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APPLICATION OF 24 GHZ FREQUENCY MODULATED CONTINUOUS WAVE RADAR FOR DETECTION OF BURIED PEOPLE

Sao Paulo, Brazil
July, 2021

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Assignment presented to the Escola Politécnica da Universidade de São Paulo for obtaining the title of Mechatronic Engineer.

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"Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world."

-- Albert Einstein

RESUMO

Eventos naturais ou comportamentos humanos irresponsáveis causam o desabamento de edificações, desmoronamento de terras e avalanches em todo o mundo, vitimando várias pessoas anualmente. A fim de minimizar o número de vítimas, as equipes de resgate empregam diversas técnicas de busca ao seu alcance, já que com o passar das horas reduz-se drasticamente as chances de sobrevivência das vítmas. Apesar dos profundos avanços tecnológicos de diversas áreas nas últimas décadas, as técnicas utilizadas por equipes de resgate em suas buscas ainda são consideravelmente rudimentares e ineficientes, tais quais escavação manual, chamado pelas vítmas e cães farejadores. Frente a isso, o presente trabalho levanta as principais tecnologias correntes e em desenvolvimento que auxiliam essas equipes a localizar as vítimas, identificando os radares como a mais promissora delas. Dessa forma, este trabalho propõe a aplicação de uma técnica de processamento de sinal de radares de onda contínua modulada em frequência (FMCW), até então estudada para medir sinais vitais, para a detecção de pessoas através de obstáculos. Nos experimentos um radar comercial de 24 GHz é utilizado. Primeiramente, o radar é utilizado para medir sinais vitais de pessoas, os quais são comparados com os obtidos direcionando-se o radar para objetos inanimados. Por meio da definição de um fator de qualidade apropriado, os dois sinais são diferenciados. O mesmo sistema mostra-se capaz de fazer distinção entre os dois alvos após a inserção de obstáculos entre eles e o radar, quando utiliza-se dois dos três materiais de construção avaliados. Em um último experimento, mostra-se que o sistema estudado distingue também uma pessoa respirando de outra induzindo apneia, simulando um corpo sem esse sinal vital. Com vista nos resultados obtidos, são apontadas direções para pesquisas e investigações futuras.

Palavras-Chave – radar FMCW, detecção de pessoas através de obstáculos, detecção de pessoas soterradas, processamento de sinais.

ABSTRACT

Natural events and irresponsible human behaviour cause buildings to collapse, landslides and avalanches worldwide, making countless victims yearly. Trying to mitigate the human losses, first attendants employ several techniques for rescuing these victims as fast as possible, since every hour counts for increasing their chances of surviving. In spite of the huge technological advances made in the last decades, the techniques available and employed by most rescuing teams are manual and inefficient, such as manual excavation, calling for victims and search dogs. Hence, this work performs a research on a multitude of applicable technologies for finding buried people, identifying radar systems to be the most promising of them. Furthermore, it proposes the application of a signal processing strategy for FMCW radars, previously studied in the context of heartbeat and respiratory rate measurement, for the detection of people through obstacles using a commercial 24 GHz device. The device is first successfully evaluated for measuring respiratory movements without obstacles, and the results are compared to the signal obtained by targeting the radar to inanimate objects. For differentiating the two of them, a quality factor is proposed. These experiments are reproduced inserting three building materials normally found in residences between the radar and the target. The system is shown to be capable of distinguishing a person from an inanimate obstacle behind two of the three obstacle materials evaluated with statistical meaningfulness. Results also have demonstrated the capability of this system to distinguish a breathing person from someone with induced apnea, emulating a body without this vital signal. Finally, some directions for future research on the field are proposed.

Keywords – FMCW radar, frequency modulated continuous wave, through obstacle people detection, buried people detection, signal processing.

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1 INTRODUCTION

In multiple scenarios civil people may be buried by the collapse of the environment around them. This can be caused by several reasons, such as explosion in war-zones, avalanches in ski stations or by storms in precarious housing areas [1]. In spite of the intrinsic differences between those situations, a common denominator for the search and rescue (S&R) teams is time: the longer it takes to find the victims, the smaller their survival chances are.

An extensive analysis of historical data on earthquake victims performed at [2] shows that in most cases the highest survival time of victims was of up to 5 days, even if it recommends keeping the intensive search operations for twice that period. A different study [3] based on S&R operations in Oregon (U.S.A.), has identified a even more dramatic scenario. It attested that the survival rate drops exponentially during the first 18 hours after the incident, reaching negligibly low rates after 20 hours. In the case of avalanches, this maximum survival time is substantially smaller due to the hazard of asphyxia, reaching a survival rate of just 4% after 30 minutes in the review on Canadian data [4].

1.1 Technologies for supporting S&R teams

This urge for quick response and high effectiveness has lead to the proposition and evaluation of multiple strategies and technologies for improving the results of first responders looking for buried people. Bellow is a list of several devices and tactics used by civil defence agents across the world [5], [6]:

- Physical void search;
- Audible call-out;
- Canine search;

- Electro-optical (EO) and infra-red (IR) cameras mounted on aerial vehicles (manned or unmanned);
- Electronic listening device;
- Geophones;
- Electronic-device (e.g. smartphones) detection;
- Victim beacon detection;
- Ground penetrating radars (GPR);

It is important to mention that each of those search tactics and apparatus has its constitutive or operational limitations. Moreover, as there is a lack of field data on the effectiveness of each one of them, civil defense teams end up employing a combination of whatever is available, following just the best practices on team allocation [6] and the applicability of each technology in the searching environment.

Audible call-out and physical void search are traditional techniques, with extensive material on how to optimize the allocation of resources. Nevertheless, both of them suffer from one common issue: they are human intensive and reach small coverage areas. Besides that, while the former usually exposes the rescuing agents to the possibility of the collapse of the structure around them, the latter is just effective if the victim is awake and in conditions of answering strongly enough to be heard. This last detail may be improved by the usage of electronic-listening devices, but they are still considerably susceptible to environmental noise [6].

A research shows that search dogs may achieve a success rate of 76 % [7] at terrestrial operations, which is a remarkable result. Nevertheless, their training is extremely long, results vary greatly among animals and their availability is usually low. Even if their "scan speed" is much higher than the one from humans, they require considerable resting time during operations. Moreover, they cannot distinguish alive victims from dead bodies, which may mislead the focus of first attendants during operation [6].

EO and IR cameras are of great help for first responders in disaster sites, specially when associated with manned or unmanned aerial vehicles (UAV's). They enable a high coverage area, have a quick response time and can move much faster than human crews [8], [9], [10]. Recent studies have also proposed using computer vision and deep learning techniques to automatize the identification of possible victims [11], [12], and to control a fleet of UAV's to operate coordinately [13] highly improving productivity. In spite of all those advantages, they have one major issue: optical methods are limited to surface analysis, not being able to detect buried people.

