0, t_1 and t_2 lose meaning as it is no longer possible for the system to differentiate which arriving wave was transmitted at which point in time. Therefore Equation 2.3 is no longer valid for measuring distance to target with this type of radar system.

2.2.1 Continuous wave and Doppler shift

In order to produce useful measurements with a CW radar system, the ToF measurement needs to be replaced with another type of measurement. One such measurement is Doppler shift measurement.

Before applying Doppler shift to the CW radar system, the phenomena is briefly introduced. In the simplest terms, Doppler effect is the observed change in a wave's frequency due to relative motion between the source and observer of the wave. [12] A simplified visualization of the Doppler shift phenomenon is presented in the Figure 2.4.

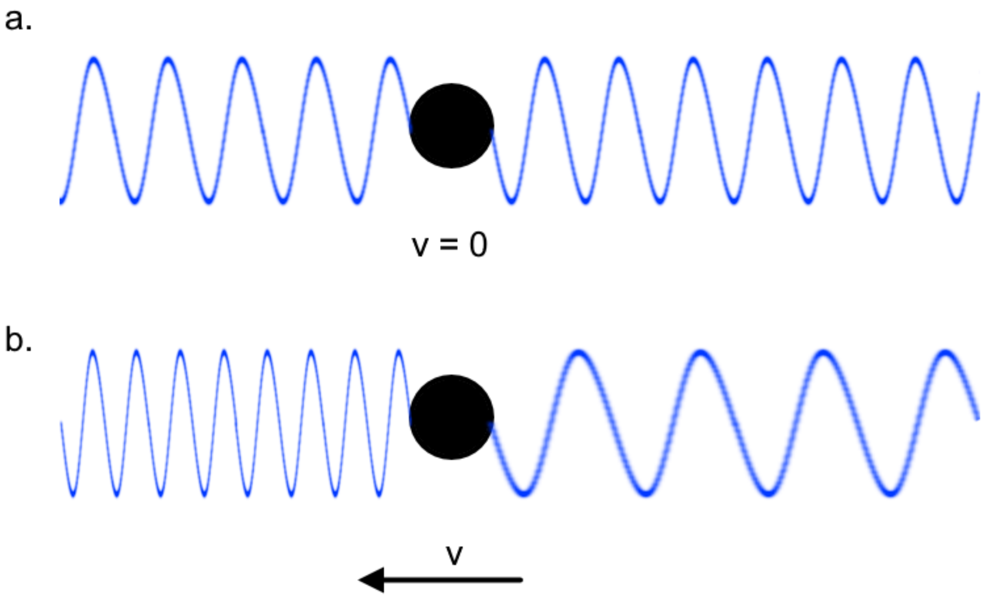

Figure 2.4. *The Doppler effect.*

Figure 2.4 presents two objects referred as *a* and *b*. Object *a* is stationary and object *b* is moving at velocity *v* in the direction of the arrow. In this example, both objects can be seen as transmitters of a signal with some frequency *f* and the reference space itself acts as the observer. As object *a* is stationary relative to the reference frame, the wave it transmits has the same frequency *f* in both directions. Object *b* is moving at velocity *v* and therefore its transmitted wave is subject to the Doppler effect in relation to the observing reference frame. Wave that is transmitted in the direction of the motion is compressed and thus has a higher observed frequency *f'*. Similarly, the wave transmitted to the opposite direction is stretched out and thus has an observed frequency *f"* that is lower than the original frequency *f*. [12]

The Doppler shift in the frequency is dependant on the original waves wavelength and the magnitude of the relative speed between the source and observer [10]. This relation can be expressed as Equation 2.5

$$f_d = \frac{2v_r}{\lambda} \tag{2.5}$$

where f_d is the shift in frequency, v_r is the relative velocity between the source and the observer and λ is the waves wavelength. [10]

As Equation 2.5 only contains relative velocity v_r, it does not matter whether the source or the observer is actually moving, the Doppler shift produced is the same. Same principle extends to reflected waves and a moving object reflecting waves can be considered a new moving transmitter. This can be used as a base concept for a new type of radar measurement. Doppler shift produced by a moving target is presented in Figure 2.5

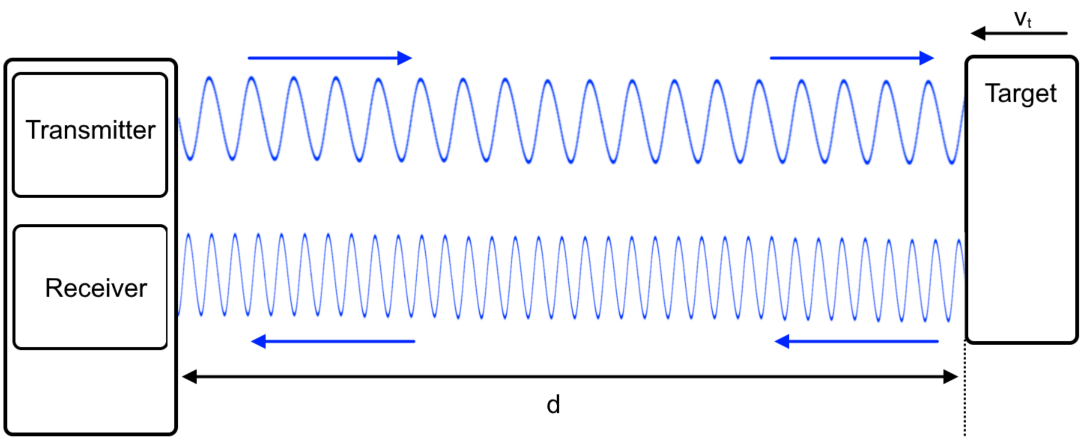

Figure 2.5. *Continuous wave radar Doppler shift measurement. The return path of the signal is separated to a different level in order to improve visual clarity.*

Contrary to the scene presented in Figure 2.3 where the target is stationary, in Figure 2.5 the target is moving, which causes the return signal of the measurement system to be Doppler shifted. If the system measures both the frequency transmitted f_t and the frequency received f_r, it can derive relative velocity between itself and the target. Mathematically this is achieved by solving v_r from Equation 2.5, resulting in Equation 2.6

$$v_r = \frac{f_d\lambda}{2} = \frac{(f_t - f_r)\lambda}{2} \tag{2.6}$$

where v_r is the relative velocity between the source and the observer, f_d is the shift in frequency, f_t is the transmitted frequency, f_r is the received frequency and λ is the waves wavelength.

2.2.2 CW Radar advantages and limitations

The previous section outlined how a CW radar system can be used to measure the velocity of a target by measuring the Doppler shift in the CW frequency. There are many useful applications for this technology and such CW radars are widely utilised. One common example are the hand held speed measurement devices law enforcement use to monitor car speeds in traffic [8].

CW radar also has a built in property if differentiating between stationary and moving targets as a simple CW radar system only detects moving targets that cause a Doppler shift in the received wave. This is useful for moving target identification (MTI) radar systems surveying large areas [10].

The major limitation of a primitive CW radars system is the inability to measure distance to the target. This limitation can however be overcome by further developing the principle of operation of the radar system. One possible way to gain range measurement capability would be to pulse the transmission of waveform, resulting in a hybrid of pulsed radar and CW radar. This technique is utilized in the MTI system presented in [10].

2.3 FMCW radar - TI mmWave radar platform

While accurate and continuous velocity measurement capabilities are useful, in most cases modern radar systems are required to produce more information. One adaptation of a simple CW radar is the FMCW radar. In this section this type of radar will be presented.

2.3.1 Frequency modulation

Frequency modulation of the transmitted waveform means that the frequency of the wave changes with time. In typical FMCW systems this means that the frequency transmitted increases with time. [14] This effect is visualized in Figure 2.6.

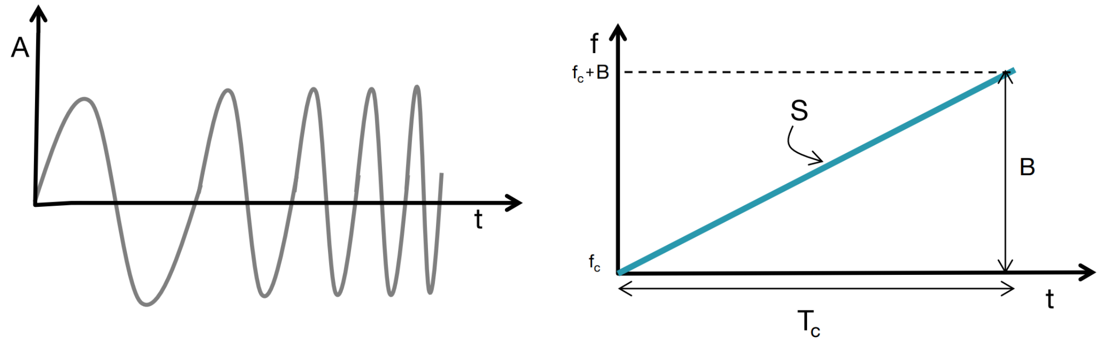

Figure 2.6. *Frequency modulated continuous wave with an increasing frequency. Image modified from [15].*

One full cycle of the changing frequency signal is referred to as a chirp. The main parameters of such a chirp are marked on the f-t graph in Figure 2.6. T_c refers to chirp time, depicting the total duration of the frequency cycle, f_c is the starting frequency of the chirp, B is the bandwidth of the chirp and S refers to the slope formed by the frequency-time relation. These chirp parameters are one of the main factors defining the capabilities of an FMCW radar system and will be discussed further in the coming sections [15].

Previously discussed CW radar systems had the shortcoming of not being able to discern distance from the unchanging radar signal. Adding frequency modulation to a CW waveform changes this as the return signal gains an instantaneous frequency which depends of the time it is received.

2.3.2 FMCW Radar system

FMCW radars utilize the signal's changing frequency to achieve several different types of measurement. In order to describe how these measurement are accomplished, first the system must be understood on a block diagram level.

Usually FMCW radar systems employ multiple antennas to separate transmitting (TX) and receiving (RX) functions onto separate antennas. This results in a system block diagram depicted in Figure 2.7.

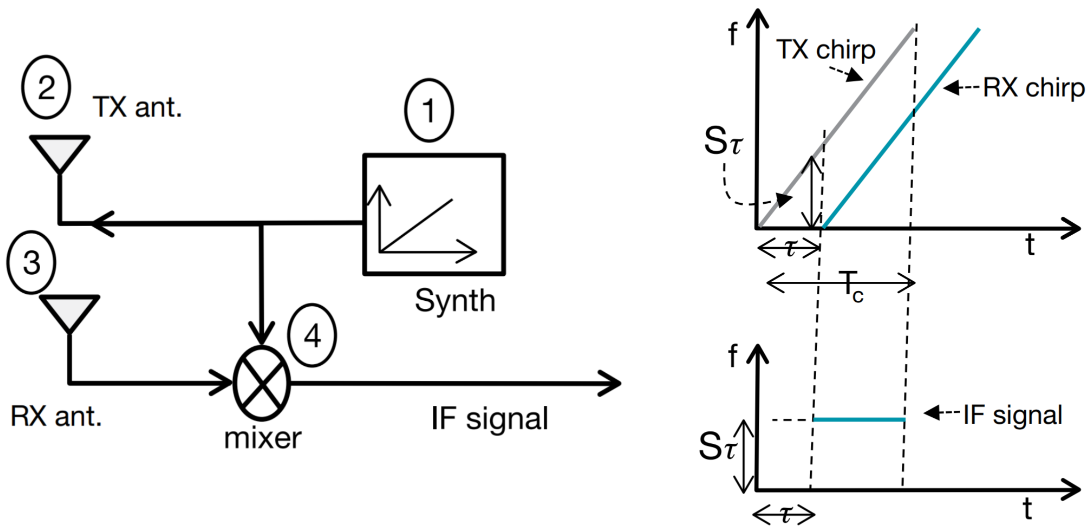

Figure 2.7. *FMCW radar system block diagram (left) and graphs of system signals (right). Figures from [15].*

In addition to the antennas, there are two main component in the block diagram labeled *1* and *4*. Label *1* refers to a local oscillator which produces the frequency modulated chirp and the label *4* refers to the mixer which is fed both the TX and RX signals. In the context of this thesis a mixer is examined at a superficial, functional level. Mixer is a three port device that takes in two signals and outputs a third signal. The output signals frequency and phase are dependant on the two input signals. Mixers have many uses like up-conversion of a signal for transmission or down-converting a received signal to a more easily processable intermediate frequency (IF). In this context the mixer can be regarded as a component which takes in the TX and RX signals and outputs a wave signal which has a frequency and a phase equal to the difference of frequencies and phases of the two input signals. [14][15][16]

If the TX and RX antennas were short circuited together, the two mixer would have two identical input signals, resulting in a theoretical 0 Hz output signal. However, if the TX antenna is allowed to send the signal which is then reflected back and received by the RX antenna, the mixer would also be fed the same waveform from both inputs but the one from RX antenna is delayed by some specific time due to the round trip time to the target. This results in the mixer outputting a signal of a non-zero frequency.

As the waveform utilized has a defined and linear change in frequency, as presented in Figure 2.6, the mixer output frequency will have a constant frequency as seem in 2.7. Therefore the mixer's output is only affected by the delay of the RX signal. As this delay is dependant only on the round trip time from the reflecting target, there is a direct relation between distance to target d and the mixer's output frequency f_{IF}. This relation can be shown to be Equation 2.7. [15][16]

$$f_{IF} = \frac{S2d}{c} \tag{2.7}$$

where f_{IF} is the intermediate frequency from the mixer, S is the slope formed by the frequency-time relation, d is the distance to the target c is the speed of light.

Rearranging 2.7 in relation to d, distance calculation from IF can be achieved.

$$d = \frac{f_{IF}c}{2S} \tag{2.8}$$

From the gained theoretical understanding of FMCW radar, it is possible to derive maximum performance figures of a radar system. Derivations for the following relations can be found in [15].

It can be shown that maximum range resolution of an FMCW radar is limited by the system's bandwidth as described by Equation 2.9

$$d_{res} = \frac{c}{2B} \tag{2.9}$$

where d_{res} is the range resolution, c the speed of light and B the system bandwidth.

Maximum range of an FMCW radar systems can be shown to be theoretically limited by frequency slope and the sampling frequency of the analog-to-digital converter (ADC) digitizing the IF signal [15]. Maximum range is presented in Equation 2.10

$$d_{max} = \frac{f_s c}{2S} \tag{2.10}$$

where d_{max} is the maximum range, f_s the ADC sampling frequency, c the speed of light and S the frequency slope.

While bandwidth limits the range resolution of a system according to 2.9, leveraging the return signals phase enables the radar system to measure finer movements. This is leveraged by the velocity measurement technique utilized by FMCW radars. To obtain accurate velocity information, the radar system sends two or more consecutive chirps as illustrated in Figure 2.8. Assuming the target is moving in relation to the radar, both the IF frequency and return signal phase will be different for each return signal, however the change in frequency is likely to be below the systems measurement accuracy while the change in phase is likely to be substantial. [15][16]

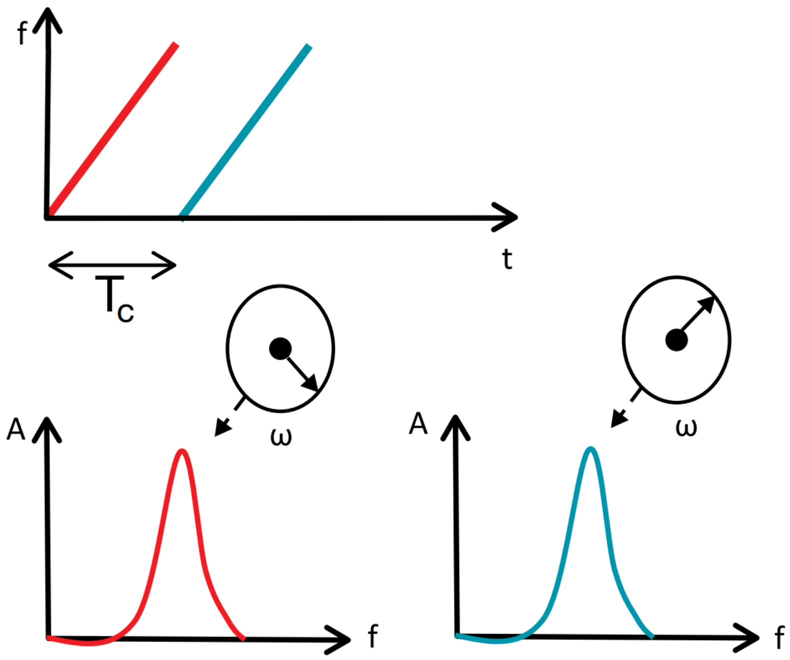

Figure 2.8. *Phase difference of consecutive chirps reflected from a moving target. Figures modified from [15].*

From the difference in the return signals' phases, relative velocity between the radar system and the target can be calculated. This relation is presented in Equation 2.11

$$v = \frac{\lambda\omega}{4\pi T_c} \tag{2.11}$$

where *v* is the target's velocity, λ the signals wavelength, ω the phase difference and T_c the duration of a single chirp.

The maximum velocity this type of measurement is able to unambiguously discern is limited by the repeating nature of a signals phase as positive phase shift of over 180 degrees is not discernible from a negative phase shift of under 180 degrees. Maximum measurable velocity for this type of system is presented in Equation 2.12 [15][16]

$$v_{max} = \frac{\lambda}{4T_c} \tag{2.12}$$

wherev_{max} is the maximum measurable velocity, λ the signals wavelength and T_c the duration of a single chirp.

