POLITECNICO DI TORINO

Master's Degree in Electronics Engineering

Master's Degree Thesis

Movement detection of people in indoor spaces with radar sensors

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Summary:

Introduction:

Growing enthusiasm for the development of smart homes and intelligent building management systems highlights an important and developing market that focuses on boosting energy efficiency, strengthening security measures, and preserving privacy. This pattern underscores the urgent need to develop trustworthy methods for human detection and sensing. These technologies are essential for energy conservation because they automate and optimize the functioning of heating, ventilation, and air conditioning (HVAC) systems. They also greatly advance the development of security systems. These systems need to incorporate privacy-preserving methods to fully realize the benefits of automation and security within intelligent applications. Radar technology is crucial for maintaining human privacy in intelligent buildings. Radar systems differ from camera and microphone-based systems in that they utilize reflected electromagnetic waves to detect presence without the need to capture images or audio. This allows for strong security measures while maintaining privacy in an indoor setting.

For human movement detection, various technologies exist, including those that use tags and tagless sensors. However, wearable sensors present certain user concerns. Radar sensor technology provides numerous benefits, including the ability to operate without a direct line of sight and immunity to weather conditions like rain, fog, and wind that can hinder optical technologies. In this thesis, I selected a Frequency Modulated Continuous Wave (FMCW) radar sensor for human movement detection based on these advantages.

Objective:

The objective of this thesis work is to investigate state-of-the-art sensor-based indoor human movement detection techniques and aim to implement a detection system with a focus on FMCW radar sensors. Detecting indoor human movement without relying on tags attached to objects or wearable devices presents a significant research challenge.

Among the different types of sensors, radar sensors have proven to be particularly effective for indoor human movement detection. Because these FMCW radars have a modulated bandwidth, they possess advanced sensing capabilities, such as detecting target positions as well as their velocity, range, and angle of arrival. Given these capabilities, this thesis focuses on exploring and studying the radar demo kit BGT60TR13C, developed by Infineon Technologies. Its superior perceptive abilities enable the Infineon BGT60TR13C demo kit to detect indoor human movement.

Methodology:

The experimental portion of this thesis used a BGT60TR13C radar operating at a frequency of 60 GHz to locate and detect human movement. During the controlled indoor experiments, I performed two trajectories (linear and U-shape) in the radar's field of view. Gathered ground-truth data to assess the effectiveness of the suggested strategy. I used point cloud data and the Density-Based Spatial Clustering of Application with Noise (DBSCAN) method during the experimental process to improve robustness.

1) A Linear Pathway
2) Trajectories in U form

I positioned the radar 1.4 m above the ground, ideally at position 0 on the x-axis. The field of vision covered an angular range of [-45°, +45°]. I assessed two different movement patterns: U-shaped and linear trajectories. The results indicate that the ability to track and detect objects is acceptable when they are approximately in the range of radar.Table 1 presents the specified radar configuration, essentially determining the maximum detection range within the experimental setup to be about 4 m.

Table 1: Radar Configuration

Tx/Rx Antennas	1/3
Samples Per Chirp	64
Chirps Per Frame	32
Start Freq (GHz)	58
End Freq GHz)	59
Bandwidth (GHz)	1.0
Max range (m)	4.0

The human subjects walked at a moderate speed along a U-shaped trajectory and performed straight movements within the confined indoor setting, ensuring that all their actions remained within the radar's field of view. In this experimental work I marked the floor with a U-shaped, straight-line path and took precise measurements to provide ground-truth information. I repeated this procedure several times to obtain a comprehensive dataset. The main focus is on movement detection, clustering, and using Doppler shift analysis to extract velocity, angle, and range information. This workflow employs several well-known signal processing methods. These include beamforming to focus on specific directions of interest, DBSCAN to group detected points in the space domain, and the Fast Fourier Transform (FFT) to convert time domain signal into frequency domain. In this experiment I set the radar sensitivity by using a threshold value ranging from 0 to 1. Raising the threshold to a value closer to 1 decreases the sensitivity, which could result in the radar failing to detect important movements. On the other hand, reducing the threshold to 0 increases sensitivity, enabling detection of even the smallest motions of objects. I use a systematic experimentation process to determine the most effective threshold values that enable precise differentiation of human movements. This threshold, combined with the DBSCAN clustering technique, enables accurate detection of human movement while reducing the occurrence of false alarms caused by non-human objects. This integrated technique greatly enhances the accuracy of human movement detection, presenting a major improvement compared to conventional radar-based detection systems.

Challenges:

The challenges I encounter in this work using FMCW radar sensing are the processing of radar-generated point clouds, which pose certain obstacles. The presence of excessive noise and clutter in these points of cloud data complicates the task of distinguishing between genuine and misleading target. To address this problem, the DBSCAN algorithm and the modified threshold sensitivity can exclusively detect human movement while disregarding other immobile objects, including little insects, which are of no interest to us. This approach allows for clear differentiation between mobile individuals, stationary objects, and noises in the environment.

Results:

After successful detection, I record object data into a comma-separated value (CSV) file to enable more thorough analysis later. This CSV file is the basis for computing performance measures like Mean Error and Root Mean Square Error (RMSE). The graphic visualization of both the measured values and the ground truth data establishes a reference system and improves clarity. I first receive the data in polar coordinates, which include measurements of angle and range. A data conversion procedure converts the polar coordinates into Cartesian coordinates. Cartesian coordinates simplify the detection and interpretation of the discovered data. This conversion process is essential for creating a more in-depth comprehension and interpretation of the data that the radar has collected. The outcomes show that the U-shaped trajectory strategy is not as effective as the linear trajectory approach, as showcased in Table 2. By manipulating the threshold value and applying the DBSCAN algorithm to the point cloud data, I have effectively recognized human movement within the room.

Table 2: Summary of the results

Experimental Type	Straight Line	U-Shape
Samples Per Chirps	64	64
Chirps Per Frame	32	32
Start Freq (GHz)	58	58
End Freq (GHz)	59	59
Bandwidth (GHz)	1.0	1.0
Max Range (meter)	4.0	4.0
Detection Range (m)	2.0	2.0 to 4.0
Velocity (m/s)	0.5 to 2.0	0.5 to 2.0
Threshold Sensitivity	0.0005 to 0.0012	0.0005 to 0.0012
RMSE Error	0.2012	1.2684

Conclusion:

The growing importance of human movement detection using FMCW radar offers numerous advantages. This thesis work employs a systematic methodology that aims to enhance the precision of human movement detection compared to conventional techniques. Smart buildings, security systems, and environments focusing on energy conservation could potentially use this system. The BGT60TR13C FMCW radar is used to detect motion and estimate distance, which makes it ideal for room presence detection. Utilizing this data to automatically regulate lighting, heating, and ventilation according to occupancy can result in significant energy savings. Furthermore, this technology enhances security by monitoring the building's surroundings to identify unauthorized individuals.

To enhance the system's efficiency in real-time scenarios, it is possible to tune the radar threshold value and radar parameter according to the indoor environment. This thesis demonstrates the potential for enhanced human movement detection

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Chapter 1

Introduction

Indoor localization has emerged as a fundamental technology that facilitates progress in numerous fields, such as security, healthcare, and smart residences. Low signal constraints significantly compromise the efficacy of Global Positioning Systems (GPS), despite their remarkable accuracy in localizing objects in the open air. As a result, the creation of resilient interior localization systems is imperative. However, current solutions frequently depend on wearables or badges, which may cause inconvenience for users and incur significant implementation and maintenance costs.

The aim of this thesis is to explore the use of radar sensors as a potential solution to the difficulties encountered with traditional indoor localization methods. By utilizing radar sensors, it is possible to eliminate the requirement for physical tags or wearables, which in turn improves user convenience. Furthermore, radar-based tracking has the potential to improve a wide range of services by providing accurate and up-to-date information on human activities. This skill is particularly useful in industries like healthcare, where precise patient monitoring can lead to better health outcomes. Additionally, security surveillance can use radar sensors to track customers while preserving privacy, and production environments can use them to enhance workflow and safety.

I can construct intelligent and secure settings that greatly improve people's quality of life by combining indoor localization with radar sensor technologies. The goal of this thesis is to look at the Infineon BGT60TR13C FMCW radar in order to get around the problems with current indoor positioning methods. The goal of this study is to create advanced indoor human movement detection systems that provide smooth, inconspicuous, and accurate solutions for monitoring and deducing human actions in various contexts.

The subsequent sections of this thesis are organized as follows:

Chapter 2 explores the fundamental principles of radar technology, specifically focusing on the Infineon BGT60TR13C FMCW radar used in the experimental setup. The chapter explores the operational mechanics of FMCW radar, providing an explanation of its functionality, inherent advantages, and potential obstacles. In addition, the chapter provides a comprehensive explanation of the configuration and characteristics of the particular radar model employed in the experiment.

Chapter 3 presents the motivation and specific methodological techniques used in the research. The text provides a comprehensive explanation of the precise procedures utilized to attain the intended outcomes, as well as the methodologies implemented to process the point cloud data and the DBSCAN approach. The chapter also examines the impact of different radar parameters on the data and provides detailed explanations of the data processing techniques employed.

Chapter 4 displays the results of detecting different trajectories within the radar's range of view. Chapter 5, the final chapter, frequently serves as a summary. The final chapter provides a comprehensive overview of the main findings uncovered throughout the thesis. Furthermore, it explores a variety of opportunities for future research in this area of study.

Chapter 2

Radar

2.1 Radar Fundamental

Radar, short for Radio Detection and Ranging [1], is an advanced electronic technology that uses reflected electromagnetic energy to identify and analyse things. Radar surpasses simple verification of existence; in certain conditions, it can precisely determine an object's orientation, height, distance, trajectory, and velocity. Radar systems utilize electromagnetic waves to accurately determine the position of airplanes, ships, human localization, and other impediments that may be difficult to see due to distance, darkness, or adverse weather conditions. I can categorize the fundamental operational concepts of radar into four main stages:

Transmission: The radar begins the operation by emitting a brief burst of radio waves.
Reflection: Radio waves travel through space and bounce off anything in their path.
Reception: With great attention to detail, the radar antenna carefully records the reflected waves, also known as echoes.

Processing: The radar precisely measures the time it takes for the signal to travel to the target and return, allowing the object's distance to be determined. Additionally, by carefully examining the received signal's characteristics, the radar can obtain valuable data on the target's dimensions, form, and even speed (achieved using Doppler radar). Figure 2.1 depicts this entire process.

Depending on the radio wave they emit, I can classify radar sensors into specific types [1].

1. **Continuous Wave (CW) Radar:** These radars emit a radio wave without interruption and evaluate the change in frequency of the reflected wave to calculate the target's velocity using the Doppler effect. However, they do not possess the ability to ascertain the distance of the target. People also occasionally refer to them as unmodulated radars.

2. **Pulsed Radar:** These radars operate by emitting brief bursts of radio waves. By calculating the duration of a pulse's round trip to the target, they may ascertain the target's distance.

3. **Pulse Doppler Radar:** These radars combine characteristics from both pulsed radars and continuous wave (CW) radars. They emit short radio wave pulses and evaluate the Doppler shift of the reflected pulses to simultaneously calculate the target's distance and speed.

4. **Frequency Modulated Continuous Wave Radar (FMCW):** FMCW radars broadcast a radio wave that continually varies in frequency. The beat frequency between the transmitted and reflected waves can be determined by analysing the target's range. FMCW radars possess the capability to accurately determine the velocity of the target [2]. The following section, 2.2, elaborates on this.

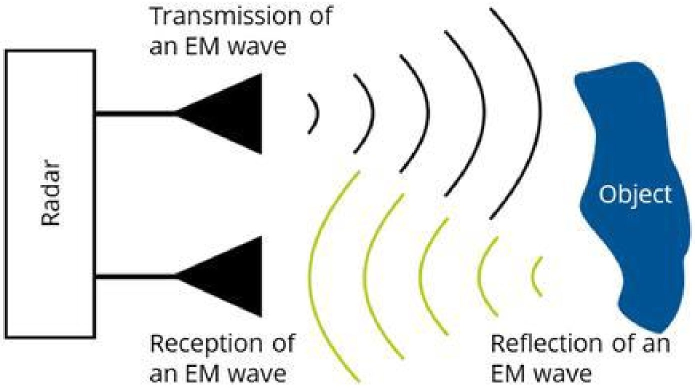

Figure 2.1: illustrates the fundamental operating principle of a radar system. The item is detected by comparing the transmitted (TX) and received (RX) electromagnetic waves [3]

2.2 Frequency Modulated Continuous Wave Radar Advantages and Limitations

FMCW is a radar system that emits a continuous wave with a frequency that changes over time. This modulation enables the radar to accurately determine both the distance (range) to an item and its relative velocity. These radars have relatively high accuracy, as indicated by references [2] and [4].