One strategy that is more appropriate for this is the use of repetition S&R or avalanche radio beacons by possible victims, which can be easily detected with appropriate equipment. Similarly to their maritime use, people that believe to be exposed to burring risk (e.g. hitchhikers and skiers) may carry them to their activities. The limitation of those beacons is evident, since civil people at home are highly unlikely to acquire such high cost and specialized devices for the remote possibility of being victims of natural disasters or similar events [5].

Another technique based on a similar strategy but more versatile is the identification of signal transmitted by mobile phones. As these devices are reaching a majority of the population worldwide and are normally carried by or close to people in daily life, they can attend more cases. [14] has proposed a combination of two working principles to make this strategy accurate, one based on the time of arrival of data packages transmitted by those devices and another based on the measurement of radiated signal strength, having resolutions on the order of 50 m and 0.1 m respectively. The first disadvantage of the proposed system is that it requires turning off all the commercial antennas in the region for it to work, which might have a major impact in the overall S&R operation. Moreover, this method implies a search for phones and not to the victims themselves, which, besides being an disadvantage on its own, may lead to the identification of dead bodies removing the crew focus from victims that may still be alive.

This capability of detecting alive people requires the use of equipment that intrinsically measure vital signs from the distance, instead of simply the presence of a body or man-made objects. One such device is the geophone, which is a transceiver that converts ground motion into electric signal. A proper processing of this signal can be done to identify microscopic ground displacement induced by natural body movements, such as heartbeat and breathing [15], [5]. In spite of this strong advantage of geophones, its most noticeable drawback for such purpose is its high sensitivity to environmental noise, which may hide the signal of interest. Therefore, its usage in S&R operations requires extremely "silent" environment, which may be an unrealistic assumption about the conturbate scenarios like urban areas with vehicles and people moving nearby, besides rescuing teams themselves [5].

A new technology that have been subject of intense research on the field in the last two decades is the radar. On one hand, most of the proposed methods benefit from one major characteristic of geophones, the indirect measurement of natural body movements due to vital activities (e.g. [16], [17], [18]). On the other hand, being an active sensor (i.e. including both a transmitter and receiver for the signal of interest), it is much more flexible than all the previous methods described. As one may -ideally- generate electromagnetic (EM) waves in adjustable base frequencies and intensity, it should be possible to select the set-up which is more appropriate for each field condition.

In spite of those advantages, radar systems also have some major drawbacks to be overcome if they are to become a standard technology for rescuing teams looking for buried victims. First of all, there is a trade off between the penetration of EM waves in the ground and the signal resolution achievable with them. While the former is favoured by longer wavelengths, the latter is generally improved at higher frequencies. Moreover, the propagation of radar signal in the ground is highly dependent on its dielectric properties [18], which may strongly vary within meters at the operation site.

1.2 Objectives

Hence, the present project proposes further investigation on the applicability of radar systems to S&R of buried people. In order to push forward this research domain, the following objectives are proposed for this study:

- To make a literature review on radar technologies and signal processing schemes that correlate with the application of buried people S&R;
- To identify state-of-the art technology that may improve the results obtained by the literature so far;
- To perform proof-of-concept experiments that evaluate the applicability of the most promising technologies previously identified;
- To propose directions for further research on the field.

1.3 Document organization

In order to guide the reader through the steps done to achieve these objectives, we have started with a brief overview on the urge for quick responding in disaster scenarios as well as on manifold technologies currently available for first respondents looking for such victims. This overview has introduced the need for more suitable devices that further improve the performance of civil defense teams for saving lives after all sorts of disasters.

In Chapter 2, we make a deeper dive into multiple radar schemes used both for measuring vital signs and for identification of people through obstacles. This chapter will present a briefing of the systems proposed in the literature mostly in the last decade.

Afterwards, the reader is introduced to a state-of-the-art technique for vital signs measurement using frequency modulated continuous wave radars (FMCW) in Chapter 3. Then, Chapters 4 and 5 propose experiments and evaluate the results of such technique for the detection of people through wall, strategy that, for the best knowledge of the authors, has not been proposed so far.

In the light of the results of both experiments, Chapter 6 discusses the usage of such radar technologies on the target field. Finally, Chapter 7 presents the conclusions of this project, besides suggesting areas that require further development on the topic.

2 RADAR SYSTEMS ON DETECTION OF BURIED VICTIMS AND CORRELATED AREAS

The use of radar systems for detecting buried victims is an active field of research, and, to the best knowledge of the author, there are no commercial products that employ such technique up to this date.

As stated previously, the problem presents major nuances that make it specially challenging. One such issue is the low predictability of ground composition and properties, which heavily impacts the performance of radars [18]. For instance, the same set-up (i.e. hardware, wave-length and signal processing scheme) is unlikely to perform equally well in the case of avalanches, landslides or building collapses due to significant changes in the permeability, reflectance and noise level of the terrain. Therefore a deep understanding of the multiple systems parameters is required for choosing the best approach according to the scenario faced.

In order to maximize the coverage of technologies that can improve the work of S&R teams, in this chapter it is proposed a study of radar systems developed for three different applications.

First it is analyzed the usage of radars for monitoring vital signs, such as respiratory rate (RR) and heartbeat rate (HR), since measuring a signal requires similar techniques to identifying and classifying it. Moreover, the digital processing techniques may inspire some detection schemes, such as template matching with a reference ideal signal.

Closer from the target of this project is the detection of moving people through barriers (e.g. walls, ceilings), with major applications for military purpose. Finally, it will be reviewed the main research efforts done to this moment for detecting vital signs of people through barriers.

At the light of these analysis, directions for further investigation will be presented, which also motivates the technical studies and propositions evaluated in the following chapters.

2.1 Vital sign measurement with radars

Vital sign monitoring by radar have been under study for a few decades [19] and soon it is expected to meet the needs of the increasing home healthcare and medical markets, among others [20]. There are three main radar categories used for this purpose, notably CW Doppler, Ultra-Wide Band (UWB) and FMCW. These three sensing systems are based on the modulation of the backscattered signal by body movement, enabling measurement of heartbeat rate (HR) and respiratory rate (RR) .

Early studies in this field are based on the Doppler effect induced by cardio-respiratory movement in transmitted signal. In a study to analyze apnea overnight, it was proposed [21] a custom transceiver for a Ka-band (26.5 GHz to 40 GHz) radar, whose backscattered signal was digitized, filtered and windowed. With a proper analysis of the Fast Fourier Transform (FFT) spectrum, an accuracy with respect to a contact sensor was higher than 93%, regardless of the patient's surface facing the radar (front, back or sides) when the signal strength above a threshold. It has also been evaluated [22] the correlation between operating frequency and power, aiming in minimizing the transmitted power for achieving "sufficient" accuracy.