In a situation where more than one targets are present in the radar system's Field-of-View (FoV), additional chirps are required for differentiating their velocities. A set of several chirps is referred to as a frame. The theoretical bases for velocity resolution is left outside the context of this thesis and more information can be found from the Texas Instruments white paper and lectures on FMCW radar. Velocity resolution calculation for an FMCW radar system is presented in Equation 2.13

$$v_{res} = \frac{\lambda}{2T_f} \tag{2.13}$$

wherev_{res} is the maximum measurable velocity, λ the signals wavelength and T_f the duration of the frame.

2.3.3 TI mmWave radar platform

As the theoretical foundation for understanding operation of an FMCW is now laid out, the focus of this thesis shift into the actual Texas Instruments mmWave product family of silicon integrated FMCW radars. Transitioning from a purely theoretical view of radar into practical radar systems expands the list of system blocks to consider. A block diagram of an integrated FMCW radar system is presented in Figure 2.9.

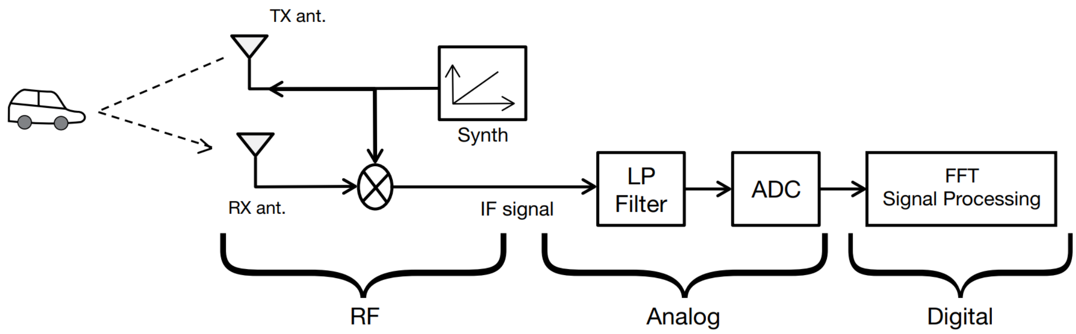

Figure 2.9. *FMCW radar sensor system diagram. Image from [15].*

The transmitted waveform must be synthesized and an actual mixer is needed. On mmWave chips these are integrated directly in to the silicon as the chips RF front end. In order to do the actual processing required for radar measurements, the IF signal outputted from the mixer must first be digitized. To achieve this, an ADC is also integrated into the chip. For signal conditioning reasons, the system also includes an integrated low pass filter before the ADC. Together these form the analog part of the block diagram. After the radar signal is digitized by the ADC, the signal is stored in the digital processing units of the chip. When a complete frame is recorded, the signal processing capabilities of the chip are used to produce measurements presented in this section. [15][16]

3. TEXAS INSTRUMENTS MMWAVE RADAR

This chapter first presents the Texas Instruments mmWave product family at a level of detail which gives the reader adequate knowledge base for considering mmWave sensor family based solutions for their intended use case. After base knowledge is established, the second half of this chapter will go into design considerations that a designer of an mmWave based system must take into account when designing the system.

3.1 System overview

Texas Instruments mmWave sensors are a product line high resolution of single-chip FMCW radars. They are capable of point cloud type distance measurements from very close, less than a meter, distances up to several hundred meters away. Depending on the type of antenna used, mmWave sensors can achieve a FoV up to +/-60 degrees in both azimuth and elevation. [17]

The mmWave product family consists of multiple different product variations. Actually the product family itself is divided into two sub-families: automotive mmWave sensors with product names beginning with *AWR*, and industrial mmWave sensors with product names beginning with *IWR*. However, these two product lines are functionally largely the same. Main differences between *AWR** and *IWR** sensors are the intended operating conditions and guaranteed reliability in form of a certification. For example, sensor *AWR6843* complies with the automotive reliability standard AEC-Q100 and targets hardware integrity level of ASIL-B, industrial version *IWR6843* does not list AEC-Q100 compliance and targets hardware integrity level of SIL-2. This thesis will focus on the Industrial mmWave sensor product line.

Within the industrial mmWave prodcut line there are several chip options to choose from. All of these products have very similar base architecture and radar functionality but have varying levels of features, performance and interfaces. Differences between these products are shown in Table 3.1.

Table 3.1 shows a few major differences between the industrial mmWave products but mostly the chips have very much in common. The newer *IWR6843* stands out as the only one utilizing the 60-64 GHz band (60 GHz band) whereas the other models utilize

Table 3.1. *mmWave sensor family product comparison. Information gathered from [17].*

	IWR6843	IWR1843	IWR1642	IWR1443
Frequency range (GHz)	60-64	76-81	76-81	76-81
Number of receivers	4	4	4	4
Number of transmitters	3	3	2	3 (2 simultaneous)
TX power (dBm)	12	12	12	12
ADC sampling rate (MSPS)	25	25	12.5	37.5
CPU	ARM R4F @ 200MHz	ARM R4F @ 200MHz	ARM R4F @ 200MHz	ARM R4F @ 200MHz
DSP	C67x DSP @ 600MHz	C67x DSP @ 600MHz	C67x DSP @ 600MHz	-
Radar Hardware Accelerator	yes	yes	no	yes
RAM (MB)	1.75	2.00	1.5	0.5

the 76-81 GHz band (77 GHz band). According to Texas Instruments there are regulatory restrictions for the 77 GHz band in most global regions whereas 60 GHz band is not currently limited by regulations. It therefore can be hypothesised that Texas Instruments will likely focus on products utilizing the 60 GHz band in the future. [18]

Apart from different frequency bands, each models' RF capabilities are very similar, each having four receive channels and a maximum transmit power of 12 dBm. However there are also some differences, the lower end models *IWR1642* and *IWR1443* are only capable of utilizing two simultaneous transmit channels. Additional differences present in the RF ADC sampling rates as presented in Table 3.1.

Each product in the industrial mmWave sensor family is equipped with an ARM R4F central processing unit (CPU) core running at 200 MHz. Supporting this, products *IWR6842*, *IWR1843* and *IWR1642* also include a Texas Instruments C67x digital signal processing (DSP) core clocked at 600 MHz. Additionally, models *IWR6842*, *IWR1843* and *IWR1443* are also equipped with a separate Radar Hardware Accelerator. While each model has the same CPU, complexity of the application run on the device can be limited by the amount of random access memory (RAM) of the device, which is different on each model.

As presented in Table 3.1 model *IWR6843* is equipped with each processing core available as well as the maximum amount of receive and transmit channels. Additionally as stated in this section, IWR6843 is the newest of these products and represents the likely future direction of development for the product line. Therefore in order to simplify further examination of mmWave devices, this thesis will focus on the *IWR6843* chip. However most information covered is also directly applicable to the other models in the Industrial mmWave product family, as well as on the automotive mmWave sensor family.

The *IWR6843* chip is also available as *IWR6843AoP*, which has the radar antenna integrated directly onto the chip. This product is discussed more in Section 3.5.1.

3.2 Interfaces and peripherals

In addition to the radar functionality of the mmWave line of sensors, the products provide many of the standard interfaces and peripherals usually found in modern standalone embedded processing devices such as general purpose analogue to digital converters, pulse-width modulation (PWM) outputs and integrated communication interfaces such as serial peripheral interface (SPI) ports. There are however some differences in the available peripherals between the offered models of the mmWave sensor integrated circuit (IC). Some of these differences are presented in Table 3.2.

Table 3.2. *Peripherals provided by the Industrial mmWave product family. Information gathered from [17].*

	IWR6843	IWR1843	IWR1642	IWR1443
General purpose ADC channels	up to 6	up to 6	up to 6	up to 6
SPI	up to 2	up to 2	up to 2	up to 2
UART	up to 2	up to 2	up to 2	up to 2
CAN	-	1	1	1
CAN-FD	1	1	1	-
I2C	1	1	1	1
LVDS for raw ADC data	yes	yes	yes	yes
PWM	yes	yes	yes	no
JTAG	yes	yes	yes	yes

Models *IWR6843*, *IWR1843* and *IWR1642* almost identical in terms of interfaces, only difference being the lack of a regular controller area network (CAN) port on the *IWR6843*. *IWR1443* is marketed by TI as a *"low power sensor"* and in the context of interfaces differs from the other chips by not implementing controller area network flexible data-rate (CAN-FD) and PWM ports [17].

3.3 Architecture

Functionally an *IWR6843* IC is divided into three main blocks; the RF sub-system (RFSS), Master sub-system (MSS) and the DSP sub-system (DSS). This division and each sub-systems' primary components are presented in Figure 3.1.

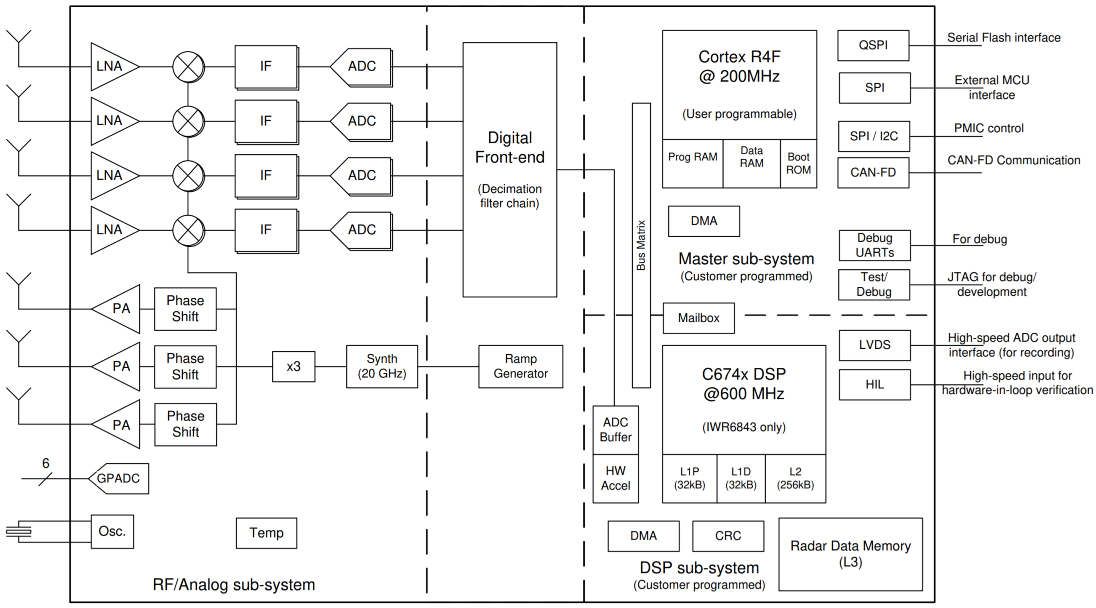

Figure 3.1. *IWR6843 Block diagram [19].*

Radar front end functionality of the chip is contained within the RFSS. This includes both the transmitting circuitry, including the ramp generator, the RF synthesizer and both phase shifters and power amplifiers for each of the three transmit channels, and the receiving circuitry, including separate mixers, IF filtering and ADCs for each of the four receive channels. Additionally, the oscillator circuitry and general purpose ADCs are assigned to the RFSS.

The chip as a system is controlled by the MSS. Main part of this subsystem is the chips Cortex R4F core, on which user code can also be executed. Majority of the chips communication interfaces are located in the MSS. In addition to interfaces used on a deployed system, the debug interfaces of the chip are located in the MSS.

DSS contains the signal processing power of the chip, including the main DSP unit. Circuitry needed for the basic radar processing are also located in the DSS. These include the radar ADC buffer, radar data memory and a hardware accelerator unit. High speed interfaces for transferring raw radar data and hardware-in-loop functionality are included in the DSS.

3.4 Performance

This section examines performance and capabilities of the mmWave family products. First capabilities directly related to the chip, such as range and resolution, are presented. Then external factors, such as operating conditions and target's physical attributes, are explored.

3.4.1 Accuracy, Resolution, Range

Unlike for some less versatile sensor types and implementations, it is not straightforward to declare mmWave sensor maximum performance metrics. This is due to the fact that one sensor can be configured in almost endless variations by altering everything from the the actual radar transmissions via the chirp parameters to the post processing algorithms used to produce the final information. Besides from a large number of variables, it is important to note that not all capabilities are enhanced by a parameter change; improving one aspect of the performance may come with diminished performance in other aspects. This is well illustrated by the table provided by Texas Instruments in their *Programming Chirp Parameters in TI Radar Devices (Rev. A)* guide presented in Table 3.3 [20]

Table 3.3. *Example chirp configurations and their performance provided in [19].*

Parameter	Units	LRR	MRR	SRR	USRR
Max unambiguous range	m	225	125	45	22.5
Sweep bandwidth	MHz	300	540	750	1500
Ramp slope	MHz/us	10	12	15	30
Inter-chirp duration	us	8	10	12	50
Number of chirps	-	256	128	128	128
Range resolution	m	0.50	0.28	0.20	0.1
Chirp duration	us	30	45	50	50
Max umambiguous relative velocity (1)	kmph	92.28	63.75	56.56	35.3
Max beat frequency	MHz	15	10	4.5	4.5
ADC sampling rate (complex)	Msps	16.67	11.11	5.00	5.00
Number of samples per chirp		500	500	250	250
Range FFT size	-	512	512	256	256
Frame time (total)	ms	9.728	7.04	7.94	12.8
Frame time (active)	ms	7.68	5.76	6.4	6.4
Radar data memory required	KB	**2048**	**1024**	**512**	**512**

(1) The maximum velocity can be increased beyond the max unambiguous velocity by using higher level algorithms.

Examination of the table provides insights into the maximum expected performance of different chirp configurations. Configuration named LRR, an acronym for long range radar, lists the longest unambiguous maximum range of 225 meters, while configuration named USRR, an acronym for ultra short range radar, list the same range parameter as mere

22.5 meters [20]. While configuration LRR results in an unambiguous maximum range order of magnitude greater, configuration USRR results in a superior range resolution of 0.1 meters compared to the LRR's 0.5 meters.

While multiple factors affect the actual maximum range, insight into this difference can be gained by examining Section 2.3.2 Equation 2.10 which states that the theoretical maximum unambiguous range is dependant on the ADC sampling frequency and and frequency slope. Plotting the appropriate parameters from Figure 2.3.2 into Equation 2.10 following results are obtained:

$$d_{max} = \frac{f_s c}{2S} = \frac{16.67Msps \times 3 \times 10^8 \frac{m}{s}}{2 \times 10 \frac{MHz}{us}} = 250.05m \tag{3.1}$$

$$d_{max} = \frac{f_s c}{2S} = \frac{5.00Msps \times 3 \times 10^8 \frac{m}{s}}{2 \times 30 \frac{MHz}{us}} = 25.00m. \tag{3.2}$$

These theoretical values differ from the values provided in Figure 3.3. This is likely due to the provided values being intentionally dimensioned to be smaller than theoretical values in order to avoid over-promising performance. Regardless, these results indicate that Equation 2.10 can be used for estimating maximum range of an mmWave solution.

Similarly to the maximum range estimation, Section 2.3.2 Equation 2.9 provides a way estimating range resolution. Plotting the appropriate parameters from Figure 2.3.2 into Equation 2.9 provides the following results:

$$d_{res} = \frac{c}{2B} = \frac{3 \times 10^8 \frac{m}{s}}{2 \times 300MHz} = 0.50m \tag{3.3}$$

$$d_{res} = \frac{c}{2B} = \frac{3 \times 10^8 \frac{m}{s}}{2 \times 1500MHz} = 0.10m. \tag{3.4}$$

These results match the values provided in the table of Figure 3.3. This indicates that 2.9 can be used for estimating range resolution of an mmWave solution. Similar relations of performance gain and loss depending on the system parameters exist also for velocity measurements, target differentiation and other characteristics. Additional equations for estimating mmWave performance can be found in Section 2.3.2 of this thesis. More detailed information for designing chirp parameter configurations can be found from *Programming Chirp Parameters in TI Radar Devices (Rev. A)* [20].

In addition to numerical performance examples Texas Instruments provides a chart of maximum achieved detection ranges for various common objects. This chart is presented in Table 3.4. While the chart provides useful information for estimating maximum detection range in other use cases, it is important to note that the results were obtained in close to optimal environment, an empty parking lot, and with various different sensor hardware and chirp configurations. Therefore the results should be viewed as reasonable peak performance expectations for an optimised solution rather than results for a singular all-purpose sensor deployment [21]

Table 3.4. *Detection range results from Texas Instruments application note [21].*

Object	EVM Measured Range (m)												
	1	5	10	20	30	40	60	80	100	120	140	160	199
Truck (1)	●	●	●	●	●	●	●	●	●	●	●	●	
Car (1)	●	●	●	●	●	●	●	●	●	●	● (2)	● (2)	● (2)
Motorbike (1)	●	●	●	●	●	●	●	●					
Bicycle with human (1)	●	●	●	●	●	●	●						
Human (3)	●	●	●	●	●	●							
Metal chair (3)	●	●	●	●	●								
Soda can (3)	●	●	●	●	●								
Wooden chair (3)	●	●	●	●									
Plastic chair (3)	●	●	●										
Cup of coffee (3)	●	●	●										
Large dog (3)	●	●	●										
Small dog (3)	●	●											
Coins (US quarters) (4)	●												

(1) xWR1443 using high RCS chirp configuration from object versus range.
(2) xWR1642 using long range chirp configuration from traffic monitoring.
(3) xWR1443 using low RCS chirp configuration from object versus range.
(4) xWR1443 using best range resolution chirp configuration from the out-of-box (OOB) demo.

In conclusion, performance of an mmWave system is dependant on both the hardware chosen and radar chirp configuration used, as well as the post processing performed on the acquired data. Some specific measures of performance such as range and resolution have radar parameter interdependencies which prevent simply maximising performance on each metric, rather a compromise between different measurement performances must be made.