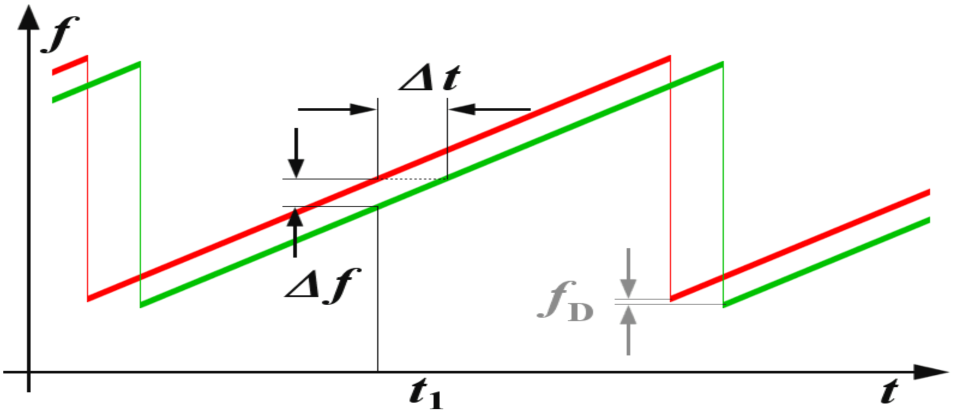

Figure 2.2: The operational mechanism of frequency-modulated continuous wave (FMCW) radars. The symbol Δt represents the time differences, Δf denotes the difference in frequency between the transmitted (TX) and received (RX) signals, and f_D represents the frequency alteration caused by the Doppler effect [5]

Figure 2.2 illustrates the operational concept of frequency modulated continuous wave (FMCW) radars. These radars emit a signal that has a consistent frequency and continues periodic fluctuations within a specific time. I can estimate the range between the sensor and the detected objects by calculating the differences between the received (RX) and transmitted (TX) signals.

In addition, like continuous wave (CW) radars, the Doppler effect is involved when the detected item moves in relation to the radar. The process alters the received signal's frequency, which directly correlates with the target's radial velocity. While a target is approaching the radar, the frequency will increase, while the frequency will decrease when the target is moving away [6].

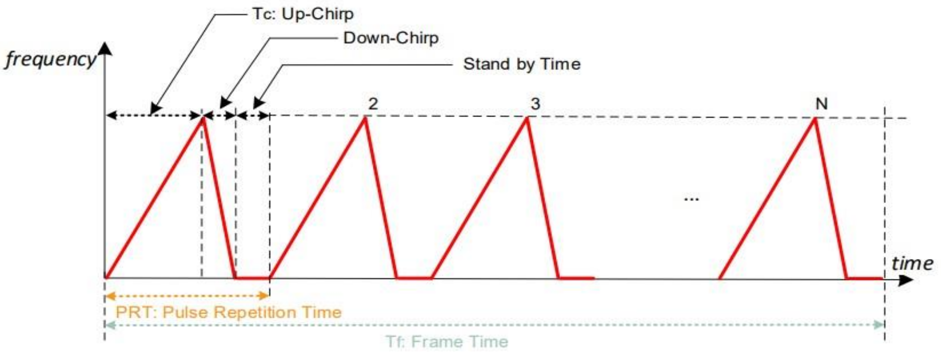

Figure 2.4: Utilizing multiple chirp configuration of Frequency Modulated Continuous Wave (FMCW) for the purpose of Doppler estimation [2]

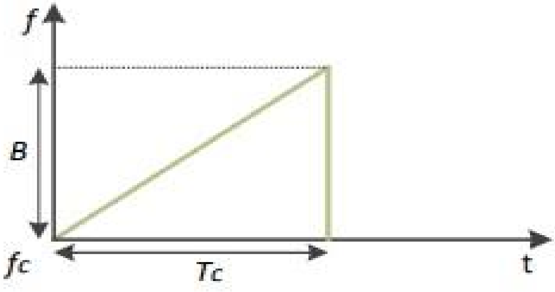

Figure 2.3: Chirp signal with frequency as function of time [2]

The frequency modulated continuous wave (FMCW) radar emits a signal with a frequency that changes linearly over time. This particular signal is usually known as a 'chirp,' as shown in Figure 2.3. Over time, the chirp signal's frequency can either increase (up-chirp) or decrease (down-chirp). As shown in Figure 2.4, A chirp can be characterized by three essential parameters: its initial frequency (fc), its bandwidth (B), and its total duration (Tc). A series of chirps with consistent beginning and ending frequencies will make up the radar's signal. Figure 2.4.

Figure 2.5 illustrates the fundamental structure of an FMCW system, with the numbers 1, 2, 3, and 4 denoting the respective functions:

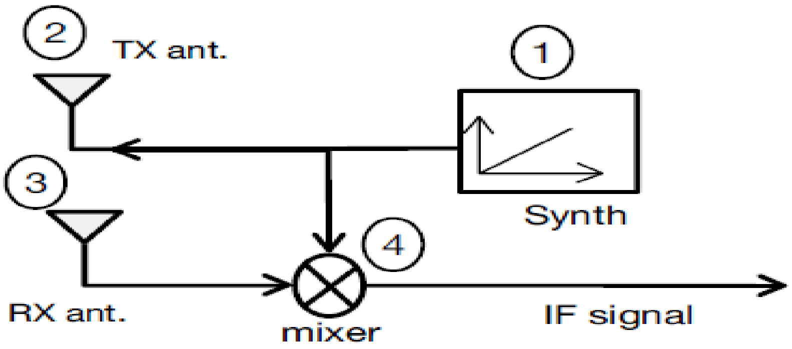

Figure 2.5: Block diagram of FMCW radar [4]

Synth represents the synthesizer, which generates the chirp.

Tx represents the transmitted antenna (Tx), which is responsible for transmitting CHIRP.

In Figure 2.5, the receiving antenna (Rx) is responsible for receiving the reflected back signals.

The mixer is responsible for mixing and produces an intermediate frequency (IF) signal. Figure 2.6 demonstrates the detection of a beat signal by subjecting this IF signal to a Fourier transform. The beat signal demonstrates a consistent frequency that is closely linked to the time delay (τ) encountered between the transmitted (TX) and received (RX) signals, as depicted in Figure 2.7. The frequency's magnitude, S * τ, is used to determine the extent of the identified target.

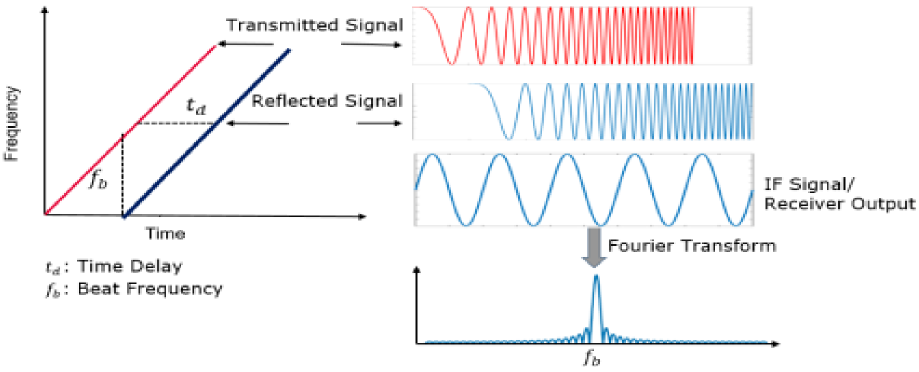

Figure 2.6: Representation of beat frequency produced after mixer by applying Fourier Transform [7]

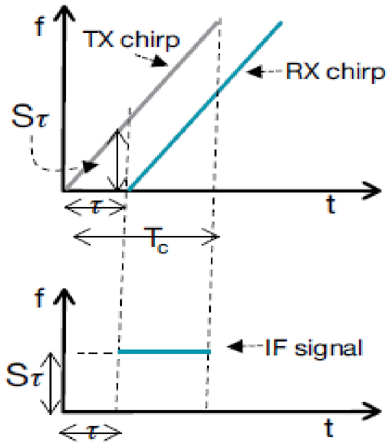

Figure 2.7: Displays the intermediate frequency (IF) that is produced by the mixer output [4]

Equation (2.1) represents the formula used to calculate the target's range from the radar [2].

$$R = \frac{C \cdot T_c \cdot f_b}{2 \cdot B} \qquad 2.1$$

The variables in the equation are as follows: R represents the target distance, C represents the speed of light in a vacuum, Tc represents the chirp duration in seconds, fb represents the beat frequency corresponding to the target, and B represents the signal bandwidth.

The Doppler effect changes the phase of the IF output signal by a proportional amount between chirps. This can be found using equation (2.2) [4] and is directly linked to the target's radial velocity (vr).

$$\Delta w = \frac{4 \cdot \pi \cdot v_r \cdot T_c}{\lambda} \qquad 2.2$$

Where λ represents the wavelength, measured in meters (m). Using equation (2.2), it is feasible to calculate the radial velocity [4] of the target, which can be determined using the formula (2.3).

$$\mathrm{Vr} = \frac{\Delta w \cdot \lambda}{4 \cdot \pi \cdot Tc} \qquad 2.3$$

During the process of determining the speed of a detected object, the radar system may face a problem when the difference in phase between consecutive chirps exceeds the limitation of $|\Delta\omega| < \pi$. The phase difference's periodic nature, with a period of 2π, can hinder the radar's ability to precisely determine velocity. Hence, there exists a maximum limit for the velocity that the radar is capable of detecting. More precisely, when the change in angular velocity ($\Delta\omega$) reaches the value of π, there is a limitation on the maximum velocity that can be detected. Reference [4] provides an expression for the maximum velocity, given by equation (2.4):

$$\mathrm{Vmax} = \frac{\lambda}{4 \cdot Tc} \tag{2.4}$$

A higher Vmax necessitated a shorter transmission time between chirps.

FMCW radars can determine the angle at which the signals they receive originate. However, this is only achievable if the radar has more than one receiving antenna. Using phase shifts, FMCW radars equipped with multiple antennas may be able to determine target angles. Due to the target's angle, a phase difference emerges as the signal reaches each antenna with a slightly variable travel distance (Figure 2.8). Equation (2.5) allows us to examine this phase difference using a Fast Fourier Transform (FFT).

$$\omega = \frac{2.\pi.d.\sin\theta}{\lambda} \tag{2.5}$$

The radar can determine the additional distance traveled by the signal and, consequently, the target's angle relative to its position by using the variables ω (phase shift), d (antenna separation), θ (target angle), and λ (signal wavelength). By inverting equation (2.5), I can detect the angle of arrival of the detected object [4].

$$\theta = \sin^{-1}\left(\frac{\lambda.\omega}{2.\pi.d}\right) \tag{2.6}$$

Similar to the velocity scenario, there exists a maximum detected angle of arrival for the target [4], which occurs when $\omega = \pi$, which is equivalent to 2.7.

$$\theta = \sin^{-1}\left(\frac{\lambda}{2.d}\right) \tag{2.7}$$

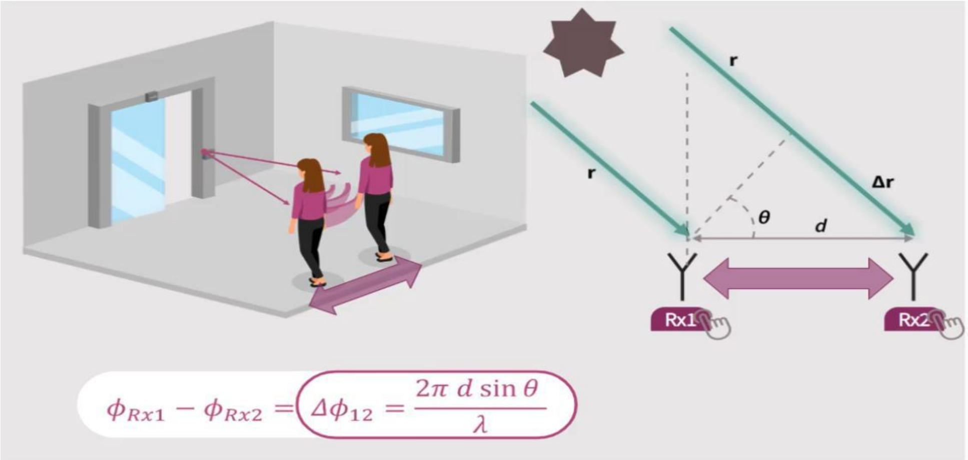

Figure 2.8: Angle of arrival (AoA) based on multiple antennas [7]