Apart from a pure FFT, other digital processing techniques have been based on the Doppler effect, trying to achieve better results with similar hardware set-up. An adaptive noise cancellation model based on recursive least-square algorithm was evaluated [23] and said to minimize the movements generated by different sources, e.g. the effects of respiration in the heartbeat sensed data. The use of the wavelet transform has also been proposed for the recovering of HR, technique that was shown to be moderately robust against increase of distance from the target [24]. While all those techniques depend on the windowing of the signal, which reduces resolution of HR variation, an approach based on peak-to-peak detection may not face this limitation [22].

CW Doppler systems are not the only approach for this problem, though, and present some important drawbacks such as high power consumption, little propagation through obstacles (e.g. clothes and walls) and significant noise by TX-RX leakage [25] [26]. As UWB pulsed radars perform better in such aspects, they have also been evaluated for remote vital sign monitoring tasks.

It has been proposed [27] a monitoring method based on the phase variation of transmitted pulses, which reflects small thorax displacement, through complex and arctangent demodulation of the signal. After phase measurement, the FFT response was used to identify HR and RR. For separating those two signals, a variable mode decomposition in the frequency domain has been analyzed [28], as well as an auto-correlation analysis before applying the FFT [29]. Besides this transformation based approach, convolution coding [30] has also been evaluated. UWB pulsed radars also introduce a new parameter to the system, the pulse waveform, which has been theoretically shown [31] to have little impact on the main desired signals, but significantly influence on the response of their harmonics. As, for instance, harmonics of RR are close to and of higher magnitude than expected HR signal, manifold harmonic cancellation strategies have been proposed for this problem, such as the custom harmonic canceller filter [31].

Nevertheless, the pulsed signal of UWB radars spread their power over the frequency spectrum [32], significantly reducing signal strength in the target bands. Moreover, a time analysis also shows that narrower pulses limit the power transmitted by most devices, besides increasing complexity of the required circuitry [33].

Combining the high power capacity of CW radars with the time encoding of pulsed signals, FMCW have been studied for tracking vital signs through phase analysis. This method is also intrinsically more precise than methods based on frequency modulation (e.g. Doppler) or time-of-flight signals [33]. The signal analysis through amplitude modulation over FMCW signal has been proposed [34], but [35] argues that it is much more susceptible to phase noise in the slow-time domain, besides amplifying the unwanted effects of high order harmonics. So as to separate RR and HR, the FMCW signal phase is unwrapped and demodulated, and processed by range encoding [35] or by a combination of band-pass digital filter with discrete wavelet transform [36].

The promising results of the research with FMCW systems does not come without any drawbacks, though, and special attention shall be payed to some constitutive characteristics. As well as CW radars, they present a significant crosstalk between antennas, introducing noise to the received signal [32]. Furthermore, the thermal phase noise may deteriorate the processed signal if not properly handled.

Despite the circuitry and signal nature of those three schemes, there is a common background present in all of them. After some prepossessing, there is a common signal directly correlated to thorax displacement (UWB pulsed and FMCW radars) or velocity (Doppler), from which RR and HR can be extracted. From this point on, it is worthy analysing and experimenting which strategies proposed in one work can or not be applicable to another category of radar.

Having this initial overview of how EM waves can be used to measure vital sings in a non-invasive manner, we can analyze how they are adapted to use in scenarios closer from the goal of this project, such as through-barrier people detection.

2.2 Through-barrier people movement detection

The detection of people through obstacles (e.g. walls, dry-walls, bricks) based on radars has applications that span from people counting in internal areas, to S&R and military. It can be done either through movement detection or vital-sign measurement. The first of those approaches is a less general use case for S&R teams, since it requires the victim to be awaken, but the higher amplitude of the movements may increase the signal strength, leading to a higher detection likelihood.

Among the main challenges imposed by the obstacles to the signal processing schemes are: (1) the signal attenuation, reducing SNR; (2) the multi-path effect (signal scattered from targets at different ranges are received by the antenna simultaneously); (3) the mirror effect (i.e. the RF signal behaves such that it is mostly reflected instead of scattered), reducing the signal strength received back by the transmitter; and (4) other practical issues, such as environmental EM noise or ground displacement [37].

So as to extract individuals' motion, [38] has used one a stepped frequency CW radar between 1 GHz and 2 GHz setup in order to detect range from targets with multiple antennas, which was then differentiated for removing static objects. In a different approach, [39] uses a pulsed radar with main frequency of 2.4 GHz in a multiple-output multiple-input (MIMO) configuration for bi-dimensional motion detection. The data processing in this approach is based on a high-pass infinite impulse response (IIR) filter for motion estimation and a band-pass IIR filter for noise and clutter suppression.

2.3 Through-barrier vital sign detection and measurement

Detecting people through their vital signs is a much more general strategy than through their intentional motion, since it enables rescuing teams to find both people that are unconscious and trapped without enough space to move. Nevertheless, it combines two major drawbacks, notably the difficulty in detecting small movements and the high attenuation of transmitted signal as it passes through obstacles.

Due to this attenuation problem, many researchers have been studying the use of UWB pulsed radars. Analyzing the time of flight of a random signal generated in a custom-made integrated circuit (IC), [40] detects the small body movements by observing variations in steep flanks. After removing DC components from static objects with a high-pass filter and windowing the signal, an FFT is applied to it, so that the main signal frequencies can be analyzed. As this paper is interested just in the identification of trapped victims and not in measuring their vital signs, no further processing for separating HR and RR is performed. Other publications have also followed similar strategies in the digital processing step, in spite of operating with different frequencies up to 5 GHz [41]. In [42], it was shown that, by avoiding the normal incidence angle between the transmitted wave and the wall, the signal reflected by this obstacle was reduced increasing the relative strength of the modulated waveform of interest.

A different DSP strategy [43] uses UWB pulsed signal, with center frequency of 400 MHZ, analysing the wavelet energy spectrum in different range points in order to localize a possible victims. Afterwards, the entropy associated with each range was used as a parameter for deciding if such range window was meaningful or not.

Instead of using UWB radars for achieving deep penetration across rubble obstacles, in [44] a method based on a combination of a ground-penetrating (5 GHz) and a ground-reflecting (35 GHz) CW radars is proposed. The later provides a reference signal of the pattern backscattered by the ground, which is then "subtracted" from the former to obtain the base signal to be processed for indication of a vital sign detection. In a different method for rejecting environmental clutter signal in a 1.1 GHz setup [45], the unwanted signal was analogically removed under the assumption that it was not modulated, whereas the signal backscattered by the victim was to be modulated in frequency by his/her natural body movements.