3.4.2 Condition tolerance

For a sensor to be able to measure, it must interact and be interacted upon by the surrounding physical forces. In figures depicting a sensors principle of operation this often appears as a simple and uninterrupted process. However when moving from theoretical figures to a real operating environments, there are almost always some unwanted interfering signal also present. For example on a city street there are several sources of light always present, interfering with optical measurements. Additionally, expanding the EM frequency range from visual light, the Sun produces ultra violet (UV) spectrum EM present during daytime and everything above absolute zero emits some amount of IR light. Moving on from EM waves, the atmosphere will always have some sort of disturbances ranging from pressure waves in the form of sound to more subtle climate related barometric fluctuations. Even the street itself vibrates as people and machinery move nearby.

An important property in a sensor is it's immunity to the signal it is not supposed to measure while still remaining sensitive to the desired signal. As discussed previously the mmWave product family utilizes radio frequencies between 60 and 81 GHz for sensing. This band has many benefits, including obvious immunity to disturbances on much higher frequencies such as IR, visible light and UV ranging from 3 THz to 30 PHz. [12] As mmWave sensors do not operate in the visual spectrum, they are not affected by sigh obstructing environmental conditions such as smoke, bright sun light or artificial lights and total lack of light. [22]

The mmWave sensor family is also largely impervious to atmospheric conditions at their intended ranges of operation. While the atmosphere does negatively affect EM wave propagation in the millimeter wave spectrum, most of the losses can be attributed to free-space losses [23]. Atmospheric losses consist mostly of gaseous losses due to energy absorbed into gas molecule vibrations and moisture related losses, caused by both moisture in the air and potential rain drops. Free-space losses for a 60 GHz signal between isotropic antennas at a range of one kilometer is about 127 dB whereas water vapour content of 7.5 g/m^3 under one decibel. A heavy rain of 5 mm/h attenuates a 60 GHz signal about 2 decibels per kilometer. [23] Overall mmWave sensors are not much effected by traditional environmental conditions [22].

3.4.3 Reflective materials

When an EM wave comes in contact with an object, part of the wave will scatter out and part of the wave will be absorbed by the object. How much of the wave gets absorbed and how much gets reflected and to which directions, depends on the properties of the object, mainly the object's dielectric constant, size and shape as well as the wavelength of the EM wave. [24]

When designing an mmWave system, intended use case should always be validated with an evaluation module or similar off-the-shelf product before proceeding, as while the laws of physics and possible similar systems can provide indication of the use case's feasibility, real use cases have so many variables that it usually not practical trying to theoretically prove feasibility.

While mmWave frequency signals can penetrate most non-metallic barriers of reasonably low thickness, there are differences between materials, as can bee seen in Table 3.5

Table 3.5. *Average electrical characteristic of different materials. Modified from [25].*

Type of material	ϵ_r	tan(δ)	α [dB/cm]
Stone	6.81	0.0401	5.73
Marble	11.56	0.0067	1.25
Concrete	6.14	0.0491	1.25
Aerated concrete	2.26	0.0449	3.70
Tiles	6.30	0.0568	7.81
Glass	5.29	0.0480	6.05
Acrylic glass	2.53	0.0119	1.03
Plasterboard	2.81	0.0164	1.51
Wood	1.57	0.0614	4.22
Chipboard	2.86	0.0556	5.15

Considering heavy rain attenuates a 60 GHz signal 2 dB/km, the attenuations presented in Table 3.5 are considerable.

In addition to material differences, as stated earlier, size and shape of the object are an important factor in radar reflectivity. While the data presented in Figure 3.4 is not very scientifically precise in defining the object forms, it can provide good reference information when assessing use case feasibility.

3.4.4 Interference

In addition to interfering ambient signals from the sensor's operating environment, it is possible for an mmWave sensor to receive signals from another similar sensor's operating in the same environment. These interfering signals are by definition something the sensor cannot be immune to receiving if they are on the sensor's operating band. While there are plenty of situations where only a single mmWave sensor is present, there are also many scenarios where there can be multiple identical sensors operating in the same space. One such scenario is vehicles utilizing the millimeter wave band for both communication and radar sensing [7]. In such a scenario, it is not improbable that multiple identical systems can come within radar range of each other.

As utilization of millimetre wave in automotive communication and sensing is expected to rise considerably and thus increasing amount of research is being conducted on potential interference and methods for mitigation. [7]

One study on FMCW mutual interference divides interference occurrences in two categories; two identical systems interfering and two similar systems interfering.

Interference manifests in two forms, either as ghost targets or a rise in the noise floor. In the case of identical systems, the study found that the probability of a ghost target detection is as low as 0.000665, which the study determines as almost insignificant. Interference between non-identical system was found to cause various post-FFT noise. [26]

Various mitigation strategies for inter radar interference can be employed. Both narrowband interference causing ghost targets and wideband interference increasing the noise floor can mitigated using various statistical methods in the post-processing phase. Additionally ghost targets can be in some cases eliminated with a notch filter. [26][27]

Overall, interference between radar system can happen and thus should be considered in the design process of an mmWave system. However the probability for catastrophic interference is relatively low and mitigation methods have been developed.

3.5 Design considerations

This section discusses some key aspects of a successful mmWave product development cycle. This section is by no means a complete guide on electronics product design but a list of some important considerations for mmWave systems.

3.5.1 Antenna design and implementation

Correctly designed antennas are crucially important for ensuring mmWave radar devices are able to function correctly. TI mmWave products use antennas directly integrated to the printed circuit board (PCB) also known as PCB antennas. This results in additional requirements for the system PCB and PCB materials. [28] In general, integration of a PCB antenna to a system should be taken into account throughout the whole process rather than added as an afterthought.

Designing an integrated PCB antenna requires considerable expertise and should thus be allocated appropriate amount of design time and funds during project planning. Additionally, antennas must be tested extensively, which also requires proper resourcing. Potentially increased PCB costs due to RF PCB material requirements must also be taken into consideration when estimating product manufacturing costs.

Designing an antenna from scratch is not always the only option but one of three. TI recommends the following options for mmWave antenna development [28]

- Custom in-house designed antenna
- Custom third-party designed antenna
- TI provided reference antenna design

TI provides multiple reference antenna designs on their *Antenna Database* [13]. These antennas are validated by TI as they are used on TI mmWave evaluation modules. Additionally to being ready to use solutions, these antennas can be utilized as starting points from which to design a more application specific custom antenna, potentially reducing antenna development costs.

Supplementary information on mmWave antenna and PCB recommendations can be found from *TI mmWave Radar sensor RF PCB Design, Manufacturing and Validation Guide* [28].

In addition to providing reference antennas, Texas Instruments provides version of the *IWR6843* silicon called *IWR6843AoP*, in which AoP stands for antenna-on-package (AoP). This version of the chip integrates the radar antenna directly onto the chip, eliminating the need for a PCB antenna. Antenna design on the chip produces a relatively wide FoV of 120 degrees in both azimuth and elevation and is therefore best suitable for wide FoV applications with relatively low range requirements. Utilization of an AoP sensor has the potential to greatly reduce both development and manufacturing costs of an mmWave solution as a PCB antenna does not need to be designed and thus PCB material and stackup requirements may be relaxed. Additionally solution overall size can be reduced up to 40%. [29] [5]

3.5.2 Regulatory aspects of mmWave spectrum

When designing an electronics product, the goal usually is to produce a design that fulfils the functional requirements set for the design while being reliable and safe to operate. However if no unified definitions for safe, reliable and functional are provided, the results are bound to differ. This is one of the reasons standards exist. This subsection provides a starting point for ensuring that an mmWave system under development will comply with necessary standards. While different regions of the world have different bodies of standardization and sets of standards, there is considerable overlap and some certifications can be accepted as is even in other regions. This subsection will thus focus only on the European Union (EU) standards and regulations.

Texas Instruments provides a substantial amount of compliance documentation as part of mmWave design resources. According to their *mmWave Radar Device Regulatory Compliance Overview*, systems utilizing TI mmWave products are subject to the following EU standards [30]

- **EN 62368-1** Audio/video, information and communication technology equipment - Part 1: Safety requirements , Electrical safety
- **EN 62311** Safety, RF exposure - Assessment of electronic and electrical equipment related to human exposure restrictions for electromagnetic fields (0 Hz – 300 GHz)

- **EN 301 489-3** ElectroMagnetic Compatibility (EMC) standard for radio equipment and services; Part 1: Common technical requirements.
- **EN 305 550** Short Range Devices (SRD) Radio equipment to be used in the 40 GHz to 246 GHz frequency range;

The standard *EN 62368-1* is a generic safety standard which all low-voltage electronics must comply with. Standard *EN 62311* places limitations on how much and what type of RF energy the product can expose users to and standards *EN 301 489-3* and *EN 305 550* aim to ensure that the product does not interfere with other electronic systems as well as is not vulnerable to potential external sources of interference.

Additional compliance information, including United States market regulations, can be found from the *mmWave Radar Device Regulatory Compliance Overview*. While TI provides an excellent document on mmWave EMC, regulations must always be independently verified. [30]

3.5.3 Certification process

As discussed in the previous subsection all electronic devices are subject to standards and regulations. In order to be legal to sell, these system must be certified against these standards. Integrating regulatory compliance in the earliest stages of the design process is a good practice with all electronics products but especially important when designing radar systems like mmWave utilizing products, which are subject to additional regulations.

Texas instruments has provided an example of a typical certification process as a part of their *mmWave Radar Device Regulatory Compliance Overview*, which is presented in Figure 3.2. This can be used as a reference when planning a mmWave product development process. [30]

3.5.4 Power requirements

All electronics systems have at least one power rail to power the system. Most primitive systems may only have one voltage rail and be tolerant of considerable fluctuations in the voltage while there is no upper limit on how many and stable are required by the most intricate and delicate systems. Stable and accurate operating voltages are required to achieve accurate and intended functionality, spikes and other disturbances in the voltages may result in false readings, error states or even damaged equipment. Power requirements for the *IWR6843* are presented in Table 3.6.

In total *IWR6843* requires four different main voltage rails with current ratings ranging from 50 mA to 2000 mA. *IWR6843* datasheet also states typical power consumption levels for different modes of operation, these are presented in Table 3.7.

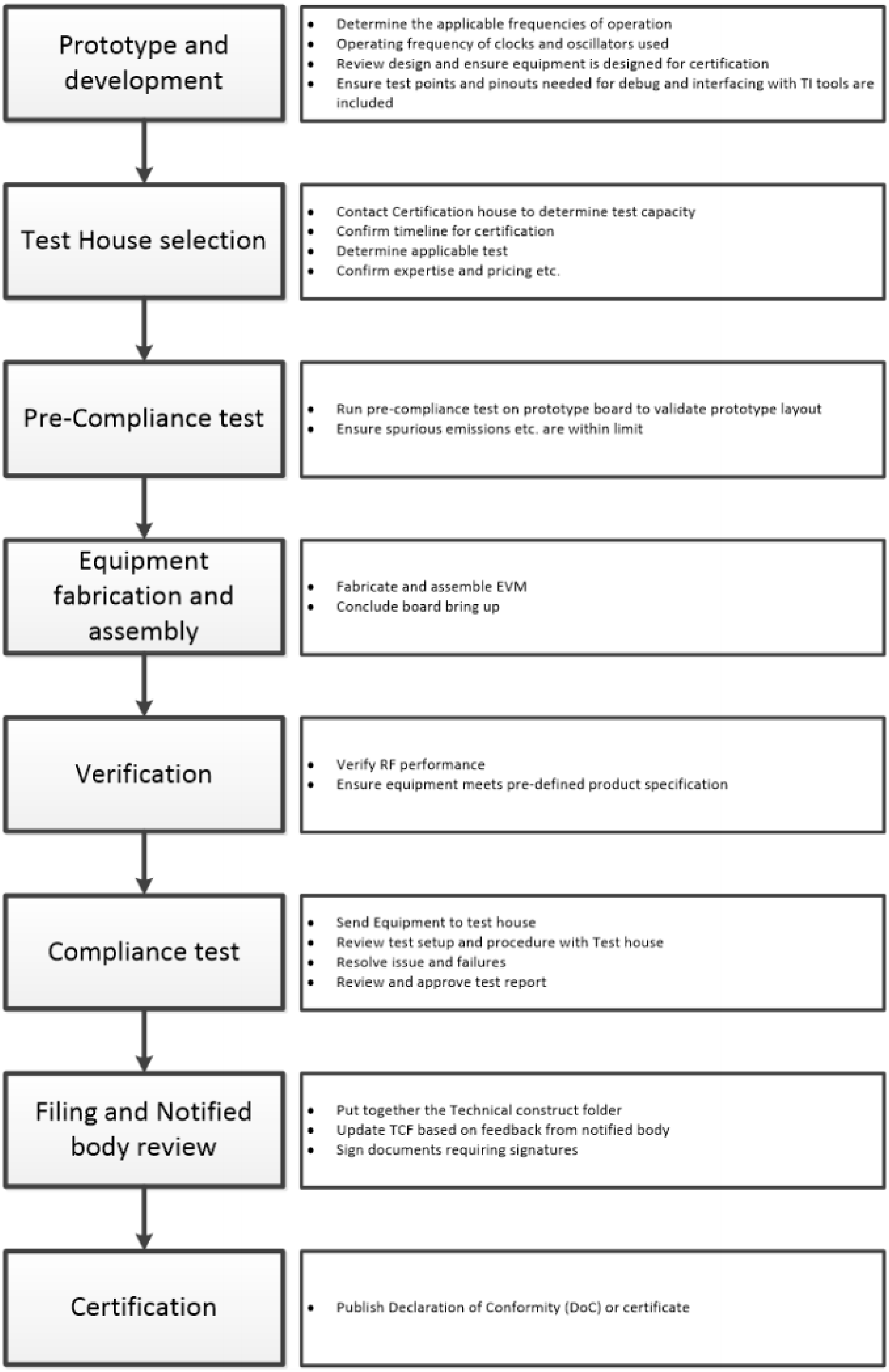

Figure 3.2. *Certification process flow provided by Texas instruments [30].*

Table 3.6. *IWR8643 maximum currents by supply. Table from [19].*

PARAMETER	SUPPLY NAME	DESCRIPTION	MIN	TYP	MAX	UNIT
Current consumption[(1)]	VDDIN, VIN_SRAM, VNWA	Total current drawn by all nodes driven by 1.2V rail			1000	mA
	VIN_13RF1, VIN_13RF2	Total current drawn by all nodes driven by 1.3V rail (or 1V rail in LDO Bypass mode), when only 2 transmitters are used.[(3)]			2000	
	VIOIN_18, VIN_18CLK, VIOIN_18DIFF, VIN_18BB, VIN_18VCO	Total current drawn by all nodes driven by 1.8V rail			850	
	VIOIN	Total current drawn by all nodes driven by 3.3V rail[(2)]			50	

(1) The specified current values are at typical supply voltage level.
(2) The exact VIOIN current depends on the peripherals used and their frequency of operation.
(3) Simultaneous 3 Transmitter operation is supported only with 1-V LDO bypass and PA LDO disable mode. In this mode, the 1-V supply needs to be fed on the VOUT_PA pin. In this case, the peak 1-V supply current goes up to 2500 mA. To enable the LDO bypass mode, see the *Interface Control* document in the mmWave software development kit (SDK).

Table 3.7. *IWR6843 power consumption stated in the datasheet. Table from [19].*

PARAMETER	CONDITION			DESCRIPTION	MIN	TYP	MAX	UNIT
Average power consumption	1.0-V internal LDO bypass mode	24% duty cycle	1TX, 4RX	Regular power ADC mode 6.4 Msps complex transceiver, 13.13-ms frame, 64 chirps, 256 samples/chirp, 8.5-μs interchirp time, DSP + Hardware accelerator active		1.19		W
			2TX, 4RX[(1)]			1.25		
		48% duty cycle	1TX, 4RX	Regular power ADC mode 6.4 Msps complex transceiver, 13.13-ms frame, 64 chirps, 256 samples/chirp, 8.5-μs interchirp time, DSP + Hardware accelerator active		1.62		
			2TX, 4RX[(1)]			1.75		

(1) Two TX antennas are on simultaneously.

Largest power consumption stated is 1.75 W. Following good design practises will result in slightly over-dimensioned power supplies but the combined power rating is likely to be around 2 W to 3 W. *IWR6843* datasheet also provides recommended maximum ripple levels on 1.0 V, 1.3 V and 1.8 V voltage rails for achieving specified levels of accuracy. These recommendations are presented in Table 3.8.

Table 3.8. *IWR6843 maximum recommended ripple levels. Table from [19].*

FREQUENCY (kHz)	RF RAIL		VCO/IF RAIL
	1.0 V (INTERNAL LDO BYPASS) (μV_{RMS})	1.3 V (μV_{RMS})	1.8 V (μV_{RMS})
137.5	7	648	83
275	5	76	21
550	3	22	11
1100	2	4	6
2200	11	82	13
4400	13	93	19
6600	22	117	29

3.5.5 Third party ready-made modules

In some potential use cases of mmWave technology the projected sales volume of the solution may be insufficient to justify the costs incurred by developing application specific hardware. In these cases pre-made 3rd-party mmWave products available on the market may be a workable solution.

Texas Instruments provides a catalogue of 3rd-party mmWave Modules as part of their *Antenna Database* [13]. Using a pre-built module may limit the design decisions available but can provide a faster application development time as only software development is required.

3.5.6 Software resources and requirements

Software development for the mmWave products is left outside the scope of this thesis. However, it is briefly discussed in this section to provide readiness to assess development efforts required to produce a functional mmWave system.