2.3 Infineon Radar BGT60TR13C

The BGT60TR13C functions as a specialized millimeter-wave radar transceiver designed specifically for short-range sensing tasks. The device operates by transmitting a signal that uses frequency modulated continuous wave (FMCW) through its dedicated transmitter channel. The transmitted signal interacts with the surrounding environment and bounces off any target items within its range. The sensor's three specialized reception channels catch the reflected echoes. Every receiver path includes specialized circuitry for baseband filtering, variable gain amplification (VGA), and analog-to-digital conversion (ADC). These methods efficiently prepare the obtained echo signals for subsequent processing. The ADCs temporarily store the digitized data in a first-in, first-out (FIFO) memory buffer. Afterwards, an external host processor, like a microcontroller unit (MCU) or application processor (AP), receives this data to perform the crucial radar signal processing. Figure 2.9 shows the main blocks needed to create a sensor system using the BGT60TR13C. [13]

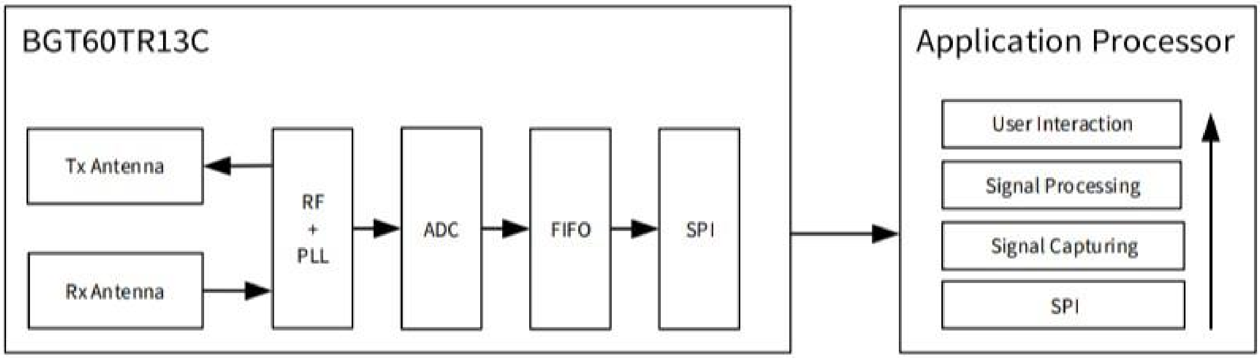

Figure 2.9: The data flow within the entire radar sensor system [13]

The initial block depicted in Figure 2.9 corresponds to the BGT60TR13C module, which is responsible for overseeing the RF signals and producing the sampled Intermediate Frequency (IF) communications. The processor block then receives these signals to perform critical radar signal processing tasks, including distance, velocity, and object classification, based on the application's specific requirements.

Figure 2.10 [2] illustrates the processing of the radar data algorithm.

1.Raw data: The algorithm processes the raw data collected by the radar and generates the target(s) parameters as output. The unprocessed data is stored in a 2D matrix format. I typically refer to these as slow and fast time.

Slow Time: This dimension is generally associated with the duration it takes for the radar pulse to scan the desired area. It offers data regarding the extent or distance of possible target.

Fast Time: This dimension corresponds to the individual samples gathered during a single slow time sweep. It frequently relates to the object's velocity (Doppler shift).

2.Windowing:

Blackman Window:
The window improves the clarity of the intended information by reducing noise in comparison to the target signal, resulting in an enhanced Signal-to-Noise Ratio (SNR).
Side Lobe Reduction:
The windowing function is employed to mitigate the undesirable spectral leakage caused by powerful signals in the data, resulting in side lobe reduction. The

presence of these "side lobes" can disrupt the identification of less powerful target.

3. Zero Padding:

This method entails adding a consecutive sequence of zeros at the end of the original data sequence. The goal is to change the size of the data to a value that is a power of two.

The rationale behind this action is that most digital signal processing methods, such as the Fast Fourier Transform (FFT) that will be used later, function with optimal efficiency when the data sizes are in the form of powers of two. This approach enhances the quality of the input signal.

4. Fast Fourier Transform (FFT):

A highly effective mathematical technique, the Fast Fourier Transform (FFT), transfers a signal's representation from the time domain, where it depicts changes over time, to the frequency domain, where it reveals the distribution of frequencies contained in the signal. When I process radar data, I apply a Fast Fourier transform (FFT) to the windowed and zero-padded range data, forming a "range image." This graphic illustrates the magnitude of the signals received from the radar at different distances (indicated by frequencies), indicating their strength.

5. Target Detection:

During this stage, the algorithm scans the FFT image to identify peaks inside the target range.

6. Doppler FFT:

This stage's primary goal is to obtain specific information about the target's velocity. The steps are analogous to range processing:

The first step involves applying a Chebyshev window to the slow-time samples in order to improve the signal-to-noise ratio (SNR) for velocity estimation. Following this, zero padding is used. Similar to range processing, I modify the data size to ensure efficient FFT operation. Finally, I apply the Fast Fourier Transform (FFT) to the windowed and zero-padded slow-time data. The Doppler Fast Fourier Transform (FFT) creates a two-dimensional picture that shows how the signal intensity is spread out in space based on both distance and speed.

7. Angle estimation:

This step is applicable to radar systems that have several receiving antennas. The algorithm can figure out the target signal's direction (AoA) by looking at the differences in phase between the range-Doppler maps it gets from each receiver. This successfully offers data regarding the target's angular position.

8.Target tracking:

During each radar scan, the system retrieves crucial target data such as distance, Doppler shift (which indicates velocity), and angle. This aids in constructing a visual representation of the target's whereabouts and motion. Next, the system links these newly obtained measures with pre-existing tracks using the Strongest Nearest Neighbour (SNN) method. In this context, the target measurement closely matches the projected track in terms of range, Doppler, and angle. Next, I employ an Alpha-Beta tracker to improve the accuracy of the target's state estimation, particularly its position and velocity, over time. This tracker integrates the newly obtained measurement with the current track estimate and forecasts the target's future state for the upcoming scan, similar to a Kalman filter.

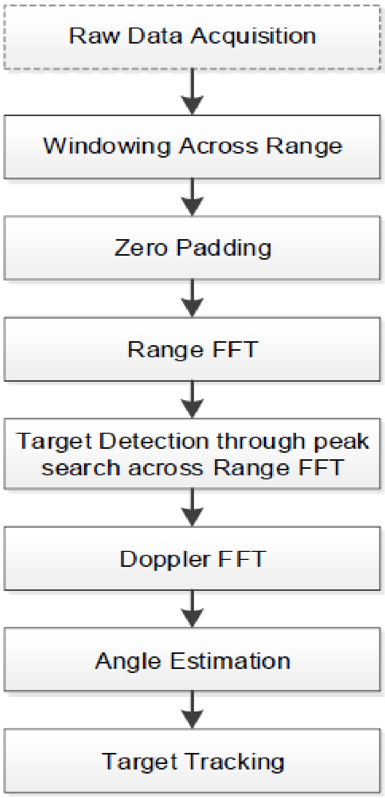

Figure2.10: FMCW Radar target detection process [2]

2.4 Tuning of Radar parameters

Tuning a radar's parameters heavily depends on optimizing its performance and ensuring precise detection and identification of target. The radar goal significantly impacts the modification of the radar parameters, as these variables closely influence the radar goal. There is a trade-off between a radar system's main goal and the specific measurements it uses to achieve that goal. The synthesizer in FMCW radar is responsible for generating a compressed, high-resolution pulse known as a CHIRP. Prior to delving into the discussion on parameters, it is imperative to establish a clear definition of CHIRP, followed by an examination of its metrics and its impact on radar objectives [14].

A chirp is a signal that exhibits a constant rate of change in frequency (df/dt) throughout time, either increasing or decreasing. An ADC (analog-to-digital converter) actively converts the received signal into a digital waveform during chirp transmission, enabling further processing. Figure 2.11 below illustrates the many stages of a chirp.

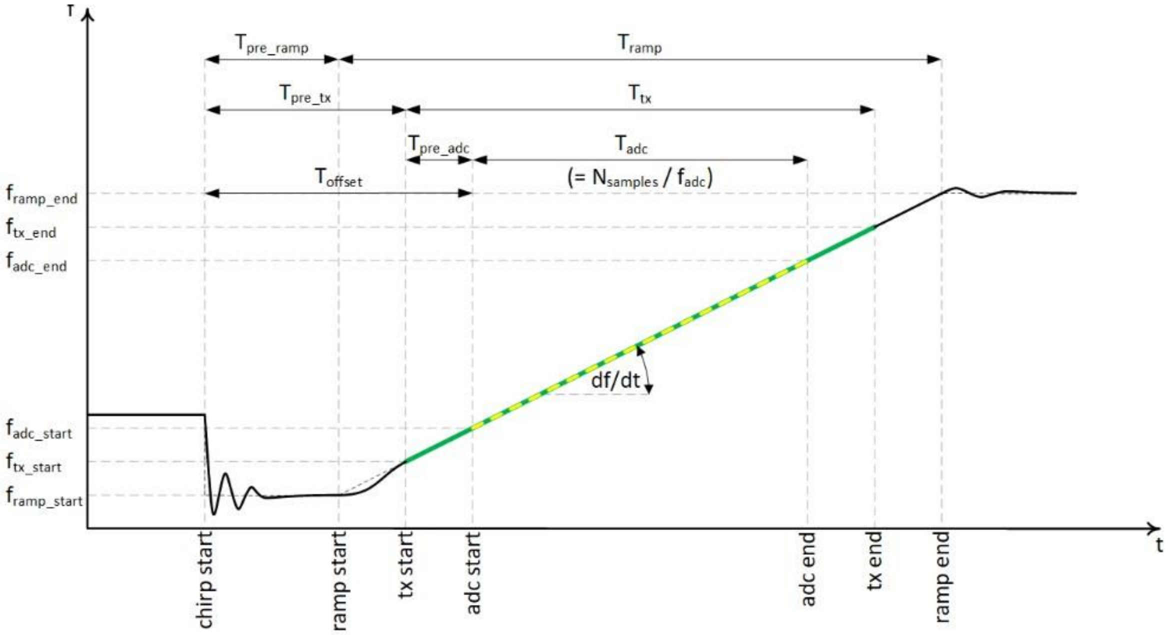

Figure 2.11: CHIRP Representation

2.4.1 Radar Metrics (Frequency, Bandwidth, Samples Per Chirp, Chirps Per Frame)

This section examines the fundamental radar metrics that significantly influence the FMCW radar system's effectiveness. The parameters of frequency, bandwidth, samples per chirp, and chirps per frame are essential for defining the radar's capabilities regarding range resolution, speed, max range, speed resolution, target detection, and overall performance.

1. Num of samples per chirp: Nsamples is the total number of samples at every CHIRP in a frame.

$$\text{Nsamples} = \frac{2 * Rmax}{\Delta R} \qquad 2.8$$

2.Start frequency: CHIRP start frequency in Hertz (Hz).

3.End frequency: CHIRP end frequency in Hertz (Hz).

4. Bandwidth: It is the difference between start frequency and end frequency.

5.Sampling rate: Sampling frequency, sometimes referred to as the sampling rate, is the number of samples taken per second from a continuous signal to produce a digital or discrete one. Hertz (Hz) is the measurement; comparable to samples per second (SPS). fadc has a great influence on sampling time Tadc. The time spent executing a single CHIRP represented by Tramp.

6.CHIRP repletion time: It is also called Pulse Repetition Time (PRT), define as a time between two consecutive chirps.

$$\text{PRT} = \frac{\lambda}{\text{Vmax}} \qquad 2.9$$

7.Num of chirps per frame or Nc: It is defined as consecutive no of chirps in a Frame**.**

$$x = \frac{2 * Vmax}{\Delta V} \qquad 2.10$$

Where ΔV is the desired speed resolution.

The above-mentioned parameters have a direct influence on Radar metrics. These metrics are.