Instead of handling the clutter noise in the analog domain, in [16] an independent component analysis (ICA) of the CW 10 GHz in-phase and quadrature (I/Q) signals is proposed, separating natural body movement from obstacles and background noise. Another approach studied [46] for identifying the low-strength signal is to analyze it by splitting the data data into buckets corresponding to different range measurements, and to analyze each frequency spectrum separately. In both cases, the target would be considered detected if and only if the relative strength of the signal corresponding to a typical HR or BR spectrum is sufficiently strong.

3 BACKGROUND ON FMCW RADARS

As exposed in Section 2, recent research have proven the applicability of FMCW radars for detecting both HR and RR, which makes them good candidates for further exploitation in the field of people detection through obstacles, or, more specifically, for buried people detection.

In the present chapter the mathematical and physical foundations of FMCW radars is presented, while the following chapters concentrate on the experiments proposed based on the techniques presented here.

From the analog perspective, an FMCW radar principle is based on the comparison between a transmitted and a backscattered wave. The wave-form is first generated by a dedicated circuit, amplified and transmitted by an antenna. The received signal is first conditioned through a low-noise amplifier and then mixed, through a circuitry that may be modeled as a two-input analog multiplier, with a fraction of the signal generated for transmission. The mixed signal is then conditioned in the analog domain, digitized and further processed digitally. A representative scheme is depicted in Figure 1.

The outbound signal of radar of a (linearly-modulated) FMCW radar can be expressed as:

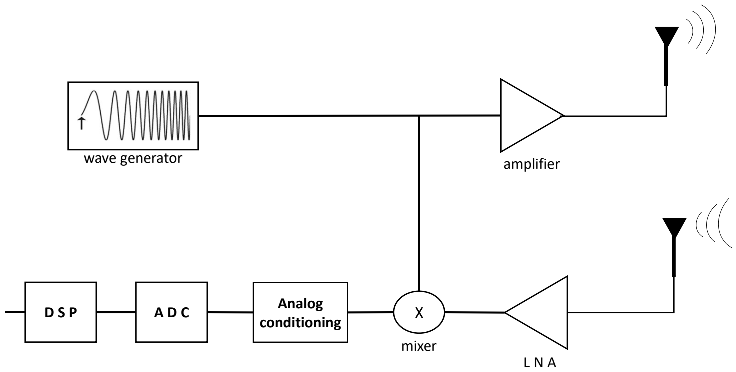


Figure 1: Overview of radar analog processing chain.

$$s(t) = cos(2\pi \cdot (f_c + \tfrac{K}{2}t) \cdot t) \tag{3.1}$$

Where f_c and K are, respectively, frequency at the beginning of a chirp period (i.e. time window corresponding to a linearly-varying transmitted signal) and the frequency slope during that respective period. Neglecting the immediate beginning and end of the chirp, the inbound signal can be inferred from Equation 3.1 as:

$$\begin{aligned} r(t) &= A \cdot s(t - t_d) \\ &= A \cdot cos\Big(2\pi\big(f_c + \tfrac{K}{2} \cdot (t - t_d)\big) \cdot (t - t_d)\Big) \end{aligned} \tag{3.2}$$

Being A the magnitude factor due to signal dispersion and absorption in its path and t_d the round trip time of the signal, which can be modeled as:

$$t_d(\tau) = \frac{2R(\tau)}{c} \tag{3.3}$$

Being c the speed of light and $R(\tau)$ the distance between the radar and the target object reflecting the signal. Take note that t_d (Equation 3.3) is a function of slow-time τ, whereas r and s are functions of fast-time t. Hereafter, the development is based on the assumption that $R(\tau)$ is constant during a certain time-frame over fast-time t.

The aforementioned mixer combines both inbound and outbound signals at time t in the analog domain, generating a new one:

$$\begin{aligned} s(t) \cdot r(t) = \frac{A}{2} \cdot \Bigg[& cos\Big[2\pi\Big(K \cdot t^2 + (2f_c - Kt_d) \cdot t - f_c t_d + \tfrac{K}{2}t_d^2\Big)\Big] \\ & + cos\Big[2\pi\Big(Kt_d \cdot t + f_c t_d - \frac{K}{2}t_d^2\Big)\Big]\Bigg] \end{aligned} \tag{3.4}$$

The constant quadratic phase terms can be neglected, since for ranges lower than several kilometers, $t_d^2 \approx 0$ (view Equation 3.3). Moreover, the analog conditioning block depicted in Figure 1 includes a low- or band-pass filter applied to the output of the mixer, so that the high frequency components does not impact the signal of interest. In practice, it removes the high frequency components, e.g. those with orders of magnitude of GHz. The result of this filtering is commonly called the intermediate-frequency (IF) signal and has a simple form:

$$IF(t) = \frac{A}{2} \cdot cos\big(2\pi(Kt_d \cdot t - f_c t_d)\big) \tag{3.5}$$

From Equation 3.5, two important observations must be made. Firstly, by combining it with Equation 3.3 one can see that the IF frequency f_{IF} has a linear correlation to the target distance, meaning that the later can easily be predicted from the former:

$$R(\tau) = \frac{c}{2K} \cdot f_{IF} \tag{3.6}$$

By making an equivalent substitution on the phase of the IF signal, one may get to a more subtle (but not less important) result:

$$\delta R(\tau) = \frac{c}{4\pi f_c} \cdot \delta\phi_{IF} \tag{3.7}$$

Equation 3.7 means that small displacements of the target δR may be detected by the phase difference between two successive chirps. Having this estimated displacement and the time interval between two measurements, one can estimate the object's speed, emulating a Doppler effect with a FMCW radar signal. It must be noted that the displacement between two slow-time instants can be unambiguously determined by means of phase analysis only if it is known to be smaller than the carrier wavelength (i.e. the wavelength of the IF signal). This condition imposes limitations for both maximum velocity and small displacement detectable.

This theory has been explored by multiple researchers and shown to be able to detect vital body movements, notably HR and BR [33], [47], [36] and [35]. This principle of operation is explored in the following chapters through some experiments in order to evaluate its applicability for detecting living people through obstacles.

4 MEASUREMENT OF VITAL SIGNS WITH MILLIMETER WAVE FMCW RADAR

Before diving into the experiments concerning the final goal of this project, in the present chapter it is evaluated the viability of measuring vital signs of people with a commercial FMCW radar operating at the 24 GHz band. On one hand, the interest for using commercial radars comes from their easy of access, improving time-to-market of techniques based on them. On the other hand, this investigation focuses on the use of the 24 GHz band, differing from most published research on vital sign measurement with FMCW, wchich are based on 76 GHz devices [47] [36] [35]. This shift in frequency dues to the higher absorption and reflection of higher frequencies in solid materials, which may make it impossible to make measurements through obstacles.

This chapter starts by describing the basic experimental setup for evaluating the detectability of living human subjects without occlusion by obstacles. Based on this common setup, the experiments performed are described alongside with the results obtained from them.