Texas Instruments provides an integrated development environment (IDE) for working with mmWave software development as well as a comprehensive library of example projects implementing various mmWave systems. While the tools provided for software development are substantial, it is crucial to consult a software development expert for full estimation of the software work needed to develop a custom application. [31]

In addition to regular embedded software experience, knowledge on algorithm development and signal processing is required for refining the radar data. If a custom antenna is utilized, algorithm development may be partially blocked until application specific hardware is able to be provided for parties responsible for algorithm development.

4. TECHNOLOGY COMPARISON

This chapter aims to provide useful information and comparisons that can aid in a technology selection process where mmWave is one of the technologies being considered. This chapter will first present some example use cases for mmWave technology. Then potential alternatives to mmWave technology are introduced and explained. Then performance, condition tolerance and cost structures of all technologies are compared. After all information is provided, findings are applied to the example use cases. Finally, potential for sensor fusion is briefly discussed.

4.1 Application cases for mmWave technology

This section presents two use case examples to be used for technology comparison. Their aim is to showcase the strengths and weaknesses of the technologies being compared.

While TI mmWave sensor can be used for much more complicated systems than presented here, it was reasoned that relatively simple examples help keep the technologies in the main role of this comparison. A more complex application for mmWave technology is presented in Chapter 5.

4.1.1 Case I: Occupancy detection

As automation keeps on expanding to new applications, there is an increasing need for detecting people and objects in constructed environments. Example use case one is detecting people and other objects inside buildings. In order to simplify further, a medium sized room around 4 by 4 meters is considered.

This use case could apply to anything from detecting people occupying a meeting room or walking down a corridor to ensuring a hazardous environment or area is clear of people. In order to keep the example simple, use of a single sensor is assumed.

4.1.2 Case II: Object detection and tracking

In addition to static systems gathering information on moving object in the system domain, another growing system class is moving systems that need information on their surroundings. Example use case two looks at detecting people and objects in a setting where there is active movement of either the target or the measurement system, or both. To make the case more specific, objects of around size of a person are considered.

This use case includes anything from simple slow moving automated warehouse robots in a controlled environment to high speed automated driving systems in self driving cars. In order to keep the example simple, use of a single sensor is assumed.

4.2 Alternative sensor technologies

This section briefly presents potential alternative sensor technologies for FMCW radar sensors like Texas Instruments mmWave sensor family. Additionally potential strengths and weaknesses are discussed.

The list of technologies by no means includes all potential alternatives, only four common ones have been chosen. These four technologies are laser measurements, ultrasonic measurements, infrared measurements and camera measurements.

4.2.1 Laser

Laser based sensors use a laser beam for distance measurement. The word laser is acronym for *light amplification by stimulated emission of radiation*. Characterising properties of a laser are directionality, monochromaticity, coherence and brightness. The basic concept of a laser works on multiple frequency bands and one way of characterising lasers is to divide them into infrared lasers, visible lasers, ultraviolet lasers and X-ray lasers. [32]

Distance measurement with a laser can be achieved similarly to the radar ToF measurements presented in Section 2.2. Operating principle of a simple laser ToF system is presented in Figure 4.1.

As the speed of light is known, distance can be calculated using Equation 2.3. Just as a radar, a laser signal employs EM waves and thus does not rely on any medium for propagation.

Laser based systems are very versatile, laser measurement ranges can vary from some centimeters in simple laser distance measurement units, up to over a hundred kilometers in more powerfull and complex devices used in atmospheric measurements [34]. Maximum range of a laser system is largely dependent on the power and directionality of

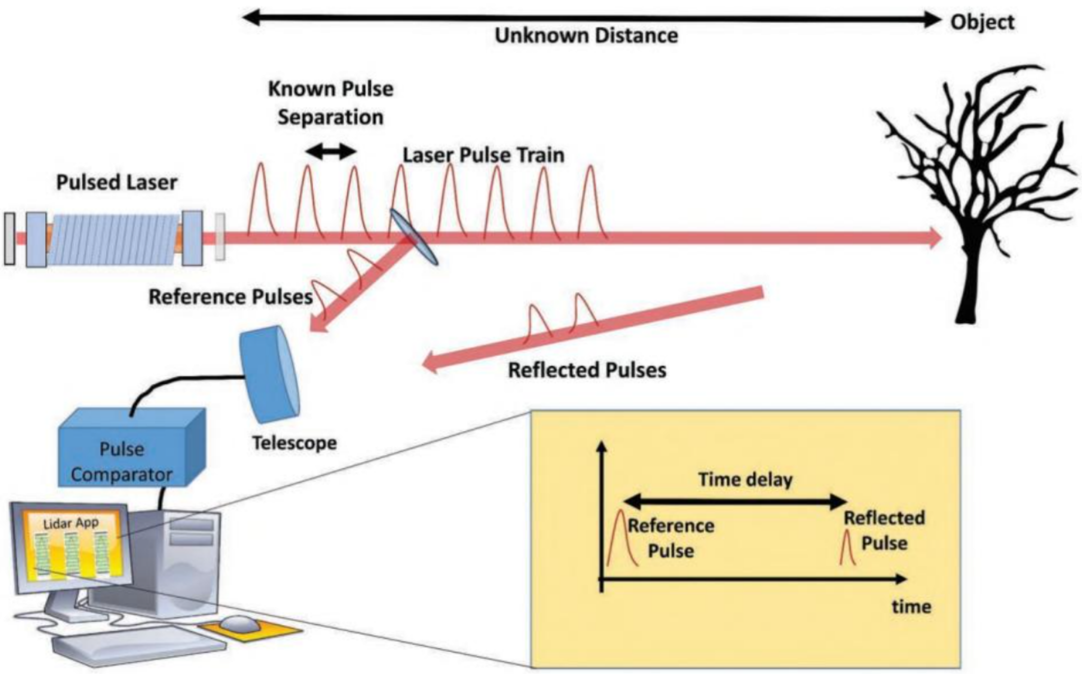

Figure 4.1. *Laser measurement principle. Figure from [33].*

the laser, sensitivity of the receiving instrumentation and the conditions of the operating environment. These conditions include atmospheric particles and moisture, as well as larger dust particles present in the atmosphere. In theory laser systems are largely immune temperature conditions and possible RF-spectrum interferences.

In addition to simple on point distance measurements, there exist laser based scanning systems, which can produce three dimensional maps of spaces and objects by moving the laser to perform multiple consecutive measurements with small offsets in azimuth and elevation. [35]

4.2.2 Ultrasonic

Ultrasonic sensors use sound waves for distance measurement. Frequencies of the signals used are beyond human hearing threshold of around 20kHz. Ultrasonic distance measurement can be achieved similarly to the radar ToF measurements presented in Section 2.2. [36] Operating principle of ultrasonic ToF system is presented in Figure 4.2.

Assuming the speed of the signal is known, distance can be calculated using Equation 2.2. While ultrasonic measurements use similar ToF measurement technique, the actual signal is quite different from a pulsed radar. Ultrasonic measurements use sound waves which are pressure fluctuations in a medium as opposed to EM waves. This means that whereas EM waves can travel in either through some medium or total vacuum, sound waves always require a medium to travel on. While sound can travel also in liquids and solids, in this context ultrasound measurements are limited to be within gas. [36]

Figure 4.2. *Ultrasonic ToF measurement.*

Maximum range of an ultrasonic sensor depends proportionally on the power fed to the transmitting power. Additional factors on the range include the medium, the frequency used and receiving sensitivity. Thicker mediums require more power and higher frequencies get more attenuated. Available industrial sensors' maximum range varies from few meter up to tens of meters while achieving accuracies of up to 0.1% [36]

As ultrasonic sensors rely on a gaseous medium as the signal propagation path, conditions on this medium can affect measurement accuracy. Following list presents some potential factors affecting ultrasonic measurement accuracy and reliability [36]

- Temperature
- Pressure
- Medium type
- Medium stratification
- Medium contaminants such as dust and steam
- Reflectivity of the target material

Strengths of ultrasonic sensors include good immunity to interference from the EM spectrum, including indifference to lighting conditions and RF noise. Ultrasonic systems can also be relatively simple and do not require very high operating frequencies so they can be relatively inexpensive.

4.2.3 Infrared

Modern IR sensing works by subjecting an IR sensitive element to the IR radiation to be measured. When subjected to the IR radiation, the element undergoes a state change that can be electronically measured. One such element type is presented in Figure 4.3. [37]

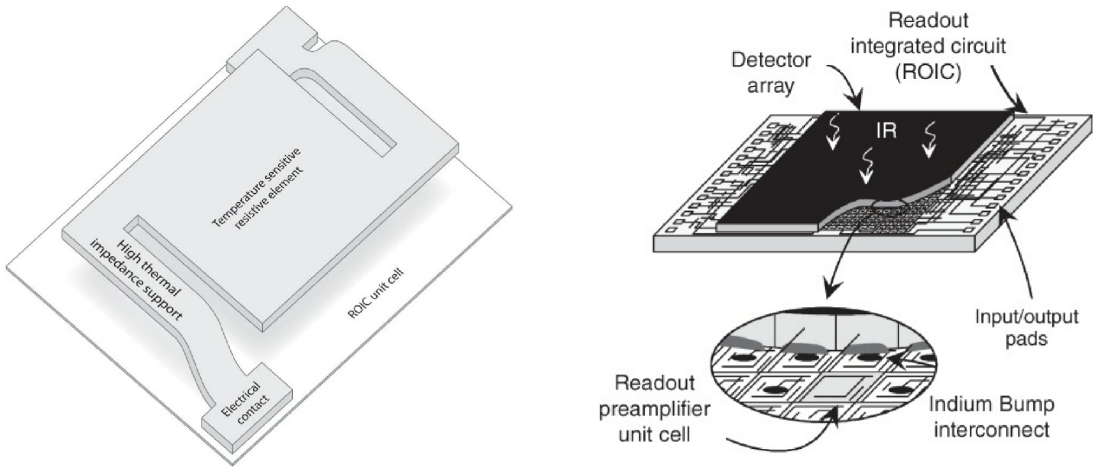

Figure 4.3. *IR sensor technology. Single sensor element (left) and an array of integrated sensors (right). Figures from [37].*

Infrared sensors are used both as individual one-pixel sensors as well as arrays of multiple sensors, producing IR images with varying pixel counts. Simplest arrays might consist of only four sensing elements but there are also implementations which have resolutions comparable to some visible light cameras. A camera like sensor array implementation is also presented in Figure 4.3.

Contrary to ultrasonic and laser measurements, IR sensor principle of operation is passive as it relies on IR spectrum EM waves reflected of the environment. There also exists infrared sensor systems that illuminate the environment with additional IR spectrum light but they will not be included in the scope of this thesis [38][39].

4.2.4 Camera

Modern digital cameras work by measuring reflected light with a large array of photosensitive sensors. Optics are used to focus the picture as desired. As with IR sensors, contrary to ultrasonic and laser measurements, camera principle of operation is passive as it relies on light reflected of the environment. The principle of operation for a modern digital camera is presented in Figure 4.4. [40] [41]

Cameras come in many forms utilizing different technologies of sensing light. In addition to the actual camera sensor, optics play an equally important role in defining a camera systems capabilities. [40][41] As different camera systems have considerably different

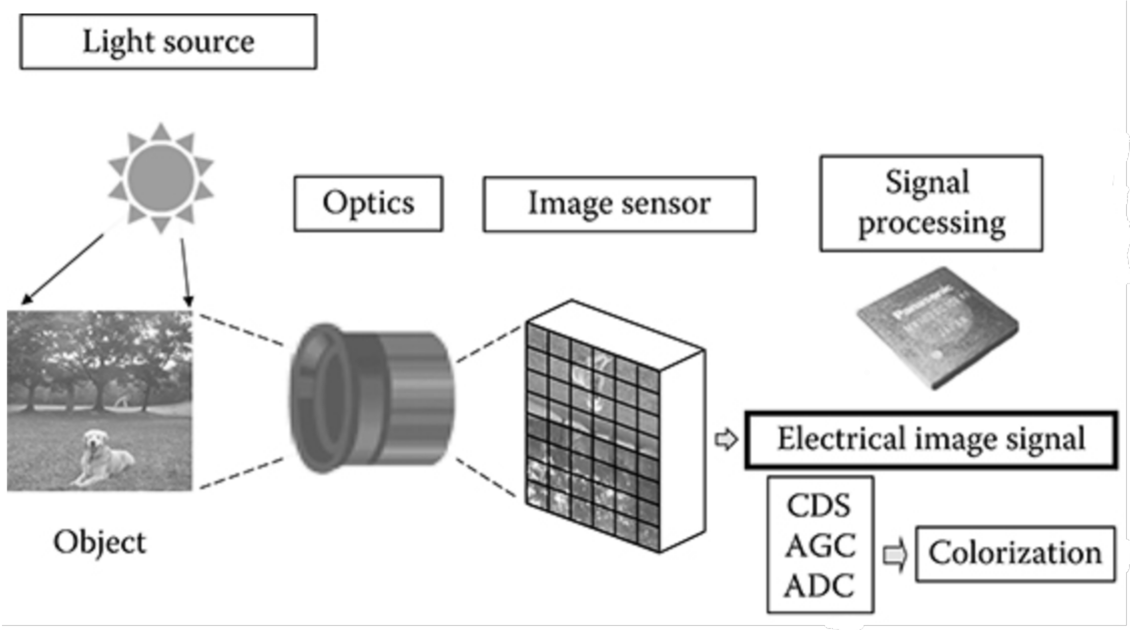

Figure 4.4. *Operating principle of modern digital camera system. Figure from [40].*

properties depending in the system implementation, properties such as range and resolution are not defined in this section.

While performance of camera systems varies from system to system, properties such as condition tolerance, which are set by the principle of operation are largely independent of system specific implementation. One of camera's weaknesses in sensor use is it's reliance on external sources for visible light to be able to sense. In order to function properly, a camera needs suitable lighting conditions and if these are not met, the sensors performance can deteriorate. [40]

4.3 Comparative analysis for technology selection

This section presents comparisons between the chosen technologies. First they are compared based on their performance potential, then operating conditions are considered. Lastly technology specific system cost structures are examined.

As each technology is looked at on a general level, drawing exact comparisons on properties like range and accuracy is not sensible as numerical values for these traits largely depends on individual technology implementations rather than the underlying principles. Therefore in order to be able to draw more general comparisons between technologies, approximate non-numerical performance grades are used.

4.3.1 Performance

Performance related properties of each sensor technology are presented in Table 4.1. Laser and IR based sensors are separated into two sub-categories as different types offer different performance in some cases.

Table 4.1. *Performance comparison of different sensor technologies. [32][33] [35][34][36][37][40][41]*

	FMCW radar	Point laser	Scanned laser	Ultrasonic	Single Cell IR	IR array	Camera
Spectrum	GHz EM waves	IR, visible, UV & X-rays	IR, visible, UV & X-rays	Sound waves	IR	IR	Visible light
Propagation speed	c	c	c	varies*	c	c	c
Measurement type	Active	Active	Active	Active	Passive	Passive	Passive
Distance measurement	Yes	Yes	Yes	Yes	No	No	No
Range	Medium	Long	Long	Short	Medium	Medium	High**
Accuracy High	High	High	Medium	Medium	Medium	High**	
Field of view	Wide****	Point	Wide***	Medium	-***	Medium***	Narrow /wide**
Resolution	Medium	-	High***	Low	-	Medium	High

**Medium dependant. **Optics dependant. ***Application dependant. ****Antenna dependant.*

4.3.2 Operating conditions

Operating condition tolerance of each sensor technology are presented in Table 4.1. Laser and IR based sensors are separated into two sub-categories as different types offer different performance in some cases.

Table 4.2. *Operating condition tolerance comparison of different sensor technologies. [32][33] [35][34][36][37][40][41]*

Sensor immunity	FMCW radar	Point laser	Scanned laser	Ultrasonic	Single Cell IR	IR array	Camera
Visible light	Total	High*	High*	Total	High	High	Low
Infrared	Total	High*	High*	Total	Low	Low	Medium**
Temperature	High	High	High	Medium	Low	Low	High
RF	Medium	Total	Total	Total	Total	Total	Total
Pressure	Total	Total	Total	Low	Total	Total	Total
Atmospheric moisture	High	Medium	Medium	Low	Medium	Medium	High
Rain	Medium	Medium	Medium	Low	Low	Low	Low
Dust	High	Medium	Medium	Low	Low	Low	Medium
Smoke	High	Low	Low	High	Low	Low	Low

**Depending on the frequency of the laser. **May require an IR filter.*

Examining Table 4.1 reveals many differences between technologies' condition tolerance. While each sensor technology has good immunity against some type of interference, some technologies exhibit better overall immunity than others. FMCW radar and laser based measurements can be categorized as a part of this more immune group while IR and ultrasound based technologies tend to be more vulnerable to the interference sources being examined.

In environments where presence of airborne interfering particles such as dust, smoke, moisture and rain are present, FMCW radar technology exhibits the best condition tolerance out of the technologies compared. In environments where a hostile RF environment is also to be expected, laser based measurements may result in better performance.

4.3.3 System cost and complexity

In embedded systems design the system's cost and complexity are often as important factors as the performance capabilities of the technology used. In order to aid in sensor technology comparison, Figure 4.5 presents rough approximations of each technology implementation's expected cost and complexity.