Maximum Speed
Speed Resolution
Max Range
Range Resolution

Maximum Speed:

Max speed is the capacity of FMCW radar to identify the object moving within the range of that speed. Measured in m/s, shortened as Vmax.

$$\mathrm{Vmax} = \frac{\lambda}{4\mathrm{PRT}} \qquad 2.11$$

Speed Resolution:

Minimum velocity difference to separate two targets of the same range from the radar sensor. Thus, during movement analysis, it is a valuable parameter.

$$\mathrm{Vres} = \frac{2 * Vmax}{Nc} \qquad 2.12$$

Range Resolution:

It is defined as minimal range separation required to differentiate two targets with equal speed.

$$\mathrm{Rres} = \frac{c}{2 * \mathrm{B}} \qquad 2.13$$

Where C is speed of light and B is the bandwidth of Transmitted Signal (start frequency – end frequency)

Max Range:

The maximum range of a radar system refers to the furthest distance at which it can identify and precisely track objects or target.

$$\mathrm{Rmax} = \frac{\mathrm{Rres} * \mathrm{Nsamples}}{2} \qquad 2.14$$

The modification of parameters and the resulting changes in the maximum range, speed, and resolution are observed in the radar graphical user interface (GUI) and are discussed in Chapter 4.

2.4.2 Threshold sensitivity

FMCW radars employ chirp signals to detect target. Upon evaluation, these chirps may contain noise from undesired target in the surrounding environment. FMCW radars use thresholding techniques to accurately separate and identify human movement signals. Thresholding determines a precise level of signal strength. I consider signals that exceed this threshold as potential target, and classify signals below it as noise. I establish the threshold value within a specified range of 0 to 1 when detecting human movement. Through actual investigation, this range has been defined to include the usual strength of reflected signals associated with human movement. I will discuss these additional factors separately [15].

Factors Affecting Threshold Setting:

- **Signal-to-Noise Ratio (SNR):** It is the main factor that determines the strength of the target signal relative to the level of background noise. A higher signal-to-noise ratio (SNR) signifies a more robust target signal and permits a reduced threshold for detection.
- **The False Alarm Rate (FAR)** is the likelihood of the radar incorrectly identifying a target that does not actually exist. Decreasing the threshold enhances the sensitivity, but it also leads to an increase in the false alarm rate (FAR).
- **The size and reflectivity of the target** directly affect the strength of the signal. Larger objects with higher reflectivity produce a stronger signal, resulting in a lower detection threshold compared to smaller or less reflective target.
- **Environmental conditions,** such as clutter and interference from other sources, can affect the background noise level**.** As a result, it may be necessary to make adjustments to the detection threshold.

Changing Threshold to a Specific Value

Usually, the threshold is expressed as a voltage level or a power level. The conversion procedure entails:

Signal Processing: The received FMCW signal undergoes filtering and processing to extract the target beat frequency. The Fast Fourier Transform (FFT) typically accomplishes this. The FFT procedure, as illustrated in Figure 2.12, entails converting a time-domain signal to a frequency domain, thereby providing a better understanding of the frequency components within the signal. The FFT output displays the magnitude of a variety of frequency components, with prominent peaks indicating dominant frequencies. I can identify the presence of target within the signal by identifying peaks that correspond to specific frequencies through the analysis of the FFT output.

Beat Frequency Amplitude: The predetermined threshold value is then compared to the amplitude of the beat frequency.

Target Detection: A target is declared as detected if the amplitude of the beat frequency exceeds the threshold.

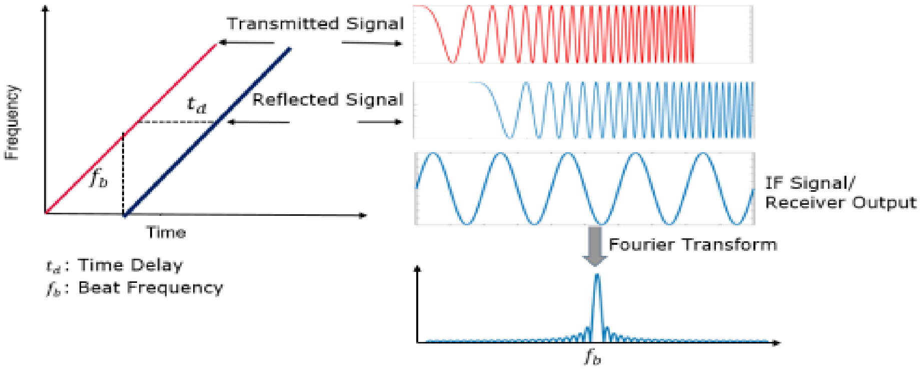

Figure 2.12: Representation of beat frequency produced after mixer by applying Fourier Transform [7]

CHAPTER 3

Methodology

The methodology chapter defines the systematic technique utilized to carry out this thesis work. This chapter comprises multiple sections, each providing a comprehensive explanation of the purpose and motivation behind human movement detection, the experimental setup, the data collection process, and the techniques used for data processing and analysis. The objective is to provide an adequate understanding of the techniques employed to guarantee the reliability and preciseness of the experimental results.

3.1 Motivation and Methods: A brief look

FMCW radars produce a substantial quantity of data points that represent reflections from the surrounding environment. Efficient processing is necessary to accurately detect human movement in this data. This work investigates three strategies utilized in FMCW radar-based human movement detection: thresholding, DBSCAN clustering, and point cloud analysis.

1) Thresholding: Given the large amount of data, thresholding is essential for reducing data. I can identify spots that humans are unlikely to generate, like weak signals, by setting specific limits for the strength and distance of signals. This improves computational efficiency by focusing computational strength toward locations that may contain human target.

2) DBSCAN Clustering: Ambient clutter, such as furniture or walls, causes noise in FMCW radar data. The Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm handles this problem. DBSCAN is highly effective in detecting clusters of data points in environments with a lot of noise, thanks to its utilization of user-defined parameters. The algorithm's resistance to extreme data values makes it well-suited for FMCW radar data, as it can accurately differentiate between human target and irrelevant background signals [16].

3) Point Cloud Analysis: FMCW radars offer comprehensive data on the distance and direction of detected points. You can use the provided data to generate a 3D point cloud, which accurately depicts the spatial arrangement of points. By analyzing the point cloud, it is possible to extract spatial information about the target, which helps to gain a more thorough understanding of human movement in indoor spaces.

Through the integration of these methodologies, FMCW radar systems can detect human motion, even in complex surroundings, providing important information for a wide range of uses.

3.2 Human sensing using radar signals.

Conventional techniques for detecting human presence indoors frequently depend on sensors that have certain restrictions. For instance, infrared sensors do not possess the ability to function in all weather conditions [8], whereas camera sensors give rise to problems over privacy [9], [10]. Different categories classify the wide range of sensors used for target detection [11].

This thesis investigates the application of frequency modulated continuous wave (FMCW) radar sensors for detecting human movement in interior environments, with a focus on their benefits in maintaining privacy.

Detecting the presence of humans indoors is important for a wide range of applications. This study focuses on the importance of maintaining privacy while detecting human movement and emphasizes the benefits of using FMCW radar. I select FMCW radar sensors based on their distinctive characteristics [12].

Privacy Preservation: FMCW radars, unlike camera sensors, do not collect visual data, hence safeguarding user privacy.

All-weather Capability: They operate efficiently irrespective of lighting or weather conditions.

Contactless Operation: FMCW radars function without human contact, rendering them well-suited for diverse situations.

Material Penetration Potential: These sensors have the capability to penetrate specific materials, providing extra functionality.

FMCW radar is highly effective in detecting humans due to its high-frequency operation and modulated bandwidth. These devices are capable of accurately and dependably detecting human presence and activity indoors. FMCW radar sensors offer a favorable solution for detecting human movement indoors while also providing better privacy protection compared to conventional approaches. Due to their excellent resolution, sensitivity, and ability to function in all weather conditions, they are well-suited for use in security, healthcare, and smart home systems. This thesis work utilizes the BGT60TR1C FMCW radar from Infineon.

3.3 Experimental setup and Data collection Process

This section provides a comprehensive description of the experimental setup used to evaluate the performance of the Infineon FMCW radar sensor, specifically the Demo BGT60TR13C model. The description includes the setup arrangement, the data acquisition procedure, and the subsequent analytical approaches. Furthermore, I employ trajectory pattern analysis to collect data and evaluate the effectiveness of the sensor. The study focuses on two distinct trajectories: linear and U-shaped. I have recorded the human detection data from both trajectories.

3.3.1 Radar Sensor Specifications and Rationale

The radar sensor used in the experiment is the Demo BGT60TR13C, manufactured by Infineon [17]. This sensor was chosen because of its unique ability to accurately measure minute and microscopic movements. The device has a versatile and wide frequency range of 5.5 GHz, specifically functioning between 58.0 GHz and 63.5 GHz. The broad frequency range enables precise identification and quantification of small motions.

The sensor's detection range spans from 0.2 m to 15 m, depending on the particular setup and needs of the experiment. These qualities render it appropriate for diverse applications, encompassing those necessitating proximity sensitivity and long-distance sensing capabilities. Table 3.1 outlines several key factors that substantiate the selection of the Demo BGT60TR13C radar sensor.

Table 3.1: BGT60TR13C Overview

Parametric	BGT60TR13C
Angle of Arrival (AoA)	Yes, with three receiving antennas
Frequency min/max range	58 GHz to 63.5GHz
Max detection range	15 m
Minimum detection range	0.2 m
No of TX and RX antennas	Tx: 1 and Rx :3
Speed detection	Yes

Table 3.1 presents a comprehensive summary of these characteristics, emphasizing the rationale for selecting the Demo BGT60TR13C radar sensor for the experiment. The sensor's sophisticated features and adaptability make it a perfect instrument for gathering precise human movement data and conducting comprehensive analysis in a controlled experimental environment.

3.3.2 Experimental Setup

The experimental setup of the Demo BGT60TR13C radar sensor involves a series of careful measures to guarantee accurate data determination and processing. The setup and placement of the radar, the field of view parameters, and the human movement and detection processes are covered in the following sections.

1) Radar Location

The radar sensor was deliberately placed at a position to maximize detection and measurement precision. The sensor was positioned at the origin on the x-axis, specifically at position 0. It was raised to a height of 1.4 m above the ground. The chosen placement, seen in Figure 3.1, was selected to optimize the radar's field of view and guarantee unhindered signal propagation.

2) Field of View (FOV)

The radar sensor's field of view (FoV) was set up to encompass an angular range spanning from -45° to +45°. The sensor's wide field of view allowed it to collect motions across a large region, which is essential for accurate human movement detection as shown if Figure 3.1. To guarantee comprehensive coverage of the radar's field of view (FOV), a minimum distance of 1.5 m was maintained between the radar and the testing area.

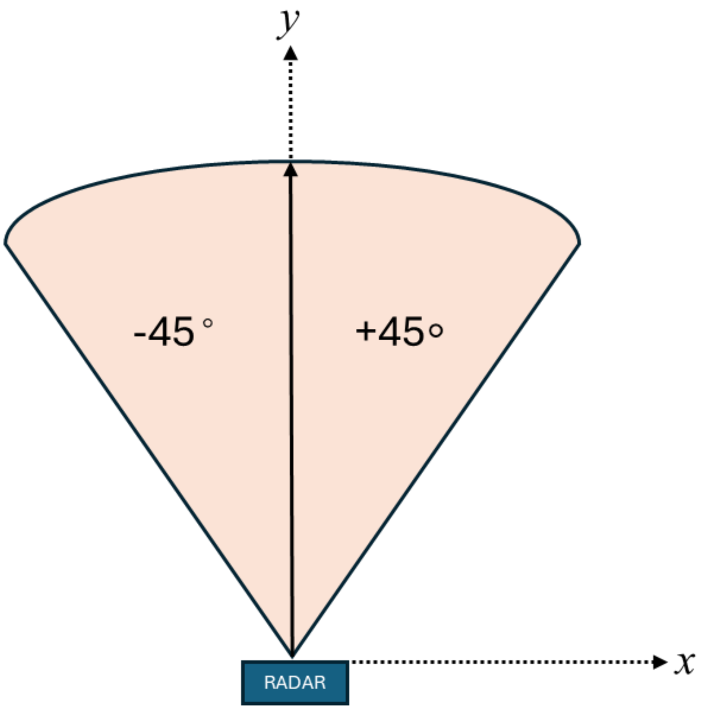

Figure 3.1: Radar's Position and Field of View Demonstration

3) Sensor’s placement:

An indoor setting is used to conduct experimental work, with conditions carefully controlled and monitored. A radar is strategically placed to optimize its Field of View (FoV) of ±45°, allowing for the detection of human movement within the designated area. The position of the radar is marked as the origin (0,0) in the Cartesian coordinate system. This configuration is used for all the experimental data collection.