4.1 Experimental setup for vital sign recover

The goal of these first set of experiments is to distinguish the backscattered signal of a radar in the presence and in the absence of a living person in front of it. The techniques used for doing so are based on the foundations exposed in Chapter 3.

In the following experiments the person will be seated in a chair at a known distance from the radar, as illustrated in Figure 2. The radar will also be let fixed aiming directly to the person's chest. The signal is acquired for 30 seconds and stored by a PC connected to the radar and processed offline.

It is important to notice that all the experimental results presented in this report have been consistently obtained across multiple repetitions of the same experiment with four human subjects, aged between 20 and 30 years.

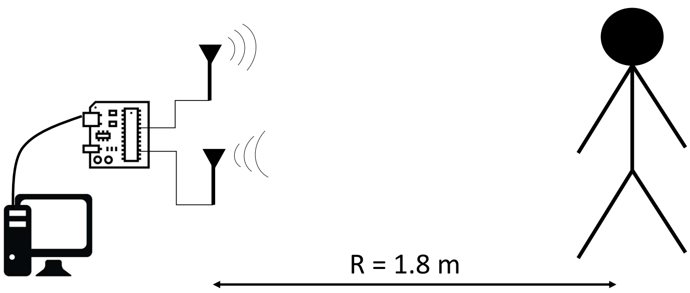


Figure 2: Experimental setup for detection of living person without obstacle.

An Omnipresence OPS243-C radar operating in FMCW mode at a base frequency of 24.05 GHz is used for this experiment. The device is powered through the computer by the same USB cable used for data. This radar includes all the analog circuitry (commonly referred to as analog front-end) and transmits the acquired ADC data for the computer, which stores it for offline processing.

4.2 Signal processing strategy

The ADC samples the IF signal at $f_{S\ ADC} = 320\ KHz$, acquiring 512 samples for a single chirp with duration of about $t_{chirp} = 1.6\ ms$. Besides that, the chirps are transmitted at an average frequency $f_{chirp} \approx 16\ Hz$.

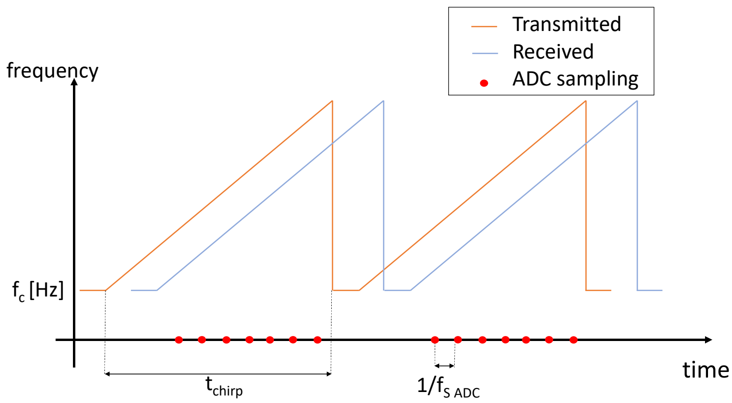


Figure 3: Illustration of sampling scheme alongside with transmitted and received signals.

According to the background presented in Chapter 3, the IF signal is expected to have the small chest displacement encoded in its phase, as shown in Equation 3.7. Hence, in order to access the temporal evolution of $\delta\phi$, the Discrete Time Fourier Transform

(DTFT) is applied, through the FFT algorithm, to each buffer (512 samples) of ADC readings performed per chirp.

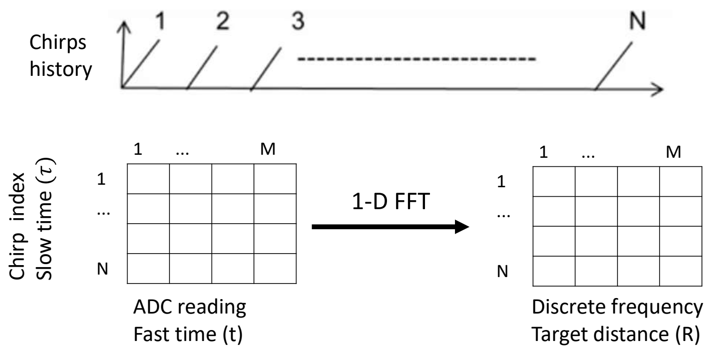


Figure 4: Overview of processing scheme used for accessing magnitude and phase of IF signal from ADC readings.

The total data set can be interpreted as an $N \times M$ matrix, being N the number of slow-time or chirp samples and M the number of fast-time samples per slow-time sample. To this matrix, the FFT is applied along each set of fast-time samples belonging to a same chirp (i.e. along each row). At the output matrix, each column corresponds to the time evolution of a frequency component of the IF signal, which is correlated to the target distance according to Equation 3.6. The amplitude of the complex representation of each frequency at a given slow-time instant corresponds to the signal strength in such frequency, whereas the complex phase corresponds to the actual phase of the signal. By analyzing the variation of this column across rows, it is evaluated the time evolution of this component either in magnitude or in phase. A visual representation of this processing scheme is presented in Figure 4.

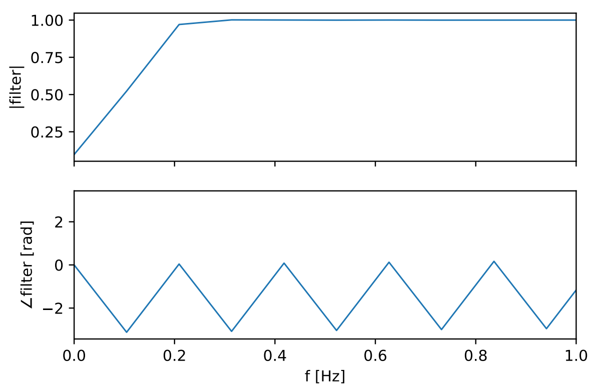
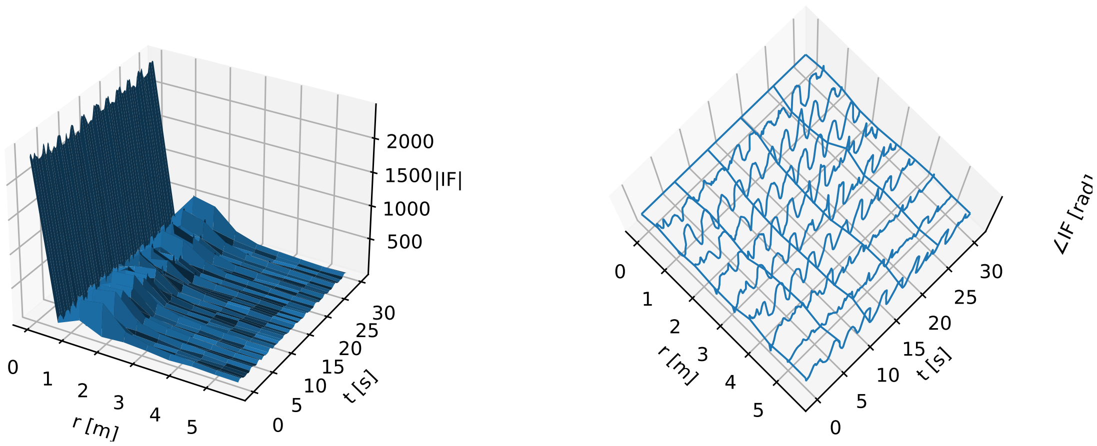


Figure 5: High-pass filter used for most data plot.