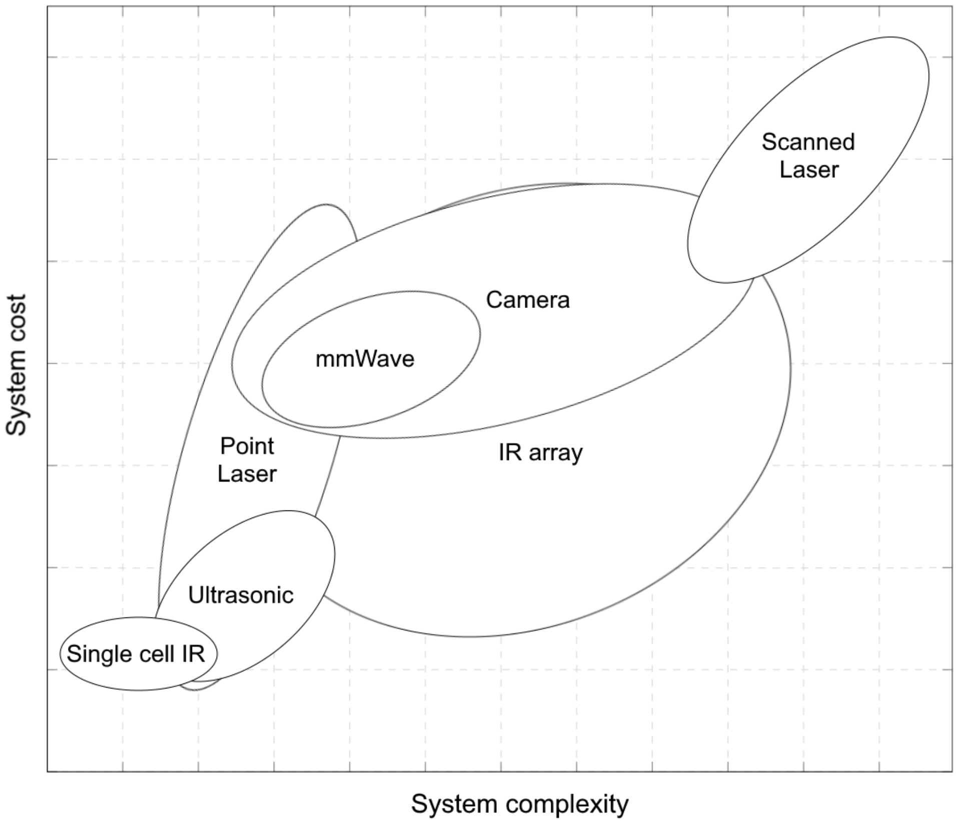

Figure 4.5. *Estimated system cost and complexity of different technologies.*

The actual cost structure depends on such a multitude of factors that a numerical comparison could produce enough material for a separate thesis. Therefore the costs presented in Figure 4.5 are based solely on insight gathered during the general research for this thesis.

4.3.4 Application case comparison

In this section technologies are compared by their potential in the example application cases presented in the beginning of this chapter. For both use cases, the technologies are first considered individually and finally the findings are combined into conclusions.

Case I: Occupancy detection

mmWave

In theory, an mmWave sensor with an appropriate antenna can cover a whole room and produce a medium resolution point cloud of the space, detecting people and large enough objects. Additionally, mmWave sensors can sense any movement in their FoV. As mmWave sensors are also relativity immune to most types of interference commonly found inside buildings, they provide a good option for occupancy detection solutions.

Point laser

A single point laser is not very well suited to surveying a volume as it can only produce single line measurement. A point laser could be used as a rudimentary trip wire or a light gate to determine if something is present across a defined line and could thus potentially indicate presence of an object.

Scanning laser

A scanning laser system can create a three dimensional map of the space being monitored and could thus be used to detect any object in a room. While a scanning laser has a very good performance potential in this use case, issues may arise from the relatively high cost of scanning laser systems.

Ultrasonic

Ultrasonic sensors measure distance from the sensor to the first acoustically reflective surface in front of the sensors. As propagation of the ultrasound is not as directional as a laser, the sensor senses a sector rather than a single point. With proper placement, for example in a corner of the room, on shoulder level, facing the opposite corner, some form of rudimentary occupancy could possibly be performed with an ultrasound sensor. However it should be noted that this type of system has a very high potential for false negatives and thus should not be deployed in any system requiring high accuracy. For non-critical systems requiring a cost effective method of estimating occupancy, ultrasound solutions could be considered.

Single cell IR

When properly placed, a single cell IR sensor can be used for sensing people in some use cases. However as inanimate objects tend towards an equilibrium with the environment temperature, it is not feasible to reliably detect them using a single cell IR sensor. Surface temperature can also become an issue in some cases where people wear enough clothing to mask their IR signature.

IR Array

IR arrays offer higher resolution compared to a single cell IR detector and thus offer more accuracy and even rudimentary location resolving. However IR arrays have the same issues of not being able to detect room temperature objects, as the single cell IR detector. IR based detection provides a relatively simple solution for non-critical systems.

Camera

A camera with appropriate optics can produce an image of the whole room being monitored and with proper image processing is able to detect any people or objects in sight. However lighting conditions in the room greatly affect a camera based system's reliability. In low-light conditions a camera begins to lose image contrast until only a dark image with no information is produced when room brightness drops to insufficient levels. Conversely, reflections from the sun or other sufficiently bright lights may blind the camera. However, if stable lighting conditions can be assumed, a camera is a relatively reliable option for occupancy detection. Depending on the system being implemented, privacy regulations may pose requirements on camera based systems.

Conclusion

All of the sensor technologies are capable of some form off occupancy detection. If only an indication of a potential occupant is required, point lasers, ultrasound and IR sensors may provide adequate performance at a relatively low cost. However, if accurate and reliable detection is required, mmWave radar, scanning laser sensors and camera are best suitable for the task. Of these technologies, camera is the most vulnerable to environmental conditions as the room must have adequate lighting conditions for the camera to function reliably. Additionally it should be noted that a camera based system requires heavy image processing to actually analyze the image for occupancy detection. Laser scanning technology is able to provide a three dimensional map of the room. While this provides very reliable information , it may be excessive in some application. While not as accurate as a laser scan, relatively cheap mmWave sensors provide enough accuracy for detecting a person in a room.

Case II: Object detection and tracking

mmWave

As mmWave sensors' main funtionality is to provide three dimensional distance, angle and velocity data, they are ideal for various object detection and motion tracking use cases. High refresh rates are also achievable with mmWave sensors so environments with relatively fast movements can be accurately monitored.

Point laser

Point laser measurements are not well suited for tracking a target due to their static nature and narrow FoV. In some special cases one directional tracking can be achieved.

Scanning laser

A scanning laser system can create a three dimensional map of the space being monitored and thus is in theory able to track movement by comparing consecutive scans. Issues with speed may arise with larger velocities as the system requires time to scan the monitored area on each refresh.

Ultrasonic

Ultrasonic sensors produce a one dimensional distance measurement, which is not optimal for tracking object in a three dimensional space. In some special cases one directional tracking can be achieved.

Single cell IR

Singe cell IR sensors cannot be reasonably used for tracking objects in three dimensional space. Detection is possible but not reliable.

IR Array

An array of IR sensors can be used to provide rudimentary tracking on a projected two dimensional plane. However obtaining accurate distance information is not easily possible.

Camera

Raw images outputted from a camera are not directly usable as object location and tracking information. However with sufficient image processing, it is possible to recognize objects, track motion and even deduce distance information.

Conclusion

Technologies best suited for object detection and tracking include mmWave radar, scanning laser sensors and camera based solutions as each of these technologies is able to provide accurate three dimensional position data. While one of the most accurate laser based solution have a tendency to be expensive, especially if high refresh rates are required. Camera based systems offer both flexibility and relatively low costs. However, additional image processing is required for producing numerical position data, which increases system complexity and cost. While having inferior angular resolution compared to light based solutions, mmWave sensors provide accurate distance sensing and velocity measurement while having similar materials cost to a camera system. Additionally, mmWave sensors provide integrated code execution and digital signal processing capabilities, removing the need for a separate processing unit.

4.4 Sensor fusion potential

Instead of choosing a single sensor technology, a designer may select multiple sensor technologies for a system. Combining data from multiple sensors can result in more accurate and diverse data compared to the sensors being used individually. However this is not always guaranteed and if the system is not carefully designed, sensor fusion can even result to inferior performance. [42]

Sensor fusion configurations can be divided into three categories:

- Complementary
  In this configuration separate sensors monitor separate attributes and the data is combined to provide a better and more diverse information.
- Competitive
  In this configuration multiple sensors monitor the same attribute and the data is combined to provide more accurate and less error-prone information.
- Cooperative
  In this configuration multiple independent sensors are used to provide information that cannot be obtained with a single sensor.

[43]

In more demanding applications mmWave sensors can benefit from each type of sensor fusion presented. While each sensor technology presented in this chapter can be combined with an mmWave radar sensor, the technologies providing most improvement potential are IR arrays and cameras as these perform well in categories where mmWave has weaknesses, like resolution and tolerance to RF interference.

For example, combining an mmWave sensor with a camera in a complementary configuration has potential for very accurate three dimensional movement tracking with good object recognition capability. For applications where improved discerning ability between animate and inanimate targets is required, an mmWave sensor could be paired with an IR array.

Best sensor combination for any use case is a sum of numerous variables. When considering a sensor fusion solution this chapter, especially Tables 4.1 and 4.2 as well as Figure 4.5, can be used for determining the most beneficial sensor combinations.

5. PROTOTYPE APPLICATION

In this chapter an example application for TI's mmWave technology is first proposed. Subsequently, a test plan is devised to assess the feasibility of such application and testing is carried out. Finally the test results are analysed and further areas of testing and study are proposed.

5.1 Concept - Road condition monitoring with mmWave

Upon considering possible mmWave technology applications, the concept of road condition monitoring usining a pole-mounted mmWave sensor was conceived. This was inspired by a Wapice's upcoming project including urban environment sensing as well as on-going research into radar based intelligent traffic monitoring systems such as presented in [44], [45] and [46].

As a prototype application this thesis presents a road side pole-mounted FMCW radar system capable of monitoring both traffic and road conditions. In order to provide insight into product development of an mmWave solution, this chapter aims to explore this type of system's implementation feasibility with an mmWave sensor. In areas of the world where the temperature dips below zero degrees Celsius for prolonged times, ensuring functionality of the road infrastructure requires clearing snow of the roads. Considerable amount of time and financial resources is spent to achieve this and in larger cities, real-time data on road network snow conditions could potentially be used to optimize snow removal operations.

Measuring snow height with millimeter frequency FMCW radar has been researched by Ayhan et al. in [47]. The paper presents and verifies a FMCW radar system operating at a center frequency of 80 GHz. The system is fixed on a platform above the snow for the measurements. The paper concludes that it was possible to measure snow height from up to 4 meters and with sub centimeter precisions. Also notable for this prototype applications use case, Ayhan et al. demonstrate an overall height estimation deviation to be in the millimeter range.

Measurement accuracy, which is critical for accurately estimating snow conditions on roads, can also be further improved by using complementary mathematical estimation techniques, such as the local resampling Fourier transform (LRFT) method presented by Wang et al. in [48]. Similar technique referred as Zoom-FFT is utilized by Texas instruments in their HARM demonstration [49].

A concept drawing of the proposed prototype application is presented in Figure 5.1.

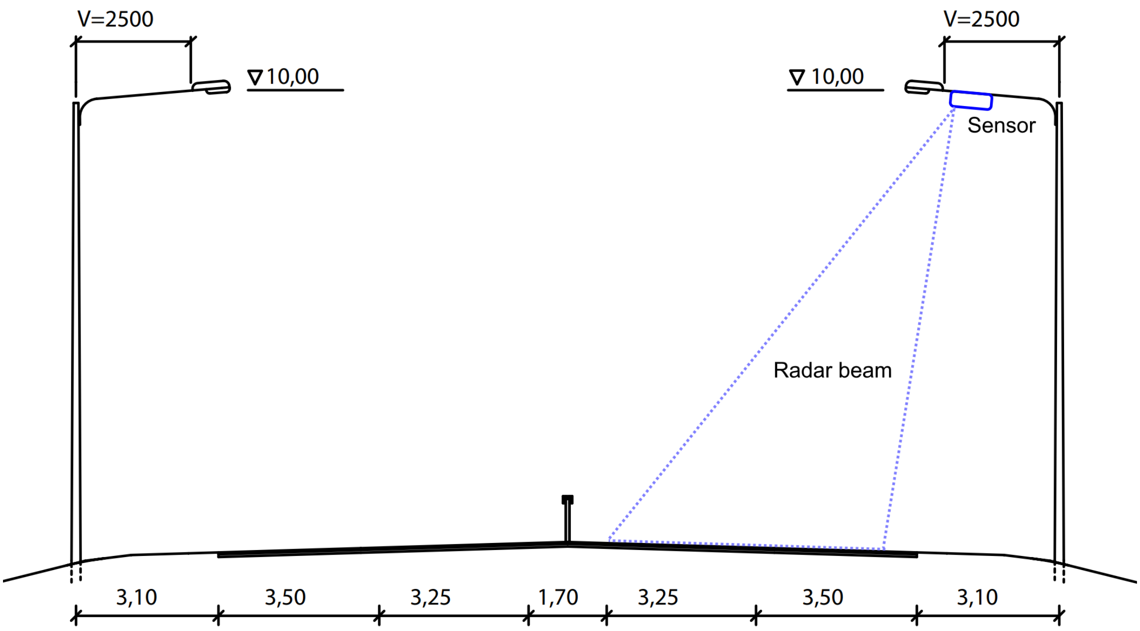

Figure 5.1. *Prototype concept drawing. Image modified from [50]*

As seen in Figure 5.1, the radar sensor would be positioned in a light pole or similar road infrastructure part providing elevation in close proximity to the road. Finnish guideline for road illumination design recommend light pole heights between 6 and 20 meters depending on road type [50]. For this thesis 10 meters is chosen for the target height of installation. From this position, the sensor could be used for both monitoring traffic and when no vehicles are in the sensors FoV the sensor could analyse the road surface. This dual purpose system could thus generate in real-time both information on traffic patterns and on road conditions.

5.2 Sensor development board and tools used

In order to evaluate TI's mmWave technology a development board was procured. TI has multiple different development boards and supplemental boards available for this purpose. From these model *IWR6843ISK-ODS* was chosen. As the name implies, this development board is based on TI's IWR6843 device and thus uses 60-64 GHz band. The acronym ODS in the product name stands for Overhead Detection Sensor. This means that the board is fitted with a relative short range but wide FoV antenna arrangement, comprising of 4 receive and 3 transmit antennas. TI states that this antenna setup is able to provide FoV of up to 120 degrees in both azimuth and elevation. [51] The development board is presented in Figure 5.2.

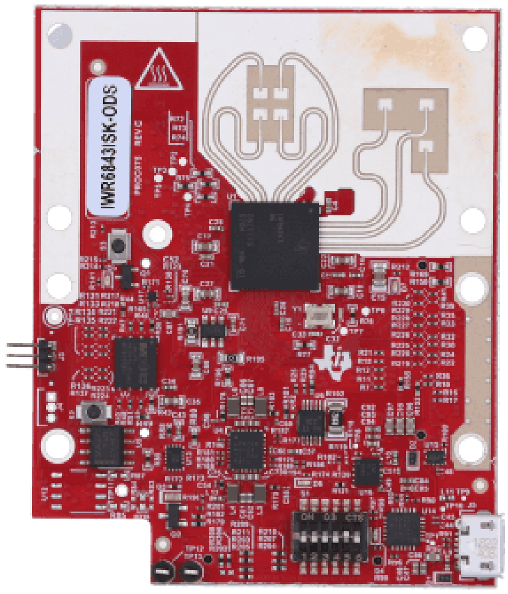

Figure 5.2. *TI IWR6843ISK-ODS Development board, top side [51].*

The boards dimensions are approximately 55 by 55 millimeters, with the actual radar IC measuring 10 by 10 millimeters. The board is powered trough unversal serial bus (USB) and communication between the IC and a computer is also provided by the same USB connection. [51]

As mentioned in Chapter 3, TI provides a comprehensive set of software resources to aid product development with it's mmWave product family. Due to the considerable work that goes into building and testing proprietary algorithms and software, only ready made tools we're utilized in the measurements made for this thesis. Initially platform capabilities were evaluated with TI's *ODS Point Cloud Demo* following instructions provided in the online guide [52]. After initial trials and board wake up were successful TI's HARM Lab was taken in use.