The reason for favouring an indoor location is to reduce the amount of disorder, which is more common in outdoor environments and would necessitate multiple radar setups in order to effectively identify human motion. This thesis primarily focuses on the detection of human movement indoors, a crucial aspect for several applications like HVAC systems, vital sign monitoring, and smart houses. Through the detection of human activity within indoor spaces, I may efficiently utilize these intelligent applications. To detect human movement indoors, two distinct trajectories were observed: Linear and U-shape.

Table 3.2: Radar Configuration

Tx/Rx Antennas	1/3
Samples Per Chirp	64
Chirps Per Frame	32
Start Freq (GHz)	58×10^{09}
End Freq GHz)	59×10^{09}
Bandwidth (GHz)	1.0
Max range (m)	4.0

4) Experimental Trajectory Pattern:

The experiment observed two distinct trajectory patterns:

- Linear Trajectory
- U shape Trajectory

I. Linear Trajectory:

In the linear trajectory arrangement, a straight line is drawn on the ground at 2 m from the radar, shown if Figure 3.2. An individual walk on this trajectory at a nominal speed within the field of view of the radar. The radar is programmed to identify and capture the human movement data in these specific circumstances. The results is shown in the following Chapter 4.

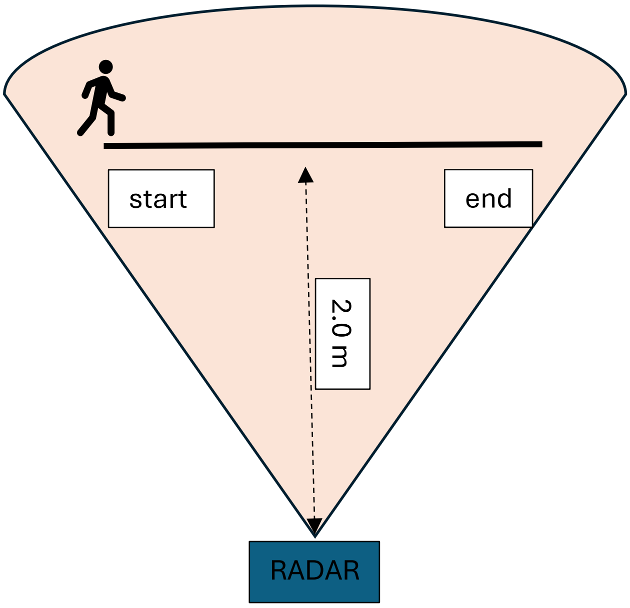

Figure 3.2: Linear Trajectory

II. U-Shape Trajectory:

The U-shape trajectory involves tracing a U-shaped path on the ground, around 2 m from the radar, depicted in Figure 3.3. An individual traverses this U-shaped trajectory at a steady velocity while staying within the radar's field of view. The reason used a U shape trajectory is to observe a vertical and horizontal segments. The radar detects and records the movements along this trajectory. The detailed result is observed in Chapter 4.

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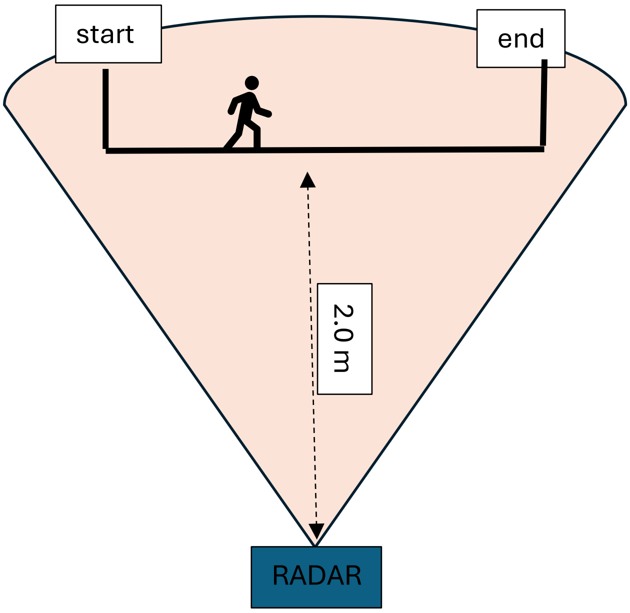


Figure 3.3: Demonstration of movement along U-Shap Trajectory

3.3.3 Human movement detection

The performance of the radar sensor was examined at various distances by Human target detection. As per the experimental configuration shown in Table 3.2. The subsequent configuration was recorded:

1) Optimal detection range:

The radar sensor demonstrated effective object tracking and detection capabilities starting from approximately 2 m away from the sensor. Within this range, extending outward from the 2 m mark, the radar exhibits the ability to consistently and accurately monitor the object's precise movement and motion. The sensor's performance is particularly robust in this specified range, allowing for reliable object tracking and detection.

2) Reduced dependability at distances greater than 3 m:

The accuracy of detection significantly decreased for target located beyond 3.93 m, as the radar allow a range of 4 m as per configuration. Beyond this range, the radar's capacity to continuously detect and monitor target movement became inconsistent. This degradation in performance is likely attributable to signal attenuation, environmental factors impacting signal reflection, and a reduction in the radar's effective field of view.

3) Maximum Range of Detection

The radar sensor was calibrated to have a maximum detection range of around 4 m. This configuration was determined by the radar parameter values and the experimental specifications as shown in Table 3.2. Although the radar has the ability to identify objects at this distance, the most dependable and precise measurements were observed within the ideal range between 2 m to 3.93 m.

3.4 Data Processing and Analysis:

Radar systems employ electromagnetic waves to detect and monitor objects. Through the analysis of reflected echoes, one can ascertain the presence, the distance, and even the movement of a target. This thesis investigates the use of radar signal processing to detect human movement. Starting with collecting data and ending with recognizing human movement using methods such as Doppler shift analysis, digital beamforming, thresholding, and target clustering using DBSCAN, this section goes over all the steps that make up the methodology.

1) Data acquisition: The ongoing process of gathering unprocessed data frames from the radar sensor.

2) Frame Processing:

- **Doppler Spectrum Calculation:** Converting the received signals into the frequency domain to detect the Doppler shifts caused by objects.
- **Beamforming:** is a technique that involves combining signals from several antennas in order to improve the ability to identify objects at precise angles and boost spatial resolution.
- **Beam Range Energy Calculation:** This process involves calculating the total signal strength at different beam angles to help detect and identify probable objects within a specific range.

3) Thresholding: Thresholding is a signal processing technique used in radar systems to distinguish between potential target and background noise or clutter. In this method, a predetermined threshold value is set based on the statistical characteristics of the ambient noise and the desired balance between target detection and false alarm rates. The received radar signals are then compared to this threshold:

- Signals exceeding the threshold are classified as potential target (e.g., human presence).
- Signals falling below the threshold are typically categorized as noise or clutter and disregarded.

The threshold value remains constant during operation and is not directly influenced by the strength of incoming signals. Instead, it is carefully chosen to optimize the radar's performance, maximizing the probability of detecting genuine target while minimizing false alarms caused by environmental factors.

4) Point Cloud Generation:

- This involves the process of sequentially going through the beam-range energy matrix.
- The system is capable of detecting elements above a predetermined threshold, which suggests the presence of a prospective object.
- I obtained the range, angle, and speed (via Doppler shift) for every detected point in the point cloud.
- The point cloud data format generates points with these characteristics.

5) DBSCAN: I use DBSCAN clustering to group points in a point cloud that are likely to represent the same detected target and are marked as being in the presence state.

6) Data Logging: Upon detection, object data is logged into a .CSV file for subsequent analysis.

- **Data Analysis:**
  The .CSV file is utilized to compute metrics such as Mean Error and Root Mean Square Error (RMSE).

7) Reference System:

The measured values and ground truth data are plotted graphically for visualization purposes and setting our reference system.

- **Conversion of coordinates:** Data is initially received in polar coordinates, consisting of range and angle measurements. Conversion process involves transforming polar coordinates into Cartesian coordinates. Cartesian coordinates allow for easier visualization and analysis of the detected data. The converted data is then plotted on a Cartesian plane for visualization purposes. This conversion step enables better interpretation and understanding of the radar-detected information.

3.4.1 Point cloud:

Radar systems use point clouds to depict the spatial arrangements and attributes of objects within their visual range. This procedure entails converting unprocessed radar data into a set of three-dimensional points, with each point representing a possible object.
Essential Actions:

1. Bean Range Energy Calculation: The radar uses beamforming to merge signals from multiple antennas, resulting in improved spatial resolution. The beam range energy matrix measures the collective signal intensity for each beam angle across the whole range.

2. Thresholding and Point Identification: I analyze the beam-range energy matrix. I consider objects that exceed a predetermined threshold to possess an adequate level of signal strength.

3. Point attribute extraction: This process entails calculating the range and angle of each detected element. This calculation is dependent on the element's position inside the matrix and the known characteristics of the system, such as range resolution and angular resolution.

4. Doppler Shift: The Doppler spectrum of the identified element can be utilized to extract the Doppler shift, which can then be turned into an estimated velocity of the object.
5. Point Creation and Point Cloud Building: I generate and include new points into the point cloud data structure using the retrieved parameters of range, angle, and optional speed. This structure denotes the identified entities in a three-dimensional spatial context.

3.4.2 DBSCAN

Density-Based Spatial Clustering of Applications with Noise (DBSCAN) is a widely utilized algorithm for data clustering. The algorithm functions by detecting clusters of data points with a high density, effectively distinguishing them from regions with low density or noise.

How DBSCAN work

The DBSCAN clustering method differs from others by its reliance on the density of points surrounding a centre point, rather than specified forms of shapes to identify clusters.[18]

There are two basic parameters for a DBSCAN:

1) Epsilon (ε)
2) MinPts

Epsilon (ε): the radius of neighbourhood around a certain data point.
MinPts: refers to the minimal number of points that must be present within the ε-neighbourhood for a point to be classified as a core point, which is a central point within a densely populated area.
Instead of these parameters there are three important point usually called core point, border point and noise, shown in Figure 3.4.

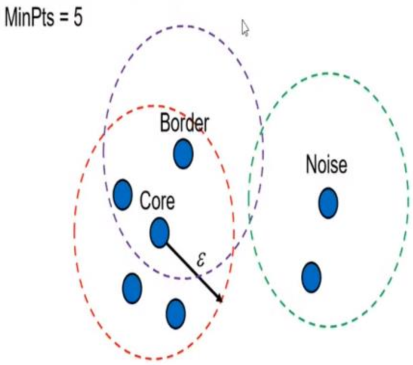


Figure 3.4: DBSCAN Parameters

Core point: The core point is the data point at which, in the eps neighbourhood cluster, the data points are equal to or more than the minpoints.

Border point: The term "border point" refers to a data point in the eps ε neighbourhood cluster where the number of data points is less than the minpoints. However, it should be noted that at least one core point exists within the same cluster, not in the neighbour’s cluster.
Noise: Noise refers to data points that are neither core nor border points.

DBSCAN in BGT60TR13C Radar:

To group radar signal data using range, angle, and speed variables [18], this study used the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm. I employed digital beamforming techniques on the range-Doppler spectrum to derive the beam range energy matrix. I analysed the matrix to identify points that fell within a specific energy range. I performed calculations to determine the range, angle, and Doppler shift (speed) for each valid point. I then transformed the points into a NumPy array and applied the DBSCAN algorithm to cluster them, setting an epsilon value of 0.2 and a MinPts of 3. The DBSCAN algorithm classified each data point, detecting groups of closely located points as clusters and recognizing outliers as noise. I determined the existence of genuine clusters by confirming that no points classified as noise indicated the presence of a target. Figure 3.5 displays the grouped data in a plot and stores the data in a .CSV file for further analysis. The selection of DBSCAN parameters allowed for the successful detection and grouping of target within the radar's field of vision, thereby improving the precision of presence detection and movement analysis. In Figure 3.5, the purple dots represent human movement detection at around 2 m.