Since the proposed signal processing is applied to ADC readings -no transfer function between ADC values and magnitude of received EM wave magnitude- a major DC component was present in all signals studied. In order to prevent it from corrupting data analysis and visualization a high-pass filter to the slow-time was applied to all data other than the IF magnitude plotted, unless noted differently. This filter is FIR, has linear-phase and 91 taps and was designed with least-square minimization in the frequency domain. As depicted in Figure 5, it has an abrupt frequency response, which is needed not to corrupt the signal of interest (RR) which may start at frequencies as low as 0.2 Hz.

4.3 Respiratory rate detection

Using this strategy to process the data from the experiment introduced in Section 4.1 and illustrated in Figure 4, it was obtained the results depicted in Figure 6.



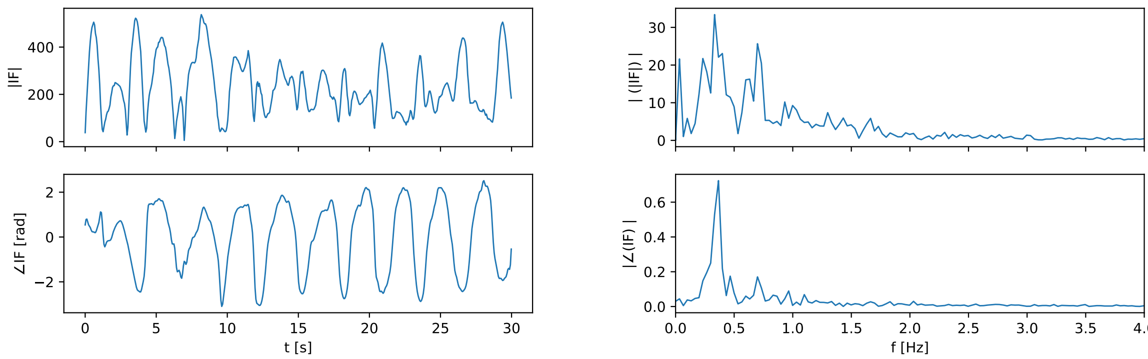
(a) Magnitude plot.

(b) Phase plot.

Figure 6: Magnitude and phase FMCW radar response while aiming directly at living human subject. DC component of magnitude plot corresponds to inherent values of ADC readings. Magnitude corresponds to IF signal strength at each the input frequency, whereas phase corresponds relative IF signal phase.

From the magnitude analysis in the frequency spectrum, depicted in Figure 6a, one may extract the signal strength of each frequency component and possibly identify objects at the observed peaks. Remind that, as shown in Equation 3.6, frequency and distance can be used interchangeably in the context of (ideal) FMCW radars due to their linear correlation. Hence, it is clear that an object was detected at about 1.8 m from the radar, which corresponds to the distance between the radar and the human subject in the experiment . The spurious peaks at DC due to edge effects of the applied digital filter, and should be neglected. Still in the magnitude plot, there is a time oscillation in range corresponding to the target, which could possibly be correlated to either RR or any other unintentional human movement. This aspect will be revisited later.

By observing the phase plot at Figure 6b, one may at first notice that there is a time oscillation, which is spread at multiple frequencies. Hence, it is not clear whether or not it could be attributed to the vital signs of the target at the known distance. So as to obtain better insights on this point, in Figure 7 it is presented both the time and frequency analysis for the time signal corresponding to the target identified through the magnitude plot.



(a) Time analysis. (b) Frequency analysis.

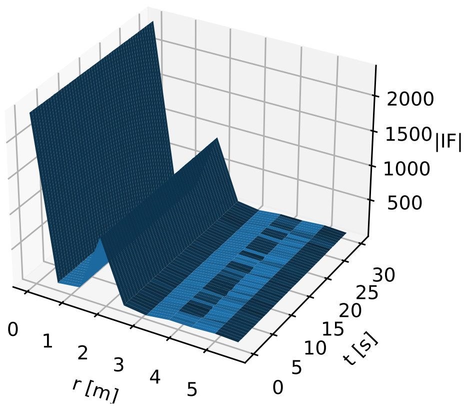
Figure 7: Magnitude and phase signal for subject's component of IF signal, plotted both in terms of time and frequency spectrum.

In Figure 7a there is a peak at 0.35 Hz, which is in the expected frequency range of healthy individuals between 0.2 Hz and 0.4 Hz [48]. Take note that the response for RR in the magnitude of the IF signal (top plots in Figures 7a and 7b) was unexpected and deserves further investigation, which is out of the scope of this project.

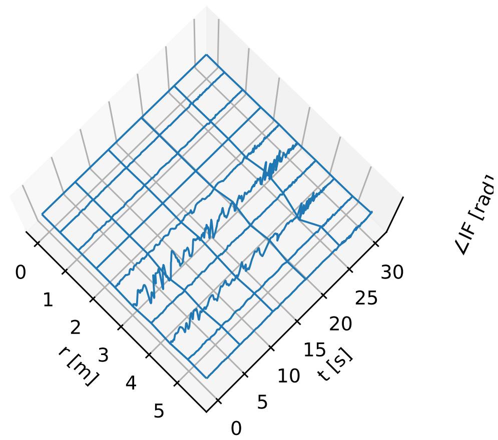
Before categorically assuming that this signals corresponds to the breathing of a person, it is important to evaluate it in the absence of someone. The first analysis done is similar to the previous experimental setup, but pointing the radar at a concrete wall instead of a person.

By comparing Figures 6 and 8 we can at first observe that the peak magnitude value remains at the plot at the 1.8 m range in both cases, but the signal at this distance range is much more stable then previously shown. Nevertheless, the value of the phase signal obtained is so low (in the order of 10^{-4} rad) it can barely be distinguished from noise. One last comment about the phase plot with the inanimate object is that some phase signal was detected close to the 3 m range, but, as the magnitude was negligibly low there (around 75 ADC points), instability of the signal make it untrustworthy.