Whereas *ODS Point Cloud Demo* is meant for testing the capabilities of the board on a generic level, the HARM demonstration has a more narrow focus. TI's guide states that *"lab demonstrates the use of TI mmWave sensors for an application requiring a high degree of range accuracy"*. To achieve this, TI has implemented a technique it calls *Zoom-FFT*. This measurement procedure first measures an aproximate distance to the target and then proceeds to perform a second more narrow but higher resolution measurement to determine range up to millimeter-level accuracies [49]. The user interface (UI) provided by the HARM demo is presented in Figure 5.3

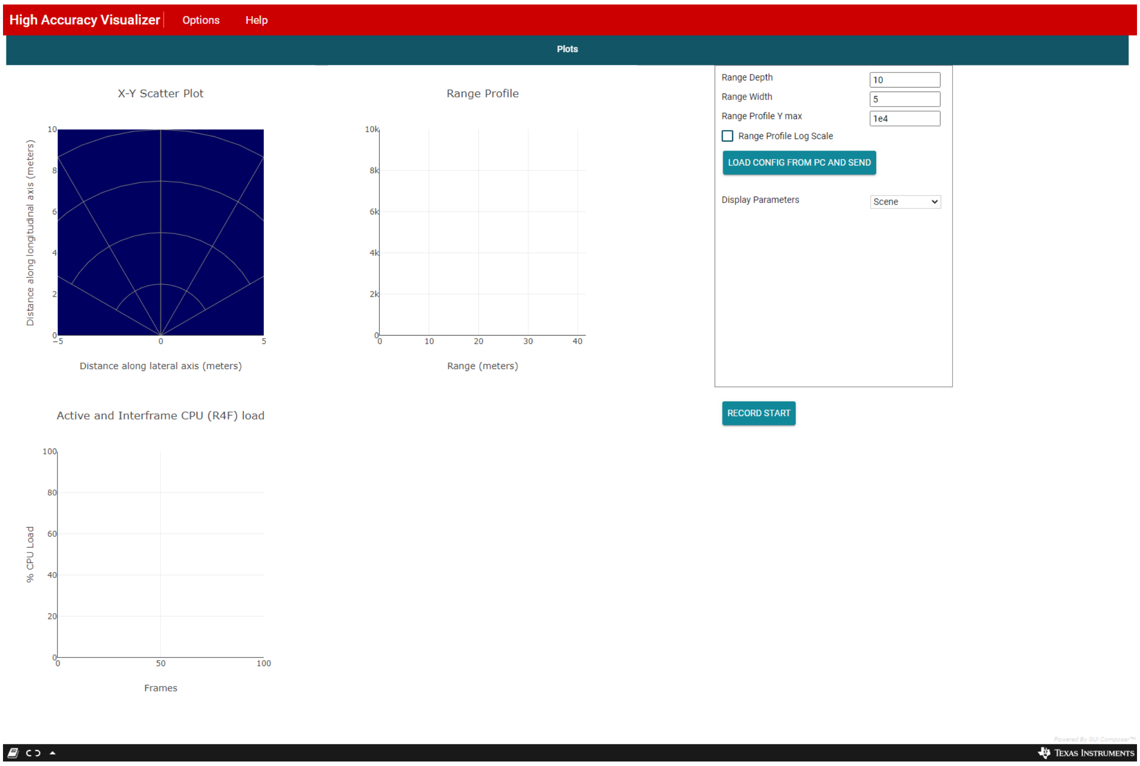

Figure 5.3. *TI HARM demo user interface [49].*

When running the software provided in [49], the sensor's relevant parameters can be controlled from the web UI. These include sensor configuration parameters, which are uploaded to the board as a .cfg file, desired range depth and range width for the measurement. When these are set, the sensor is active and will transmit live measurement data to the visualizer UI. This data is displayed in two main plots. On the left, is X-Y Scatter plot which in this use case will display only one dot and a corresponding distance reading. The second plot, titled Range Profile, provides a rough plot of readings trough a range of different distances. In addition, the UI provides functionality to record measured distance data into a comma separated value (csv) file. This capability is used extensively during testing carried out as part of this thesis.

5.3 Implementation target

This section outlines the goals set for the prototype application testing within the context of this thesis. As presented in Section 5.1, the prototype application concept is combined traffic and road condition monitoring. Out of these two functions, Texas instruments has already demonstrated that the sensor family is capable of monitoring traffic and individual cars so testing in this thesis is focused on the snow measuring capability of the sensor. [53]

The snow measurement capability has two main components: The sensors ability to accurately and reliably measure snow on top of an asphalt surface and the sensors accuracy at a range of around 10 meters. The testing will focus on assessing these two capabilities. Testing the long range accuracy demands actual long measurement ranges whereas snow measurements can be performed at a closer distance. The target of all the testing is to assess the sensors capability of accurately measuring snow accumulation from a distance of around 10 meters.

As noted in Section 5.2, developing a custom algorithm is a time consuming process. As the prototype application is not the main topic of this thesis but a demonstration of early stage research and development activities with a mmWave sensor, actual algorithm development is left outside the scope of the thesis. All measurements are made with the already available software tools. Possible effects of this is discussed in the analysis section of this chapter.

5.4 Test plan

This section presents the measurement setups and test plans designed for assessing the feasibility of the proposed prototype application. Additionally the measurement procedure and sensors assembly used for these experiments are presented.

Testing is divided into three experiments: A short range control experiments, short range snow experiment and a long range experiment.

5.4.1 Sensor assembly

While the *IWR6843ISK-ODS* evaluation module (EVM) is rated to function in temperatures ranging from −20 °C to 60 °C, the EVM was enclosed to provide additional protection during the measurements as well as aid in mounting the sensor in various measurement setups [51]. The fabricated enclosure was equipped with a threaded camera mounting adapter provided as part of the EVM kit. A silica gel pouch was added into the enclosure to absorb possible condensation caused by temperature fluctuations. The enclosure is presented in Figure 5.4.

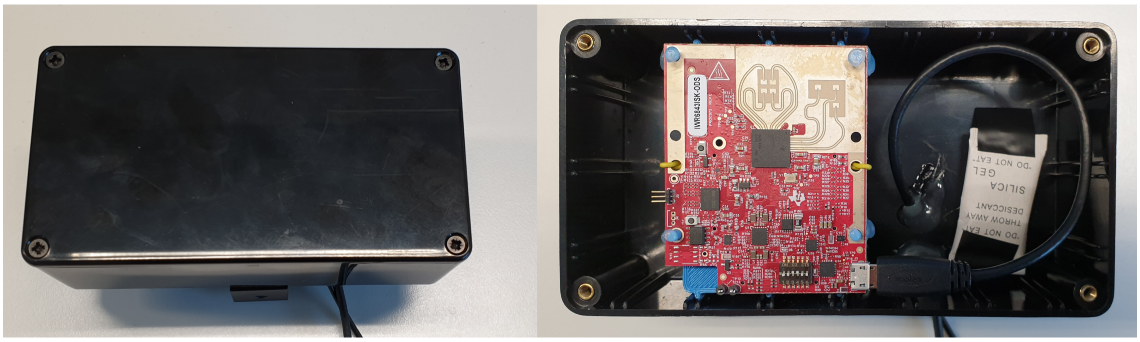

Figure 5.4. *Sensor assembly used for the measurements.*

When the enclosure is sealed, the sensor is covered by the plastic lid. The effect of this on the radar measurements was examined with brief testing and it was concluded that the lid does not significantly interfere with the planned measurements.

5.4.2 Short range control measurement setup

The purpose of the short range control measurement setup is to assess the maximum achievable accuracy and stability of the EVM at short ranges. To achieve this the EVM should be placed in an environment with minimal sources of interference and deflection. In an idea situation the setup would be located within an anechoic chamber and the sensor would hanged from the ceiling. However as using such resources for a mere demonstration would be excessive, simpler solution is used, consisting of a laboratory space and a tripod. The setup planned is presented in Figure 5.5

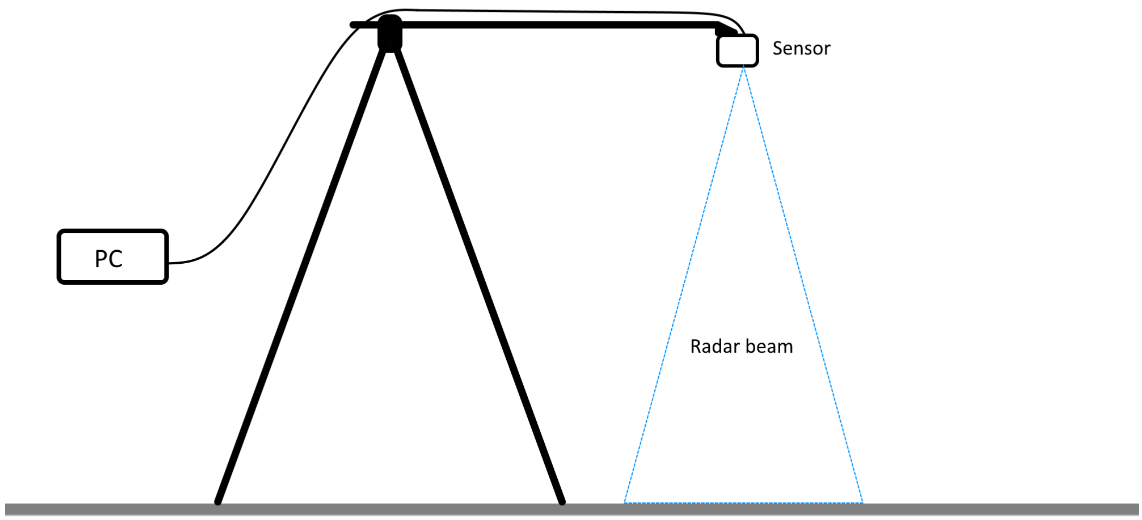

Figure 5.5. *Short range control measurement setup.*

When constructing the setup, care must be taken to ensure that the radar beam does not overlap the supporting tripod and the floor area in the sensors FoV is clear of any objects. In order to reduce unwanted radar echoes from surrounding objects, the sensor should be allowed as much empty surrounding space as possible.

The actual setup constructed inside Wapice Tampere premices' electronics laboratory is presented in Figure 5.6. In this setup, the sensors height from the floor was measured to be about 1.3 meters.

Figure 5.6. *Short range control measurement setup used for the measurements.*

5.4.3 Long range exploratory measurement setup

The purpose of the long range measurement setup is to assess the performance of the EVM at longer ranges. In order to achieve the necessary height Wapice Tampere office windows were utilized. As the prototype application height of ten meters was set, third floor was chosen. This allowed mounting the sensors around 9.5 meters above the vehicle ramp below. The sensor assembly was mounted on a metallic window ledge with a magnetic tripod. Concept drawing of the measurement setup is presented in Figure 5.7

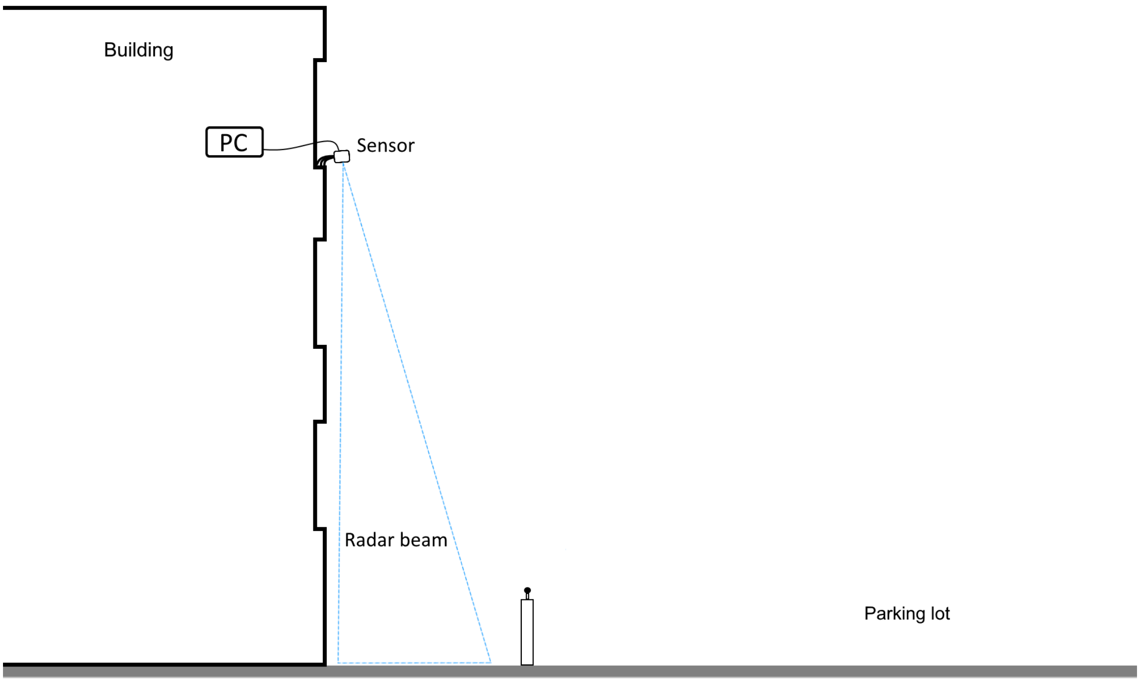

Figure 5.7. *Long range measurement setup.*

In an ideal scenario, the sensor would be mounted in such a way that the radar beam is totally orthogonal to the surface below and no interfering surfaces were near the beam. As such ideal setup was not available, the setup used may affect the results. In this setup the beam is very close to the building wall which may cause the radar signal to be diffracted from the wall, resulting in errors in the measurement. Second potential source of inaccuracies is that the area below the window is not empty but has a concrete barrier around four meters from the building wall. This barrier may cause unwanted radar echoes. Additionally, the area used is an active parking lot which may result in cars interfering with the measurements.

5.4.4 Short range snow measurement setup

The purpose of the short range snow measurement setup is to examine the sensors capability of detecting snow and changes in snow layer height at short ranges. To achieve this the sensor is mounted on a tripod at a height of around 1.3 meters and the beam direction orthogonal to the ground. As snow is used for the measurements, the setup will be located outside. In order to produce as accurate data as possible the area directly under the sensor should be cleared of any loose material. The setup planned is presented in Figure 5.8

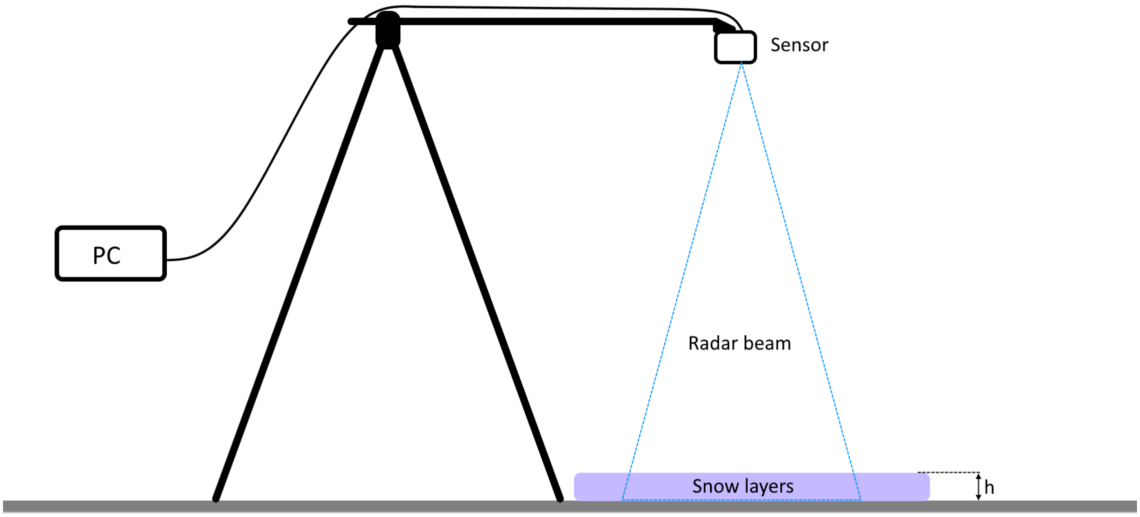

Figure 5.8. *Short range snow measurement setup.*

The actual measurement setup is presented in Figure 5.9. In the picture, there can be seen the square cleaned for the measurements and a layer of snow being measured.

Figure 5.9. *Short range snow measurement setup picture.*

5.4.5 Measurement procedure

Each measurement is performed with the Texas Instruments *IWR6843ISK-ODS* evaluation module. The module will be connected to a laptop PC and controlled trough the HARM demo running on the PC.

Before actual measurements, the sensor must be physically connected to the PC. After that a serial control and data connection between the sensor and the PC is established through the HARM demo graphical user interface (GUI). Next parameters *Range depth* and *Range width* are set in the HARM demo GUI. Next a chirp configuration file is uploaded to the sensor trough the serial control connection. The sensor interprets the configuration file and radar parameters are set. Last line of the configuration file contains an initialization command which will start the sensor. After sensor start, data is sent from the sensor to the HARM demo running on the PC and the processed data is displayed on the HARM GUI.

When the sensor is running measurement results can be saved into a .csv file by clicking the *RECORD START* button in the HARM GUI. Planned measurements are made and afterwards the recording is stopped with the GUI button *RECORD STOP*. After the record is stopped, the HARM GUI running in a browser downloads the result file to the PC.

5.4.6 Planned experiments

This chapter will present the experiments planned to assess the mmWave sensor family suitability for the proposed prototype application. Each experiment's purpose will be explained and test methods will be outlined.

Short range control experiment

The purpose of this test is to determine how stable and accurate the sensor's range measurement is over longer periods of time. Additionally the experiment produces information on the accuracy of the measurement compared to actual measured distance between the sensor and the floor.

This experiment is performed with the setup described in Section 5.4.2. In order to assess longer duration stability, the sensor is left running overnight in a controlled environment with minimal disturbances. The sensor assembly cover is left on for consistency even tough it is not necessary in indoor conditions. The overnight measurement should produce around 16 hours of data.

Long range experiments

These experiments were designed to assess the sensors accuracy and stability at longer distances, mainly around the 10 meter distance discussed in Sections 5.1 and 5.3. As a part of this process, optimal parameters for the HARM demo fields *Range depth* and *Range width* and chirp configuration are tested.

This experiment is performed with the setup described in Section 5.4.3. Both short and longer measurement times shall be used. HARM demo parameters are systematically tested with values for *Range width* ranging from 8 m to 1 m. Measurement range should be approximately 10 to 12 meters and values for *Range depth* will be varied if deemed necessary during testing.

As presented in Section 3.4.1, the sensor has many tunable variables affecting the actual radar measurement. One set of these are the so called chirp parameters. Relevant to this experiment are HARM demo *min range* and *max range* parameters. The effect of these to the accuracy and stability of the measurement results will also be assessed.

Long range measurements are not meant for experimenting with changing environments such as accumulation of snow so during these measurements the sensor is kept as stable as possible. Due to the measurement location being an active parking lot, some disturbances are however most likely inevitable.

Short range snow experiments

The purpose of these measurements is to determine whether the sensor is suitable for measuring snow accumulation. Specific areas of interest are sensor's ability to pick up snow on top of an another surface and if so, how accurate readings are produced, how much snow is needed for detection and how stable the measurement is on snow.

These experiments are performed with the setup described in Section 5.4.4. *Range depth* shall be set as 2 m and *Range width* as 0.5 m. HARM demo default chirp configuration, provided in [49] will be utilized.