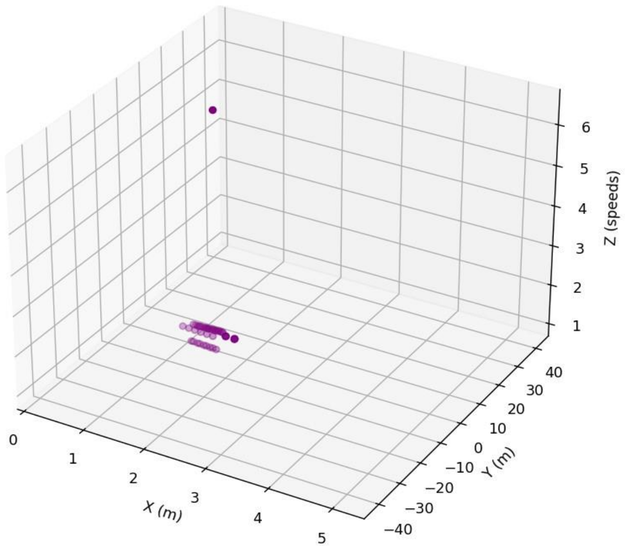


Figure 3.5: Human movement detection through DBSCAN (range, angle, and speed)

Chapter 4

Experimental Result

This chapter provides a detailed overview of the experimental results on human movement detection utilizing the Infineon Demo BGT60TR13C radar sensor. I conducted precise experiments using different trajectory patterns, such as linear and U-shaped movements, to assess the sensor's ability to identify human movements. I conducted a set of controlled experiments to replicate real-life movement situations, enabling us to evaluate the radar's sensitivity, precision, and dependability. In addition, I conducted a comparative analysis of our findings with the existing body of literature to provide a deeper understanding of our results in relation to current research. This allowed us to showcase the effectiveness and progress of our technique.

I thoroughly recorded the sensor's reactions to various movement patterns, and my discoveries reveal significant details about its functional abilities. For example, the sensor demonstrated a significant level of precision in identifying straight movements but encountered specific difficulties when faced with U-shaped paths that involved both horizontal and vertical sections. I have conducted a comprehensive examination of the sensor's capacity to accurately detect human movements. The subsequent sections present a discussion on the outcomes of the graphical user interface (GUI) and trajectory analysis.

4.1 Radar GUI analysis

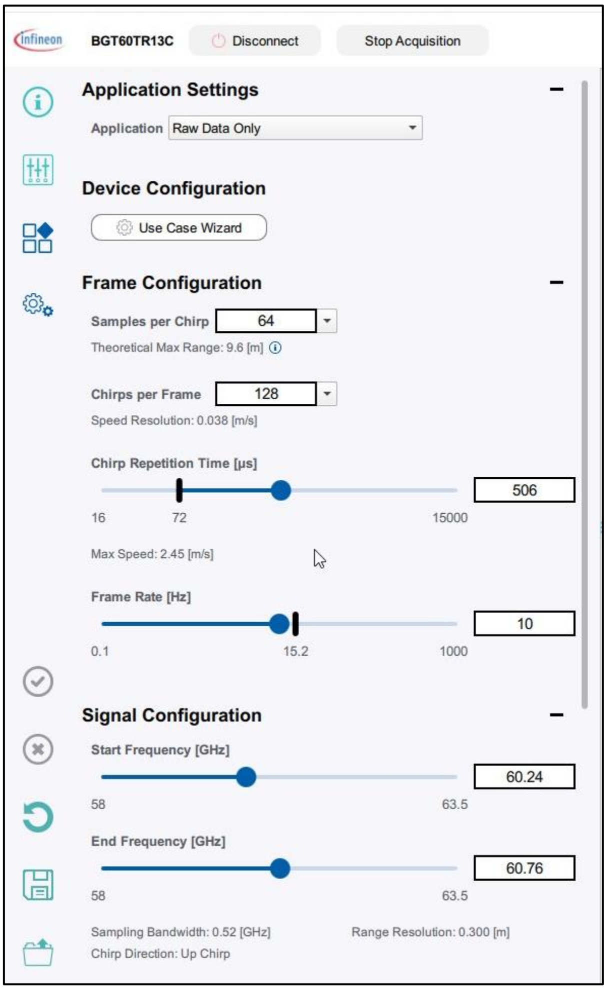
The results of the Graphical User Interface (GUI) analysis emphasize the parameters that affect the radar's detection range, range resolution, speed, speed resolution, and overall performance. I carefully changed the key parameters, such as bandwidth, chirp repetition time, number of samples per chirp (Nsamples), and number of chirps per frame (Nc), to assess their influence on detection accuracy and range. Figures 4.1 and 4.2 will clearly depict the consequences of these parameters to provide a clear and concise understanding.

The GUI analysis not only enabled the observation of detection patterns, but also provided the ability to make real-time adjustments to maximize sensor performance. The GUI Figures presented in this chapter will visually demonstrate the relationship between parameter values and their corresponding metrics, thereby offering a graphical depiction of the data that supports our results. The purpose of this graphic representation is to improve our understanding of the relationship between several factors that impact radar performance in terms of detection range.

4.1.1 Changing Bandwidth influence range

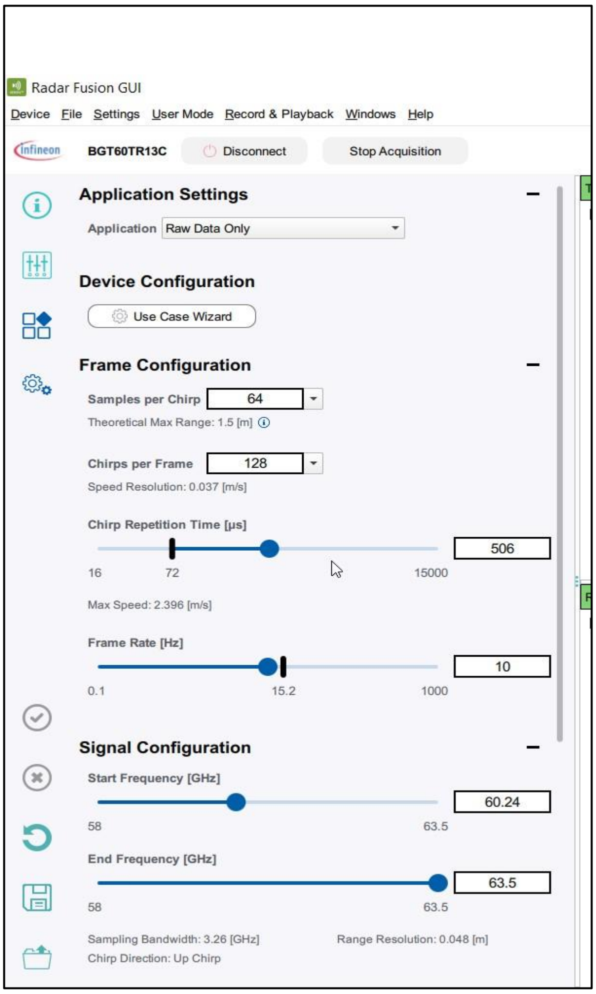
Figure 4.1 illustrates that modifying the bandwidth of a radar system's graphical user interface (GUI) has a substantial effect on its detection range. By configuring the bandwidth to 0.52 GHz, the radar system can achieve a maximum detection range of 9.6 m.

In contrast, as depicted in Figure 4.2, increasing the bandwidth leads to a significant decrease in the radar's detection range. More precisely, an increase in frequency from 60.24 GHz to 63.5 GHz broadens the bandwidth by 3.26 GHz. The bandwidth expansion is directly proportional to a 1.5-meter reduction in the detection range.



Application Settings
Application: Raw Data Only
Device Configuration
Frame Configuration
Samples per Chirp: 64
Theoretical Max Range: 9.6 [m]
Chirps per Frame: 128
Speed Resolution: 0.038 [m/s]
Chirp Repetition Time [µs]: 506 (16, 72, 15000)
Max Speed: 2.45 [m/s]
Frame Rate [Hz]: 10 (0.1, 15.2, 1000)
Signal Configuration
Start Frequency [GHz]: 60.24 (58, 63.5)
End Frequency [GHz]: 60.76 (58, 63.5)
Sampling Bandwidth: 0.52 [GHz]
Range Resolution: 0.300 [m]
Chirp Direction: Up Chirp

Figure 4.1: Minor change in bandwidth



Application Settings
Application: Raw Data Only
Device Configuration
Frame Configuration
Samples per Chirp: 64
Theoretical Max Range: 1.5 [m]
Chirps per Frame: 128
Speed Resolution: 0.037 [m/s]
Chirp Repetition Time [µs]: 506 (16, 72, 15000)
Max Speed: 2.396 [m/s]
Frame Rate [Hz]: 10 (0.1, 15.2, 1000)
Signal Configuration
Start Frequency [GHz]: 60.24 (58, 63.5)
End Frequency [GHz]: 63.5 (58, 63.5)
Sampling Bandwidth: 3.26 [GHz]
Range Resolution: 0.048 [m]
Chirp Direction: Up Chirp

Figure 4.2: Increase bandwidth

4.1.2 Changing the number of samples per CHIRP modifies the detectable range.

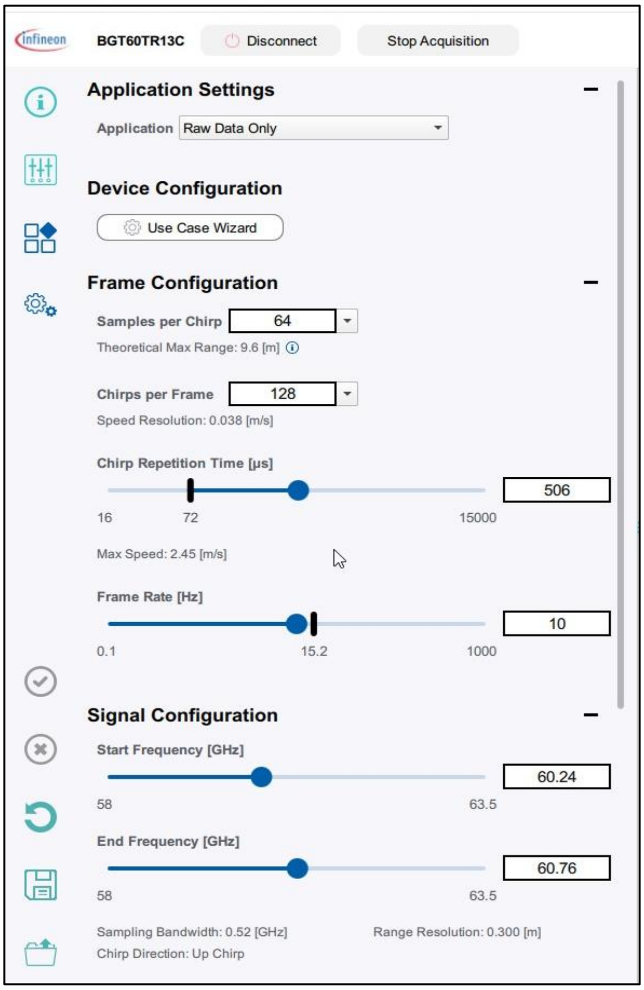
The number of samples per CHIRP is a critical factor in establishing the maximum detectable range in radar systems. A CHIRP, or compressed high-intensity radial pulse, is a signal that exhibits a changing frequency, either increasing or decreasing, over a specific time period. Through the analysis of the CHIRP signal, the radar system is able to determine the distance to an object by calculating the time delay between the emitted and received signals.

Figures 4.3 and 4.4 show how altering the number of samples per CHIRP influences the radar system's maximum detectable range. More precisely, I increase the sample size from 64 to 128 while maintaining a constant frequency.

Figure 4.3: This Figure depicts the radar system's performance with 64 samples per CHIRP. The limited number of samples decrease the maximum detectable range due to the reduced resolution. The bandwidth and the number of samples determine the range resolution. A smaller number of samples leads to a less precise range resolution, which in turn restricts the maximum detectable range.

Figure 4.4: This graph shows an increase in the number of samples per CHIRP to 128. The increase in sample quantity results in a significant improvement in the maximum detectable range. The improvement is due to the increased resolution obtained by densely sampling the CHIRP signal. By increasing the number of samples, the radar system can better distinguish smaller variations in the time delay, resulting in enhanced accuracy and a longer maximum detectable range.

Both figures shown below clearly illustrate the significant enhancement in the maximum detectable range that occurs when the number of samples per CHIRP doubles. This enhancement highlights the significance of choosing the right number of samples in the experiment and optimization of radar systems to meet certain performance criteria.