For the sake of comparison Figure 9 depicts the slow-time frequency spectrum for IF phase signal. This plot shows a signal without clear distinction up to 0.5 Hz and considerably flat after 1.5 Hz with negligible local peaks. Besides that, it is clear that the signal is much more spread in the frequency domain in the wall experiment than in the



(a) Magnitude plot.



(b) Phase plot.

Figure 8: FMCW radar response when targeting a wall 1.8 m away. Charts from signal convoluted in slow-time with band-pass filter for better visualization.

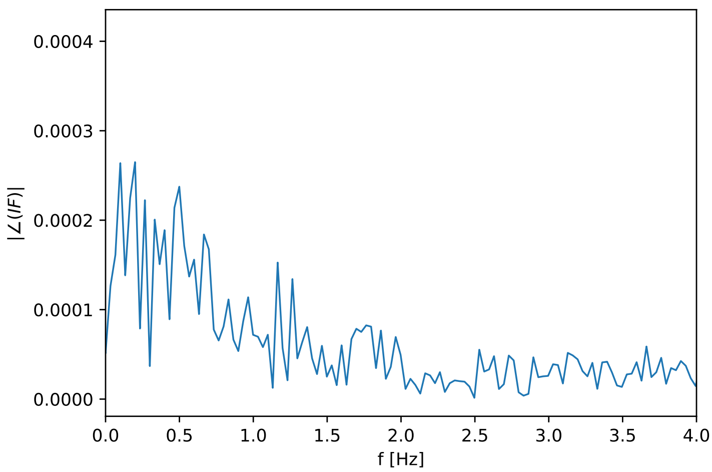


Figure 9: Slow-time spectrum of IF phase signal obtained from FMCW aiming at concrete wall.

RR one (Figure 7b).

4.4 Detection of apnea

So far we have observed that the studied signal processing technique is capable of telling apart a person from an inanimate rigid body. In spite of knowing that the peak signal frequency observed so far matches the breathing frequency range, involuntary body movements (e.g. moving upper body forward and backwards unintentionally) may also fall in the same range and could possibly be causing the signals observed in Figures 6 and 7. This issue of body motion corrupting the vital signal of interest has been pointed out in the literature [49] [50], and several strategies for reducing its impact over the signal have been proposed.

In order to both evaluate the impact of this issue in the proposed experimental setup and to verify if it is adequately measuring the respiratory rates correctly, a new test is conducted. The arrangement illustrated in Figure 2 is used again, but the human subject induces an apnea during the test for a fixed amount of time and then resumes breathing. Those two periods are continuously recorded with the radar and the results obtained are presented in Figure 10.

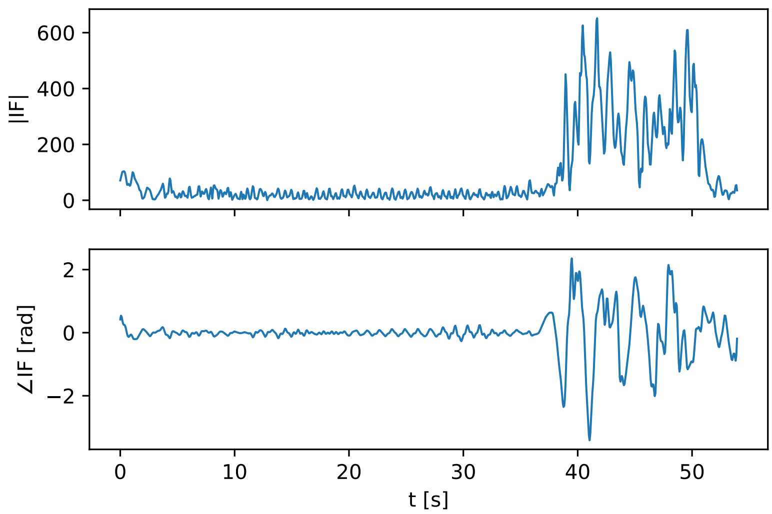


Figure 10: Slow-time IF signal of FMCW radar during apnea followed by resumed breathing of human subject. Charts from IF signal convoluted in slow-time with band-pass filter for better visualization.

Since the only difference between the first and second parts of this experiment is the breathing of the subject, we can conclude that the respiratory movement is indeed the main source of the observed signal. The two hypothesis of involuntary body movement and other radar effects being the main explanation for the signal can now be discarded, even if they may contribute as noise to the signal.

Another point that deserves attention is the presence of a small oscillatory signal during the apnea period in the phase of Figure 10. This may be either some kind of phase noise due to radar motion, or involuntary body motion, or even be correlated to heart displacement, fact that on itself has already been target of research in recent year [35]. Nevertheless, as the target of the current project is to detect people and not to accurately measure their vital signs, this issue is not further investigated.

4.5 Definition of quality factor

From the three experiments evaluated in this chapter, we were able to verify the applicability of an off-the-shelf 24 GHz radar for detecting the presence of a person through its respiratory frequency. So far this detectability was done qualitatively, through manual analysis of time series. A better approach, though, would be to have a *quality factor* for automatically identifying the detection of a person given some threshold.

As the normal range for respiratory frequency is well-known from the medical literature, this prior information can be used to build the quality factor ν:

$$\nu = \frac{\int_{\omega_{min}}^{\omega_{max}} || \angle \mathcal{F}(IF)(\omega) || \cdot d\omega}{\int_{0}^{\infty} || \angle \mathcal{F}(IF)(\omega) || \cdot d\omega} \tag{4.1}$$

Where ω is the continuous frequency, ω_{min} and ω_{max} are the limits of the frequency band considered to be of interest. Hence, Equation 4.1 is nothing but the ratio between the observed signal considered to be valid and the one obtained in the whole frequency spectrum, meaning that it must be in the range 0 to 1. As we are dealing with digital signals, this equation is implemented by its discrete equivalent in the form:

$$\nu = \frac{\sum_{\Omega_{min}}^{\Omega_{max}} || \angle DTFT(IF)(\Omega) || \cdot d\Omega}{\sum_{0}^{\infty} || \angle DTFT(IF)(\Omega) || \cdot d\Omega} \tag{4.2}$$

By applying Equation 4.2 to the data from the experiments presented in this chapter, we obtain the results from Table 1.

Table 1: Comparison of quality factor for experiments with clear view from the target. Data averaged among experiments of the same nature.

experiment	breathing	wall	apnea
ν	0.181 ± 0.046	0.081 ± 0.001	0.070 ± 0.020

By comparing the quality factors of between the experiments, we can see a significant difference according to the nature of the target.

4.6 Chapter final considerations

In this chapter the theory introduced in Chapter 3 was applied in experiments so as to recover the RR of individuals using a commercial FMCW radar. These results were compared against experiments aiming the sensor at objects whose nature differ from the target and substantial differences were observed among them.

Finally, a quality factor ν was proposed based on prior information about human breathing, and computed for all the tests conducted. This quality factor has shown to be sufficient for distinguishing between a living person and other objects.