In order to ensure consistent results and repeatability, measures should be taken to ensure that the snow used is as homogeneous as possible. The type and state of the snow used in these experiments should be documented if possible.

Experiment 1

Purpose of the first measurement is to establish a baseline for the following measurements. In an ideal situation, the measurement should produce a graph of one stable reading with very little deviation and no large level changes.

Before the experiment the area where the sensor's radar beam will hit should be cleaned of all snow, ice and other possible loose material that may interfere with the measurements. If not otherwise mentioned, every experiment begins from this clean state. When the measurement area is clean, sensor is started and left to run for atleast 3 minutes to measure a stable baseline.

Experiment 2

The second experiment is intended to see how the sensor will react to a single uniform layer of snow. In an ideal situation, the sensor will measure a lower distance when the snow layer is present.

The sensor is started on clean asphalt and an initial baseline is measured. Then a uniform snow layer with a height of 1 cm is built in the measurement area. After the layer is built, sensor is left to measure for around 3 minutes to establish a stable measurement. Then the snow is removed and the sensor is left measuring the clean asphalt for around 3 minutes. After that the sensor is stopped.

Experiment 3

The purpose of the third experiment is to test how well the sensor is able the measure and keep track of consecutive uniform snow layers of different height. In an ideal situation, the sensor will measure a lower distance after the addition of each snow layer and the reading is stable in-between additions.

The sensor is started on clean asphalt and an initial baseline is measured. Then a uniformly flat layer of snow with a height of 1 cm is built in the measurement area. After the layer is built, sensor is left to measure for around 3 minutes to establish a stable measurement. Then a second layer of snow is built on top of the first layer, producing a new uniform snow layer with a height of 2 cm. This new layer is again measured for around 3 minutes. This procedure is then repeated to create and measure snow layers of height 3 cm and 5 cm. After the final layer is measured, the sensor is stopped.

Experiment 4

The purpose of the fourth experiment is to evaluate sensor's response to very small additions of snow. Areas of specific interest are the minimum amount of snow that results in a observable change in the measured distance, the stability of the measurements and whether potential observable change is in the expected direction. In an ideal situation the sensor is able to pick up even very small additions of snow and the changes observed in the measured distance is always negative as the snow layer builds up towards the sensor.

The sensor is started on clean asphalt and an initial baseline is measured. Then small amounts of snow are gradually added to the measurement area. Care is taken to minimize potential interference to the measurement by keeping all used snow tools outside the radar beam. After each addition, the sensor is given some time to reach a stable reading and record the level. After 5 to 10 additions the sensor is stopped.

Experiment 5

The fifth experiment is intended to evaluate sensor performance and behaviour when measuring non-uniform additions of snow in varying addition sizes. In an ideal situation the sensor is able to differentiate between additions and produces measurements that reflect the amounts of snow added.

The sensor is started on clean asphalt and an initial baseline is measured. Then a non-uniform layer of snow is added to the measurement area. After each addition, the sensor is given some time to reach a stable reading and record the level. After 5 to 10 additions the sensor is stopped.

5.5 Results and analysis

Results for the planned experiments are presented in this section. Additionally result analysis is provided in the same section in order to keep the analysis and results viewable simultaneously.

The results and analysis are grouped by experiment setup and series. After the individual results and analyses, the results are analysed as a whole and prototype application feasibility is assessed.

5.5.1 Short range control measurements

The results for planned short range control measurement are presented in this section. Only one measurement in this category was taken but the individual measurement contains around 110 thousand data points. In order to make the data presentable in thesis format, two different figures were drawn from the data with 1/50 down-sampling.

Measurement results for the full 16 hour experiment are presented in Figure 5.10. The data was down-sampled to 1/50 but retains the graph shape of the full dataset.

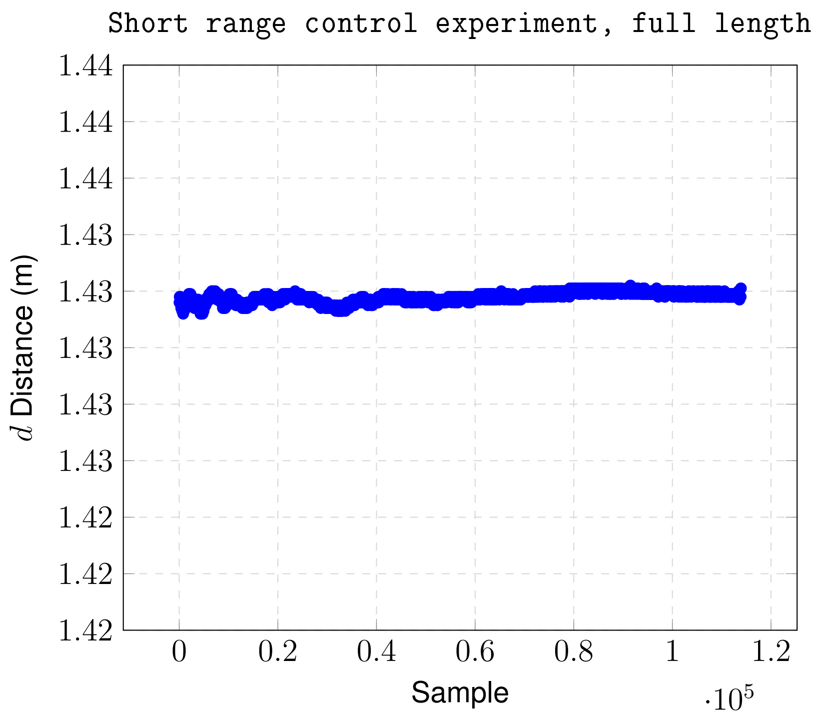

Figure 5.10. *Short range stability experiment, 1/50 down-sampled from full data.*

When graphed with y-axis values ranging from 1,42 meters to 1,44 meters, the data appears to present very little deviation. Accuracy seems to be in line with Texas instruments' claimed millimeter level accuracy [49]. There is some deviation in the data between 0 and 30k samples but the measurement stabilizes even further after 40k samples. Considering the measurement time of approximately 16 hours and around 110 thousand samples, the control experiment results show levels of measurement stability suitable for the proposed prototype application.

A 2k datapoint sample of the short range control measurement results are presented in Figure 5.11. In this measurement the sensor is measuring a static environment.

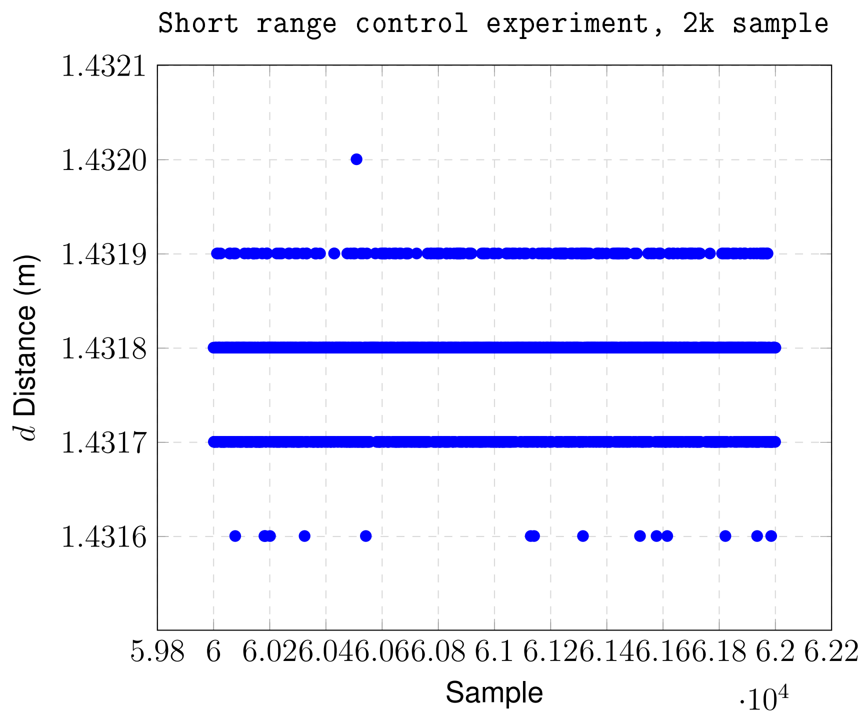

Figure 5.11. *Short range stability experiment, 2k sample from original data.*

Datapoints in Figure 5.11 are concentrated around discrete values between 1.4317 and 1.4319. This is due to the output resolution of the HARM demo and means that the sensor is operating at it's performance limit during the short range control experiment. In a static environmental, the sensor demonstrates sub-millimeter stability.

5.5.2 Long range exploratory measurements

The results for planned long range measurements are presented in this section. During the measurements, it was discovered that different configurations of the chirp parameters did not often produce significant variation in the results of this particular experiment. Due to this low variation between results, only results for configuration 6 are presented, along with an additional experiment where the sensor is manually repositioned to experiment on range resolution.

Results for long range experiment configuration 6 presented in Figure 5.12. In this measurement the sensor is measuring at a static distance of around 9.5 meters.

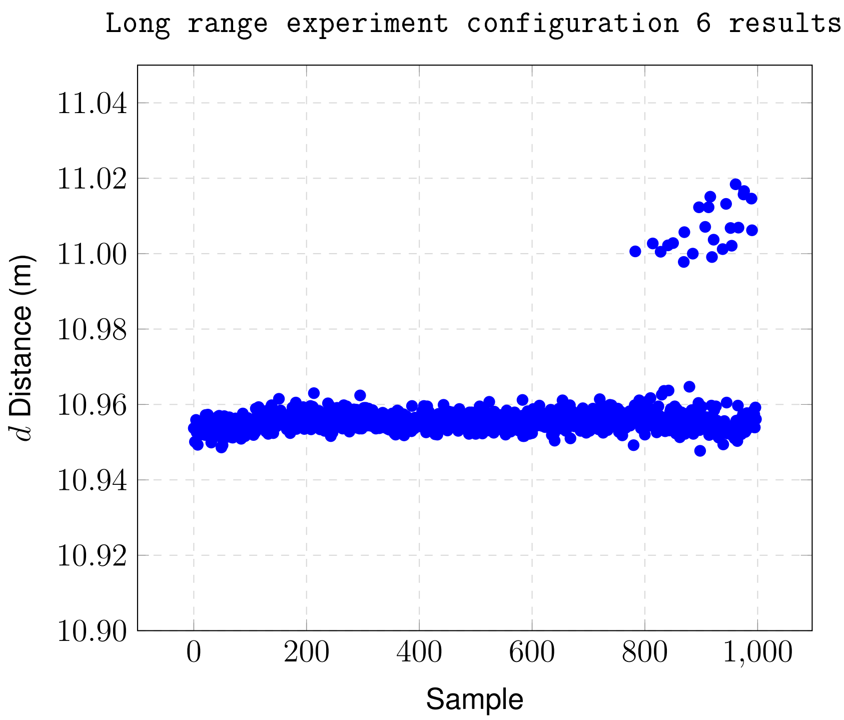

Figure 5.12. *Long range stability.*

Figure 5.12 results indicate a good measurement stability having deviation of around 1 cm. For the first 800 samples the sensor is able to resolve the distance unambiguously. After 800 samples, the data includes some outliers between 11.00 m and 11.02 m. This is likely due to the algorithm used by the HARM demo. With some basic signal processing techniques such as outlier detection and averaging, millimeter level stability may be achievable.

During the long range measurements, an unplanned experiment was performed and yielded informative results, which are included here. In this experiment, the sensor assembly was subjected to minor position adjustments and given some time to produce a stable measurement streak after each adjustment. Each adjustment was meant to move the sensor assembly lower by around a centimeter.

Results for the long range alternating distance experiment are presented in Figure 5.13. In this measurement the sensor was subjected to small vertical position adjustments.

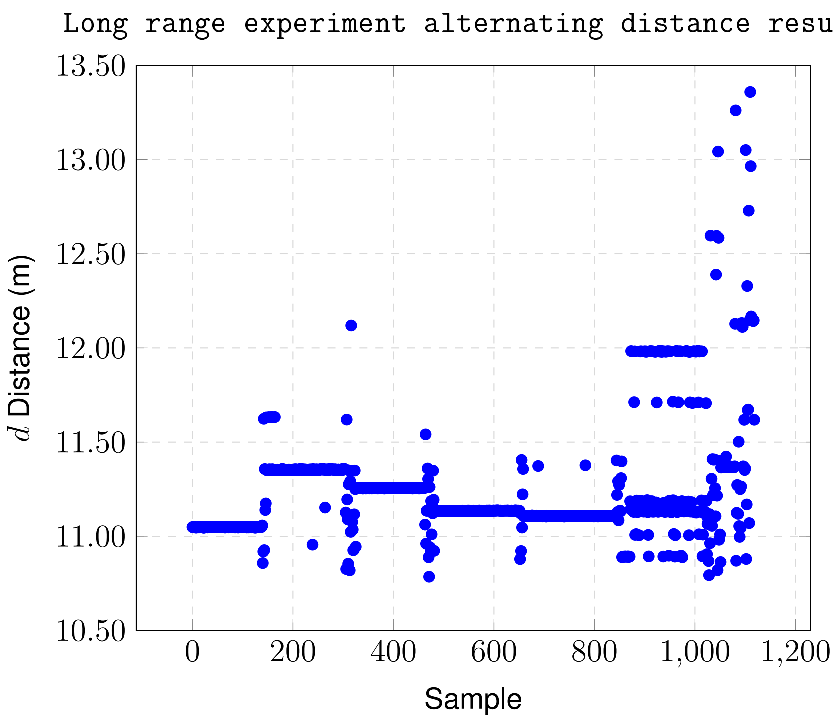

Figure 5.13. *Long range altering distance.*

Figure 5.13 results present a relatively stable distance reading apart from the instances where the position was adjusted. The initial adjustment at around 200 samples causes the measured distance to increase instead of decreasing, as it should when the sensor is brought closer to ground. Additionally the resulting change in the distance measured is around 30 centimeters, which is considerably more than the distance the sensor was moved. However, it should be noted that at a height of around 10 meters, even a small change in the angle of the sensor can cause significant changes in the sensors perceived distance to the ground. While the angle was not recorded and thus this cannot be confirmed, it provides a possible explanation for the observed data. The consecutive changes in the sensor height consistently caused a decrease in the measured distance. The final adjustment around 900 samples caused to sensor lose unambiguousity of the distance measured. While this experiment was not well controlled, it indicated that the sensor is able to detect and measure small changes in distance even at distances around 10 meters.

The long range experiments concluded that the mmWave EVM is capable of accurate distance measurements at a height of 10 meters. If an application specific algorithm and proper signal processing were to be implemented, the results indicate that millimeter level accuracy may be achievable. The experiments concluded that varying the chirp parameters have only minor effect on the measurement results in this setup. Additionally, the results indicate that the sensor may be highly sensitive to the angle of the sensor if a large plane like the ground is being measured.

5.5.3 Short range snow measurements

The results for planned short range snow measurements are presented in this section. Additionally, supplementary results from older tests are presented for comparison. These results are analysed first on test by test basis and finally all the results are analysed as a whole and the prototype application's feasibility is assessed.

Experiment 1 is designed to provide baseline for the measurement set. Results for Experiment 1 are presented in Figure 5.14.

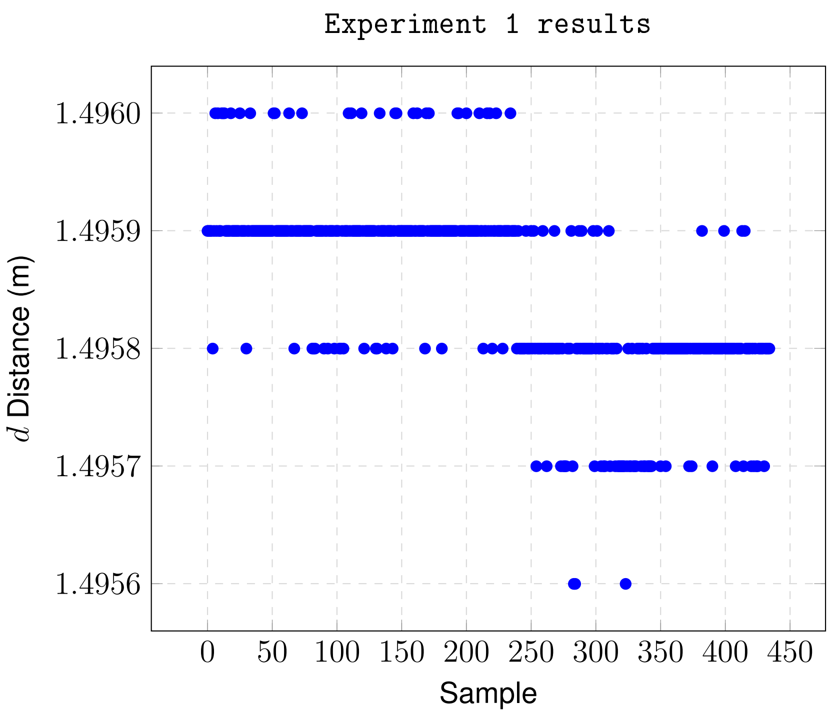

Figure 5.14. *Snow measurement 1, baseline.*

The baseline results show the sensor to be highly stable when measuring against the asphalt with no snow present. The results are comparable to the short range control measurement results, the resolution is limited by the HARM demo output precision. It is notable that the measured distance of around 1.5 meters is about 0.20 meters of the manually measured sensor height of around 1.3 meters. While off, this distance can be considered as a baseline for further experiments. It is likely that a software calibration procedure could be used to remove this offset.

Results for Experiment 2 are presented in Figure 5.15. In experiment 2 a 1.0 cm high layer of snow is built measured and the removed.