Application Settings

Application: Raw Data Only

Device Configuration

Frame Configuration

Samples per Chirp: 64
Theoretical Max Range: 9.6 [m]

Chirps per Frame: 128
Speed Resolution: 0.038 [m/s]

Chirp Repetition Time [µs]: 506 (16, 72, 15000)
Max Speed: 2.45 [m/s]

Frame Rate [Hz]: 10 (0.1, 15.2, 1000)

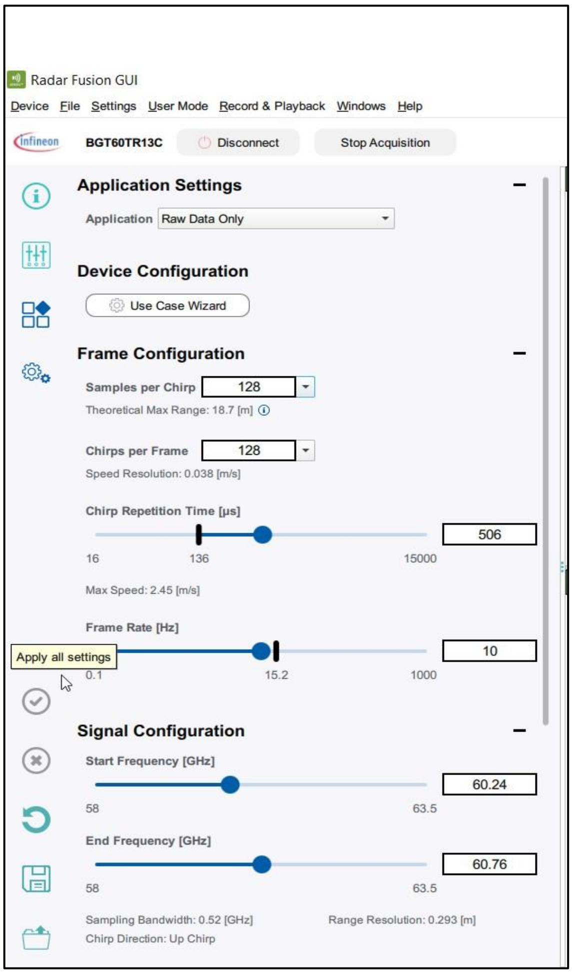
Signal Configuration

Start Frequency [GHz]: 60.24 (58, 63.5)

End Frequency [GHz]: 60.76 (58, 63.5)

Sampling Bandwidth: 0.52 [GHz]
Range Resolution: 0.300 [m]
Chirp Direction: Up Chirp

Figure 4.3 : Default sample per CHIRP



Application Settings

Application: Raw Data Only

Device Configuration

Frame Configuration

Samples per Chirp: 128
Theoretical Max Range: 18.7 [m]

Chirps per Frame: 128
Speed Resolution: 0.038 [m/s]

Chirp Repetition Time [µs]: 506 (16, 136, 15000)
Max Speed: 2.45 [m/s]

Frame Rate [Hz]: 10 (0.1, 15.2, 1000)

Signal Configuration

Start Frequency [GHz]: 60.24 (58, 63.5)

End Frequency [GHz]: 60.76 (58, 63.5)

Sampling Bandwidth: 0.52 [GHz]
Range Resolution: 0.293 [m]
Chirp Direction: Up Chirp

Figure 4.4 : Increae No of sample per CHIRP

4.2 Result of Different Trajectories:

This thesis conducted two experimental trajectories to demonstrate the effectiveness of the radar in terms of human movement detection: the linear trajectory and the U-shaped trajectory. The corresponding sections below elaborate on the outcomes for each trajectory. Both the linear and U-shaped experiments are performed with the same configuration but with different time spans. As a result, there is a little bit of variation and noise in the detection.

4.2.1 Linear Trajectory:

The experiment likely entailed assessing the radar system's capacity to detect human movement. To achieve this, I devised a specific configuration for an indoor environment, as illustrated in Figure 4.5. This configuration required objects to move in linear trajectories across the radar's field of view, a region it can monitor. I likely repeated these movements numerous times to obtain a comprehensive dataset. In the end, the experiment collected data from the radar, allowing for analysis to assess the system's efficiency in tracking these moving objects.

Figure 4.5: Experimental set-up inside the room

Figure 4.6 depicts the experimental setup, which involves drawing a straight line at approximately 2 m from the radar. The radar's position is at its coordinates (0, 0), as shown by a black dot in Figure 4.6, which covers the detectable trajectory from (-2.5, 2).

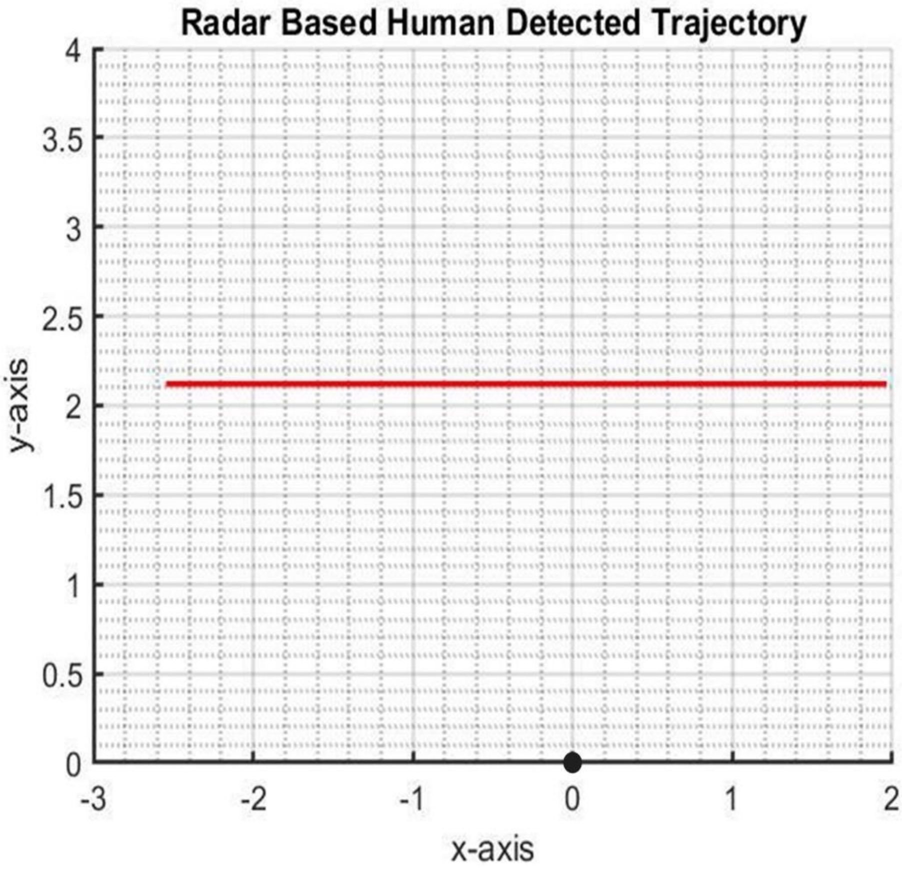


Figure 4.6: Straight Line Path

The recorded trajectory graphs clearly demonstrate that the sensor is capable of detecting human movement, as shown in Figure 4.7.

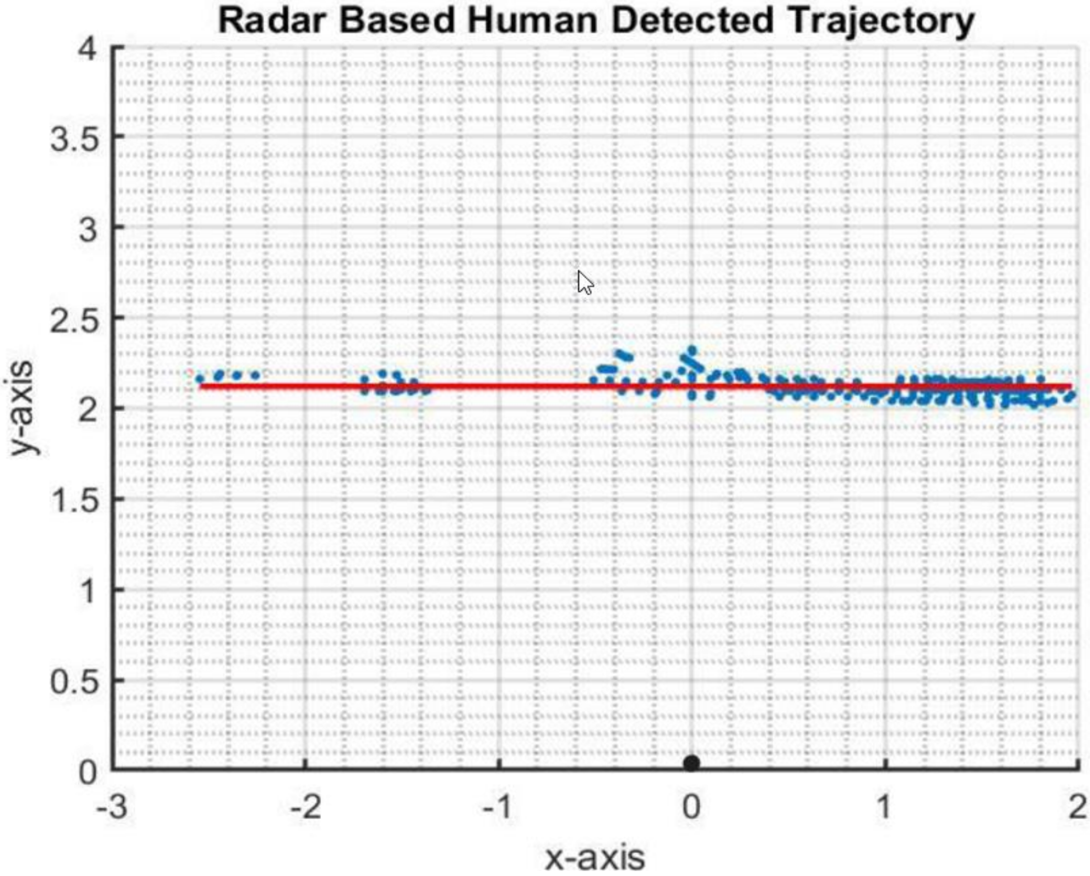


Figure 4.7: Results from the Straight-Line Movement

Figure 4.7 uses a Cartesian coordinate system to depict the results. The X-axis shows the angular orientation of the radar, while the Y-axis represents the distance from the radar in meters. A red line illustrates the ground truth, which represents the moving object's true trajectory. On the other hand, the blue dots represent the human movement detection during the experiment. High detections were observed in the central and right portions of the field of view (FOV).

4.2.2 U-Shape Trajectory

Understanding the radar's positioning is essential before describing the experimental arrangement for the U-shaped trajectory, as clearly illustrated in Figure 4.8. The reference point (0,0) establishes the position of the radar. The range of ±45° is counted from a reference line, as depicted in Figure 4.8. This figure provides a comprehensive understanding of the radar's placement and its field of observation.

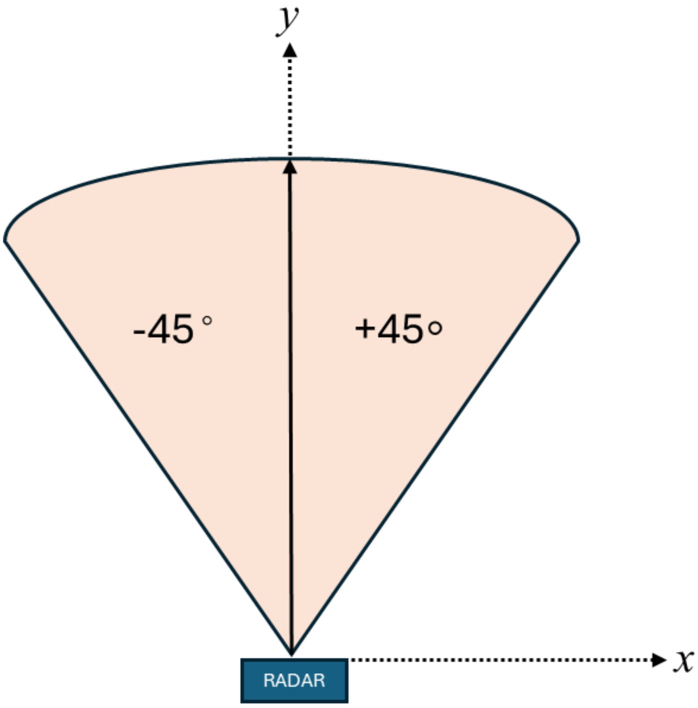


Figure 4.8: Radar Placement and its Field of Observation

Figure 4.9 depicts the experimental arrangement for the U-shaped trajectory path. The experiment can be performed in the controlled indoor environment. The U-shaped trajectory consists of both horizontal and vertical parts. The goal is to evaluate the radar's capacity to detect human motion by accurately tracking their movement along a U-shaped path.

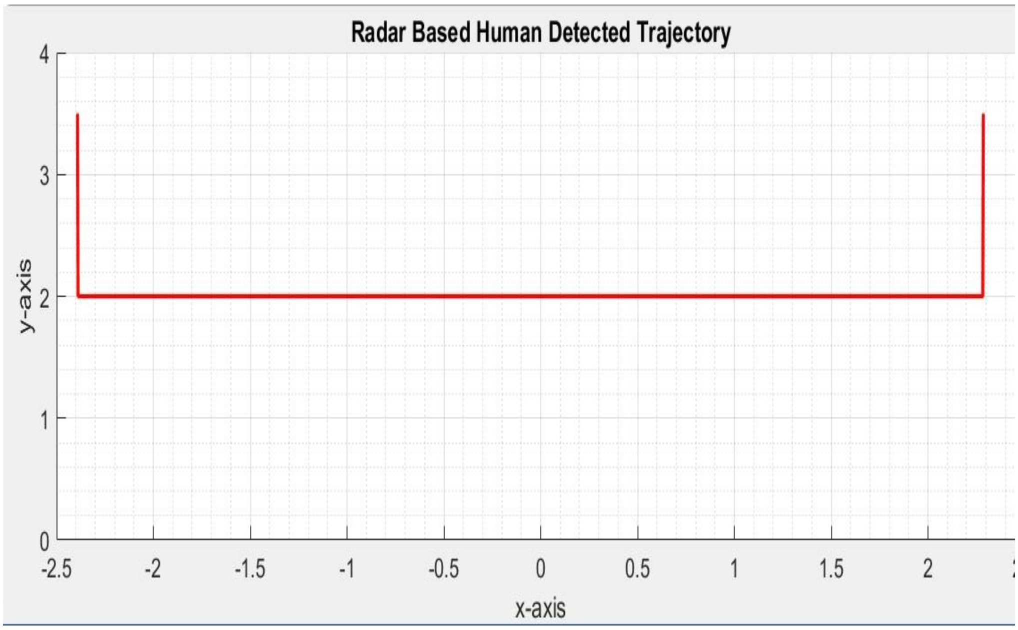


Figure 4.9: U-Shaped Path

To achieve a symmetrical detection range of ±45°, I defined the radar to set a specific limit within its operational detection range. By doing so, the radar effectively detects objects symmetrically within this ±45° range. This optimizes and balances the radar's detection capabilities, ensuring a reliable object detection on both sides. Figure 4.10 shows the radar, represented by a black dot, which covers both the angular view and the U-shaped trajectory. However, it is important to note that some regions of the U-shaped trajectory lie outside of the radar's Field of View (FoV). I positioned a portion of the trajectory outside the radar's Field of View (FoV) to guarantee that the entire path was fully covered. This method takes into account variations in human movement, like short or long curves at the end, which could otherwise go unnoticed. Using a longer U-shaped trajectory can help to reduce these potential tracking gaps.

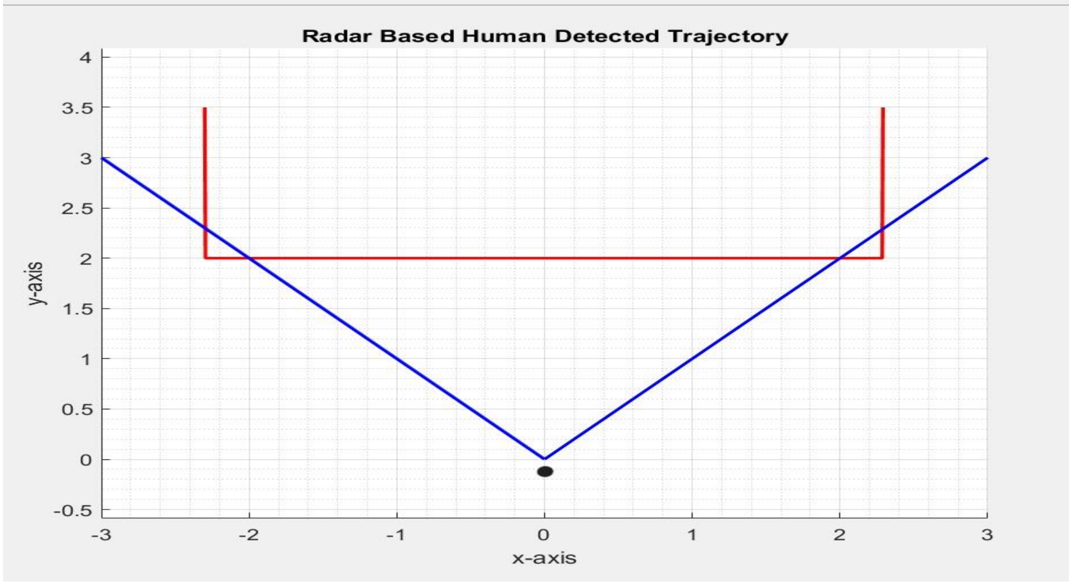


Figure 4.10: Radar position, ground truth of the U shape, and radar angular view

The subsequent section records and analyzes the radar detection results, providing a comprehensive analysis of the collected data. I intend to clarify the radar system's accuracy, reliability, and overall performance by examining the radar readings within the defined range from the reference position.

4.3 Results:

The result in Figure 4.11 demonstrates the radar system's ability to detect human movement within a U-shaped field of view. I positioned the radar at a height of 1.4 m from the ground as shown in Figure 4.5 and scanned an area with an angular range of ±45° from its reference. The configuration of the radar allowed for a maximum detection range of 4 m.

This U-shaped detection path consisted of two vertical segments at the extremes of the angular range, as well as one horizontal section connecting these segments. The radar began scanning from the upper left position, which marks the starting point of a trajectory that is 3.93 m away from the radar. The Pythagoras theorem calculates the distance, as illustrated in detection Figure 4.11. The target was then tracked along the horizontal section until it reached the upper right position as an end point.

The proposed algorithms effectively work within the U-shaped field of view, as illustrated by the blue dotted points on the graph. Although some detections are observed outside the defined field of view, these anomalies can be attributed to noise effects or uncertainties inherent in real-time operations. The radar's optimal signal processing capabilities and the refined accuracy of the detection algorithms within this range are responsible for this enhanced performance.

The precision of the measurements observed in this trajectory path is lower in comparison to the straight-line trajectory shown in Figure 4.11. In contrast to the straight-line trajectory, I also observed some noise, potentially caused by additional clutter in the room, as well as a combination of horizontal and vertical segments. This could also have an impact on the precise identification of human motion, potentially leading to reduced accuracy. In a U-shaped trajectory, detection is also based on walking speed and curve and some clutters inside the room.

Once the detection is successful, I save the data of the object into a file in comma-separated value (CSV) format, which allows for more comprehensive analysis later. The CSV file serves as the foundation for calculating performance metrics such as mean error and root mean square error (RMSE). I establish a reference system and enhance clarity by visually representing both the measured values and the ground truth data. Initially, I obtain the data in polar coordinates, encompassing measurements of both angle and range. A data conversion algorithm transforms the polar coordinates into Cartesian coordinates. Cartesian coordinates facilitate the identification and understanding of the collected data. The conversion procedure is crucial for achieving a more comprehensive understanding and interpretation of the data collected by the radar. The results indicate that the linear trajectory approach is more effective than the U-shaped trajectory strategy, as demonstrated in Table 4.1. By adjusting the threshold value and using the DBSCAN algorithm on the point cloud data, I have successfully detected human motion within the room.

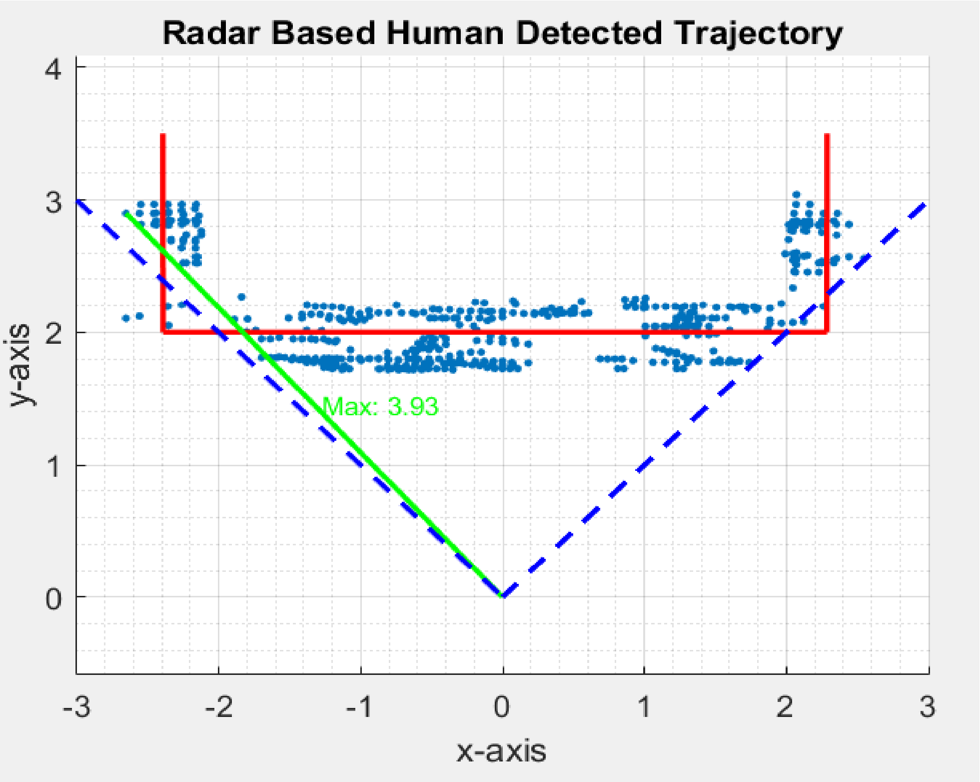


Figure 4.11: Results from the Movement Along U-Shaped Path

Table 4.1 provides a configuration and summary of the parameters. To calculate the RMSE error for both trajectories, I see that the RMSE error is higher for U-shaped trajectories because they have more sample data points than straight-line trajectories. This is due to the difference in data size between the two trajectories.

Experimental Type	Straight Line	U-Shape
Samples Per Chirps	64	64
Chirps Per Frame	32	32
Start Freq (GHz)	58	58
End Freq (GHz)	59	59
Bandwidth (GHz)	1.0	1 GHz
Max Range (meter)	4.0	4.0
Detection Range (m)	2	1.98 to 3.93
Velocity (m/s)	0.5 to 2.0	0.5 to 2.0
Threshold Sensitivity	0.0005 to 0.0012	0.0005 to 0.0012
RMSE Error	0.2012	1.2684

Table 4.1: Summary of the results

Chapter 5

Conclusion and Future Work

This thesis has emphasized the increasing importance of human motion detection using frequency-modulated continuous wave (FMCW) radar technology, notably emphasizing its multiple advantages compared to older detection approaches. This study employed a systematic strategy to improve the accuracy of detecting human movement by considering radar metrics.

Applications and Benefits

The study examined the use of the BGT60TR13C FMCW radar in different real-life situations, with a focus on its appropriateness for smart buildings, security systems, and energy conservation environments. The primary advantages of using this radar technology are as follows:

- **Room Presence Detection**: The BGT60TR13C FMCW radar is highly efficient in detecting motion and accurately estimating distance, making it a perfect choice for monitoring room occupancy.
- **Energy Conservation**: By utilizing the radar data, it is possible to automatically adjust the lighting, heating, and ventilation systems in accordance with the space's occupancy. This can lead to substantial reductions in energy use.
- **Enhanced Security:** The device enhances building security by surveilling the surroundings and detecting unauthorized individuals, hence improving overall safety measures.
- **Optimization for Real-time Scenarios:** A vital component of this study involved enhancing the radar system to achieve optimal performance in real-time scenarios. By adjusting the radar threshold values and parameters to correspond with distinct indoor conditions, I greatly improved the system's ability to detect human movement. The radar system's versatility guarantees its optimal performance in diverse environments, hence showcasing its practicality and efficacy.

Significance and Prospects for Future Research

The results of this thesis demonstrate the significant capacity of FMCW radar technology to enhance human movement detection. Effectively incorporating this technology into practical applications creates opportunities for its integration with intelligent infrastructure, fostering energy conservation and safeguarding.

In the future, it would be beneficial to do research that concentrates on enhancing the radar parameters to better suit a wider range of situations and investigating other potential uses for this technology. I anticipate significant advancements in FMCW radar technology to detect human movement, underscoring its crucial role in developing intelligent and energy-efficient systems.

Conclusion

To summarize, this thesis has shown that FMCW radar technology, namely the BGT60TR13C radar, provides a highly efficient method for detecting human movement. Applications in smart buildings, security systems, and energy conservation demonstrate the variety and potential influence of artificial intelligence. The capacity to adjust the system for maximum efficiency in different settings further emphasizes its practical worth. This research enhances the existing knowledge in this sector and establishes a foundation for future advancements and practical uses.

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