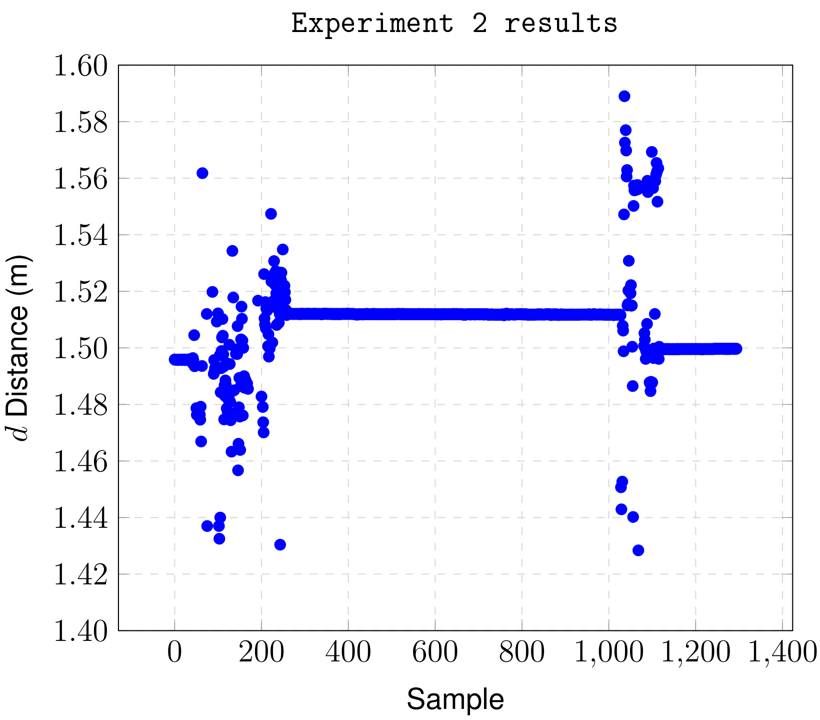

Figure 5.15. *Snow measurement 2, 1 cm layer built and removed.*

Addition and the subsequent removal of the snow layer can be clearly observed from the experiment 2 results. A stable baseline can be observed between samples 0 and 50. From 50 to 250 samples, the sensor reading fluctuates heavily as the snow layer is being built in the sensor's FoV. After 250 samples, the sensor reading stabilizes and presents only little deviation. The snow layer is removed after around 1000 samples which again causes heavy fluctuation followed by a stable reading.

From around 250 to 1000 samples when the snow layer is present the sensor measures a height difference of around 1.5 cm which is reasonably close to the actual around 1.0 cm height of the snow layer. While the data is stable and a change is observable, it is notable that the observed change in height is in the opposite direction it should be. As a 1.0 cm layer of snow is added, the actual distance from the sensor to the closest surface decreases 1.0 cm.

Experiment 2 results show that detecting a 1.0 cm layer of snow with the EVM is feasible. However, while the change is observable from the data, direction of the change is not correctly measured. It is likely that this issue can be addressed by developing an application specific algorithm instead of relying on the HARM demo output.

Results for Experiment 3 are presented in Figure 5.16. In experiment 3 consecutive layers of snow are added. These four layer had the height of 1 cm, 2cm, 3cm and 5cm.

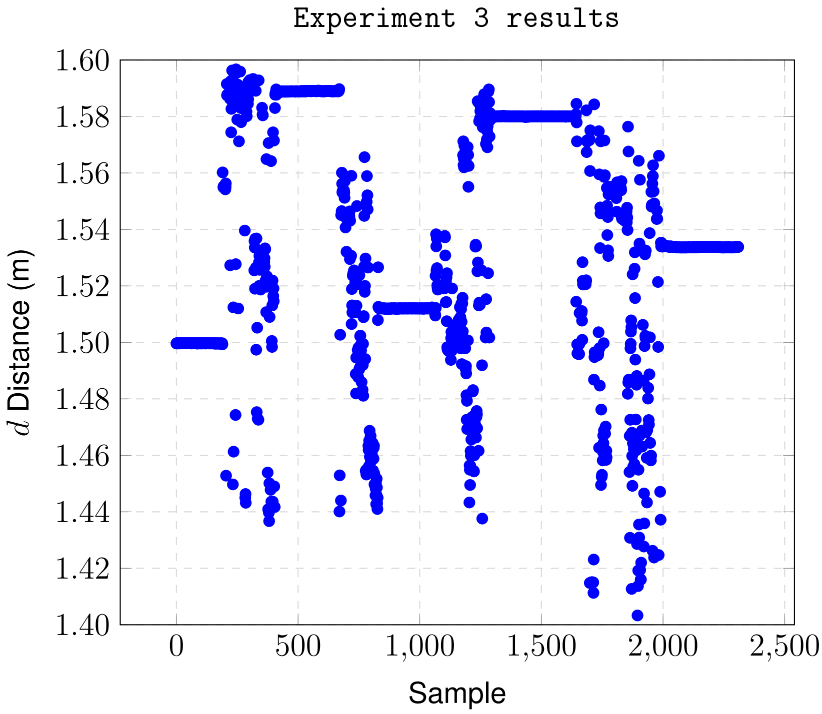

Figure 5.16. *Snow measurement 3, multiple consecutive layers.*

Experiment 3 result data presents five stable regions located at around 0, 400, 800, 1200 and 2000 samples. These correspond to the four snow layers built and the initial baseline. Similarly to experiment 2, the sensor reading undergoes heavy fluctuation during the snow layer additions but the readings exhibit good stability during the measurements in-between the additions. The height of the layers built is not reflected by the distance measured by the sensors. Changes of 1 cm produce a change in the distance reading of up to 9 cm in an arbitrary direction.

Experiment 3 results further confirm that the EVM is able to detect additions of snow in its FoV. Similarly to experiment 2, this experiment indicated that the measurement system in use is not able to reliably track distance between the sensor and the snow surface.

Results for Experiment 4 are presented in Figure 5.17. In experiment 4, snow is gradually added to the measured area while attempting to maintain a flat snow surface. Care was taken to keep the tools used outside of the sensor's FoV.

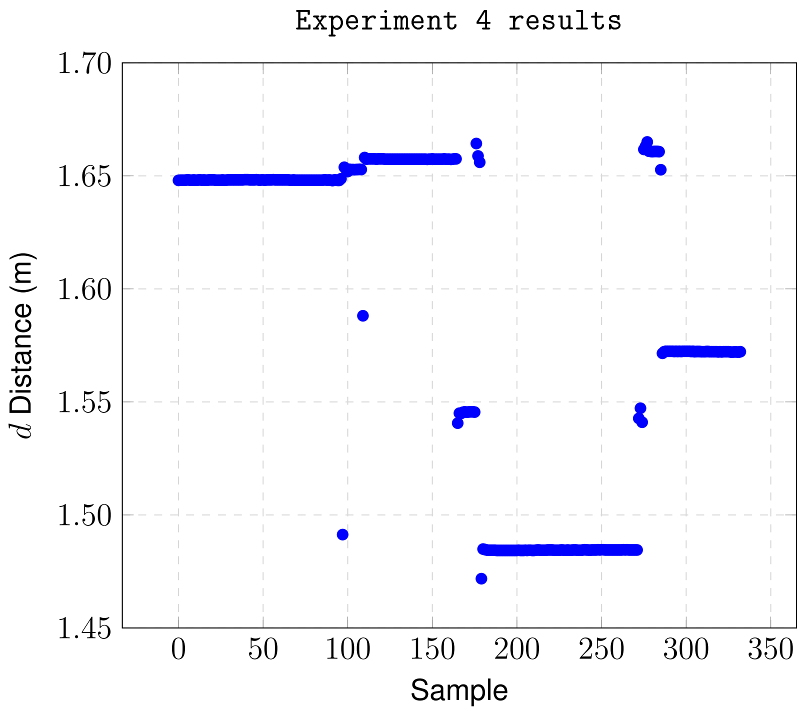

Figure 5.17. *Snow measurement 4, Gradual additions.*

Results for experiment 4 show changes in measured distance coinciding with snow additions. As snow is added quickly and without entering the sensor's FoV, there are fluctuation periods as there are when snow layers are built to a known height and flatness. While changes are detected, the measured distance does not reflect the decrease in distance caused by the addition of snow.

Experiment 4 results are in line with the observations from previous experiments; changes in the snow layer are reliably detected by the system but the absolute distance between the sensor and the snow layer is not accurately measured. While not reflecting the correct distance, the distance data is unambiguous throughout the experiment.

Results for experiment 5 are presented in Figure 5.18. In experiment 5, snow was added in random amounts without attempting to maintain a flat snow surface. Care was however taken to keep the tools used outside of the sensor's FoV. An exception for this is when at around 15 and 170 samples the sensor was deliberately obstructed with shovel to test distance measurement stability.

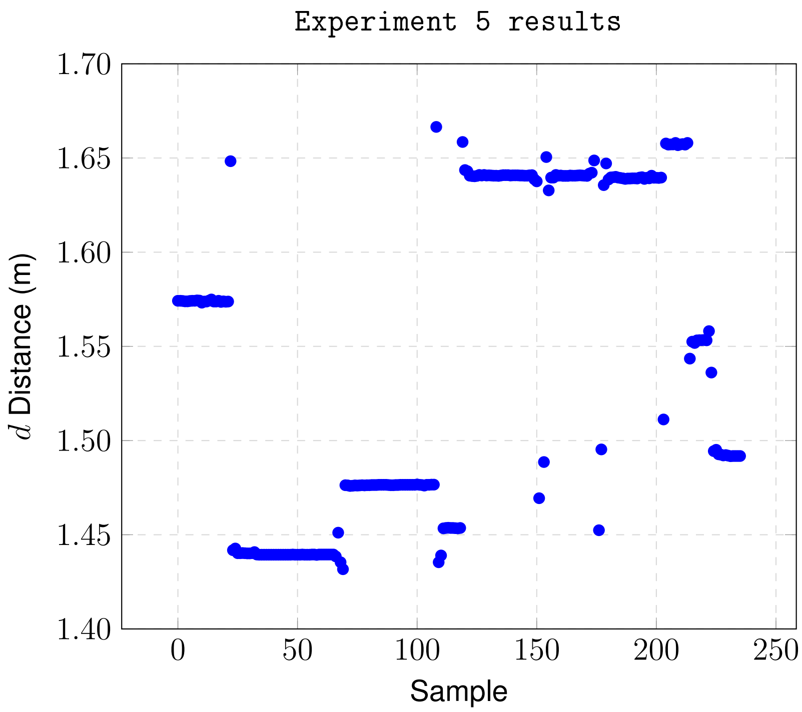

Figure 5.18. *Snow measurement 5, Non-uniform addition.*

Results for experiment 5 exhibit good stability and unambiguous distance resolving. However the distances measured do not reflect the increasing height of the snow present in the measured area. Obstruction of the sensor is detected at around 150 and 170 samples. After each obstruction the distance measured is roughly the same as before the obstruction.

Experiment 5 results further confirm previous results of reliable change detection and unreliable distance tracking. It is notable however that brief interruptions of the sensor did not result in a considerable change of the distance measured.

Next, a result from a previous exploratory measurement set is presented in Figure 5.19. The procedure used in this experiment was similar to experiment 4, consecutive arbitrary amounts of snow are added while taking care not to obstruct the sensors FoV.

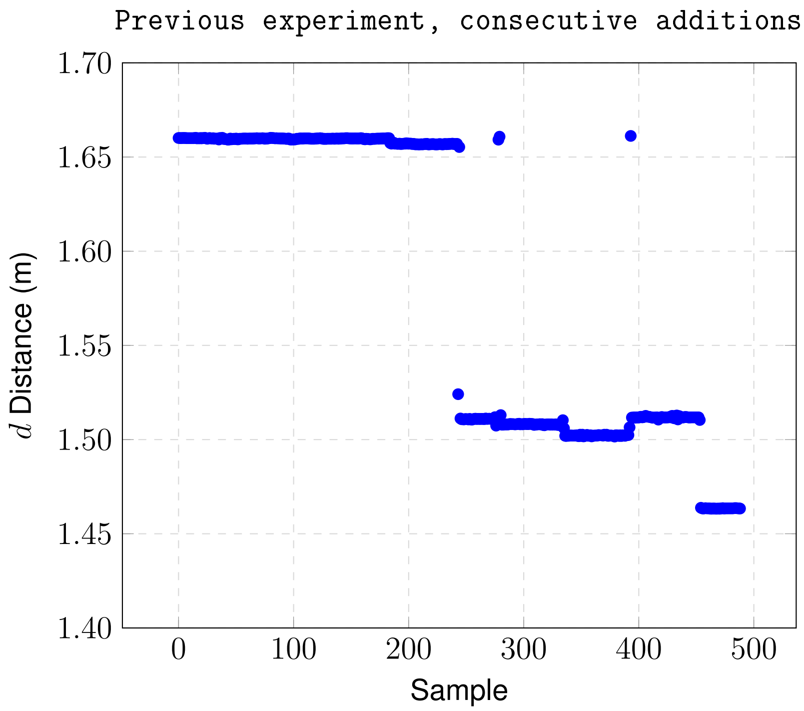

Figure 5.19. *Previous snow measurement, consecutive non-uniform additions.*

Results presented in Figure 5.19 exhibit good stability and unambiguous range resolving. A baseline is present from 0 to around 180 samples. At 180 samples, first addition of snow is made which results in a decrease in the measured distance. This is repeated sample points 240, 270 and 340. Each addition results in the measured distance decreasing. Addition at around 380 samples results in an increase in the measured distance. The final addition at round 450 samples results in a decrease in the measured distance.

Results from this experiment correspond well with the additions of snow. In addition to the change being detected, the change in the measured distance is in the correct direction on five out of six additions. However it should be noted that while the direction is correct, additions two and six result in overly large changes in the measured distance. Additions three to five result distance changes similar to the actual change in distance from the snow additions. Figure 5.19 results indicate that in some conditions the sensor is able to track the distance changes caused by the addition of snow.

5.5.4 System level conclusions

The experiments performed in this thesis provide good insight into the feasibility of the proposed prototype application. Additionally, the results obtained are in line with the performance expectations formed from Texas Instruments' documentation.

The short range control experiment demonstrated that the sensor module capable of short range distance measurement with millimeter level deviation. This level of stability is well beyond the level required by the prototype application.

The long range experiments indicate that stable distance measurement is achievable from a height of 10 meters with a deviation in the centimeter range. It was also shown that the sensor is able to detect centimeter level distance change at this range. The results indicate that the performance required to implement the proposed prototype application is achievable, especially if further signal processing stages are implemented.

The short range snow experiments demonstrate that snow is detectable with an mmWave sensor. Even the smallest additions of snow to the measured area resulted in a change in sensor setup's output. While snow detection worked well, the sensor setup was not able to reliably track the distance from the sensor to the top of the snow surface. This may be due to the HARM demo used for these measurements not being designed for this type of distance changes.

Algorithm specifically designed for the application could incorporate filter stages to improve signal stability even further. Filtering can be used, for example, to ignore rapid changes in the data and to add temporal stability to the distance reading. Additionally application context, such as maximum distance set by the distance to the asphalt, could be integrated into the algorithm.

In conclusion, the experiments have demonstrated that Texas Instruments' mmWave technology can perform on a level required to implement the proposed prototype application. However, proper algorithm and signal processing stages need to be developed to achieve full functionality.

6. CONCLUSIONS

This thesis' objective was to examine Texas Instruments' mmWave technology's potential for use in commercial embedded systems. This work was done for Wapice Ltd and aimed to produce insight, expertise and reference material which can be utilized by Wapice to offer mmWave based solutions as part of it's technology expertise. The structure of this thesis consist of four main chapters, each of which provides a different perspective to mmWave technology. The chapters can be read independently if a specific topic is sought or in order for a complete overview on the technology.

Texas Instruments mmWave product line of single-chip FMCW radar systems was found to achieve excellent performance on key detection and tracking tasks. Properly designed mmWave sensor systems are able to produce reliable and accurate three dimensional tracking and position data from close ranges of under a meter up to medium ranges of over 200 meters. In optimal conditions, millimeter-level measurement accuracies can be achieved with mmWave sensors, this capability was also demonstrated in this thesis. In some use cases mmWave sensors are capable of relatively high measurement rates of tens of measurements per second. In addition to strong measurement performance, mmWave technology was found to be largely immune to most forms of environmental conditions, such as dust, smoke and lighting conditions, which may interfere with current sensor technologies.

While mmWave technology has impressive peak performance, it should be noted that some performance aspects are intertwined in such a way that peak performance on all indicators cannot be simultaneously reached. Developing an mmWave system requires careful consideration and balancing of the sensors capabilities. As radar devices mmWave products are subject to more compliance regulations than traditional sensors, which may lead to increased certification expenses. Additionally, the requirement of a PCB radar antenna results in more design work and higher PCB costs. However, the introduction of AoP solutions eliminates the need for an external antenna and may allow certification re-use.

TI's mmWave technology compares favourably against other sensing technologies. It is able to cost-effectively achieve more accurate and robust sensing than ultrasonic or IR based technologies. When compared to cameras, mmWave is not able to produce equally high resolution images but does output direct volumetric data without need for heavy additional processing. One of mmWave's key advantages are it's integrated user programmable processing and DSP capabilities.

Overall, mmWave sensors introduce a new powerful and highly versatile sensor solution for commercial embedded systems sensing. While mmWave sensors provide overlapping capabilities with current technologies, mmWave sensors shouldn't be considered as a drop in replacements for existing sensor solutions but rather a novel class of sensors. Although adopting mmWave technology does come with some challenges, in suitable use cases it provides performance not easily replicated with other sensor technologies.

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