Nevertheless, these experiments ignore the main challenge about detection of buried victims, which is to detect people through obstacles of multiple, and sometimes unknown, compositions. Approaching this point, Chapter 5 proposes a new set of experiments to identify the applicability of this experimental setup for detecting people through obstacles.

5 MILLIMETER FMCW RADAR FOR PERSON IDENTIFICATION THROUGH OBSTACLES

After validating the use of a commercial 24 GHz FMCW radar for measuring vital signs in the previous chapter, this one proposes experiments for evaluating the applicability of millimetre wave FMCW radar systems for identifying people through obstacles.

Concerning the choice of the radar base-band, there is a trade-off between penetration and resolution. On one hand, the higher the wave-length the less the EM wave penetrates through most materials, reason why devices applied to geology and mining usually operate with radars between 10 MHz and 800 MHz [32]. On the other hand, higher frequencies usually offer higher resolution, which partially explains the choices made in [47], [35] and [36] for the 76 GHz band in order to be able to monitor HR. In this sense, the 24 GHz frequency is a trade-off between penetration and resolution that, to the best of our knowledge, has not yet been reported in the literature for through-obstacle human detection.

Moreover, the purpose of using FMCW radars in the context of buried people detection is that they combine benefits from both pulsed and monotone CW radars. The former enables the measurement of both range and velocity (by round-trip time measurement), but the nature of the pulsed signal leads to a strong spread of the signal power over all the frequency spectrum, reducing the SNR. Meanwhile, the latter minimizes this spreading, simplifying the receiver's circuitry, at the expense of being unable to detect range at all [32]. By encoding the frequency, FMCW radar systems can compute the range to the target, and through the emulation of the Doppler effect both small displ acements or velocity can be determined [47].

While searching for buried people, this combination is of utter importance, since small vibrations with a certain pattern can indicate the presence of a living person, while the range to the target indicates how deep beneath the ground first attendants may have to dig.

In spite of several recent research projects being done over FMCW radars for vital-sign monitoring, to the best knowledge of the authors, no application of this kind of system has been proposed for the detection of people through obstacles.

5.1 Methodology

The goal of these experiments is to evaluate if one may use a 24 GHz FMCW radar for distinguish the backscattered signal in the presence and in the absence of a person behind some obstacle. In order to stick to the major goal of this project, the materials evaluated as obstacles correspond to those found in houses that could possibly become debris during catastrophic incidents.

A configuration similar to the presented in Section 4.1 is used, but an obstacle is introduced as depicted in Figure 11. The distance between the person and the radar $R = 1.8\ m$ is the same as used previously, as it corresponds to a possible use case of the system in a disaster scenario. The obstacle is also placed at a fixed distance $d = 0.8\ m$ from the radar, so as to standardize the tests conducted. Due to availability of materials, the depth of the obstacles is not constant, hence it is indicated in Table 2.

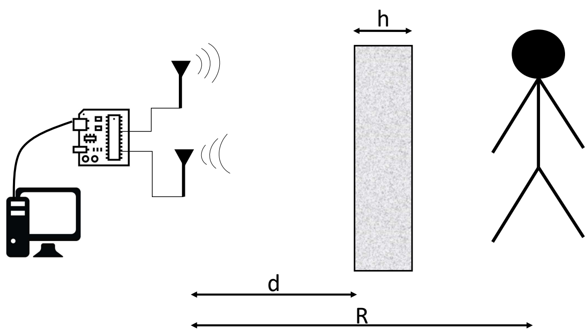


Figure 11: Layout of through-obstacle experiments.

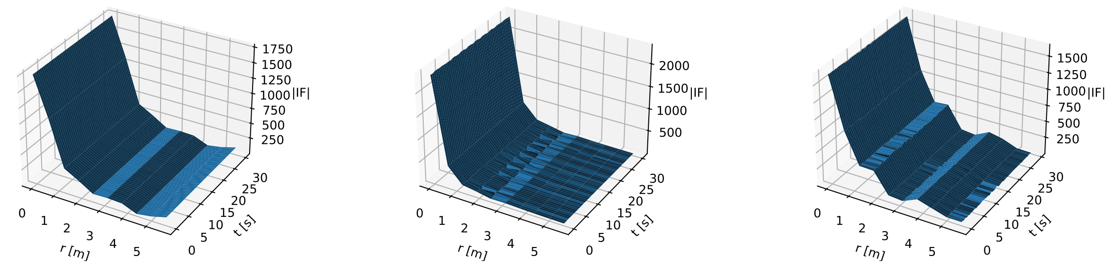
Table 2: Properties of used obstacles

material	h
wood plank	40 mm
masonry wall	150 mm
glass	8 mm

Apart from the placement, all parameters and methods are identical to what was described in 4.1.

5.2 Through wall vital sign detection

In Figures 12 to 15 the results obtained from the experiments described in Section 5.1 are presented.



(a) Masonry wall. (b) Wood plank. (c) Glass.

Figure 12: Time series of FMCW IF signal magnitude for detection of person through obstacles of different materials.

Whereas in Chapter 4 the only peak in magnitude would correspond to the exact distance to the target (human or not), when facing obstacles the signal strength presents peaks on multiple ranges, even if neglecting the DC component. A common point on these three experiments with different obstacle materials is the high absolute signal value for $r = 0.7$ m, which corresponds to the distance between the radar and the obstacle. This shows that in all three cases a expressive portion of the transmitted signal was reflected by the first obstacle, which corresponds to a potentially reduced transmission rate across it.

Another point to be observed is that the multiple peaks with respect to the range in all the experiments (e.g. $r = 3.2$ m in Figure 12a and $r = 3.9$ m in Figure 12c) correspond to other objects that were -mistakenly- believed not to interfere in the experiments. Nevertheless, this observation has demonstrated that a signal strength analyses is not enough for distinguishing living people from other objects that may be present in the scene. In fact, the wood obstacle experiment is the only one where no major peaks but the obstacle itself was found. Hence, it is important to analyze the IF phase, presented in Figure 13.

From these results, it is observable that the only experiment with a strong phase signal in the expected range ($r = 1.8$ m) is the one with the wood obstacle. In both Figures 12a and 13c some non-zero signal is visible ranges different from the prior one.

It could be argued that each material has a different refractive index ($n_{wood\ @\ 3\ GHz} = 1.2$, $n_{glass\ @\ 3\ GHz} = 1.9$, $n_{dry\ brick\ @\ 3\ GHz} = 2$ [51]) so that there would be a delay in the time of flight -remind Equation 3.6. However, the relative thickness of the obstacles is a small fraction (<5%) of the total distance traveled by the EM wave. Moreover, this hypothesis is not coherent with the different frequency/range axis where the peaks were observed across results.

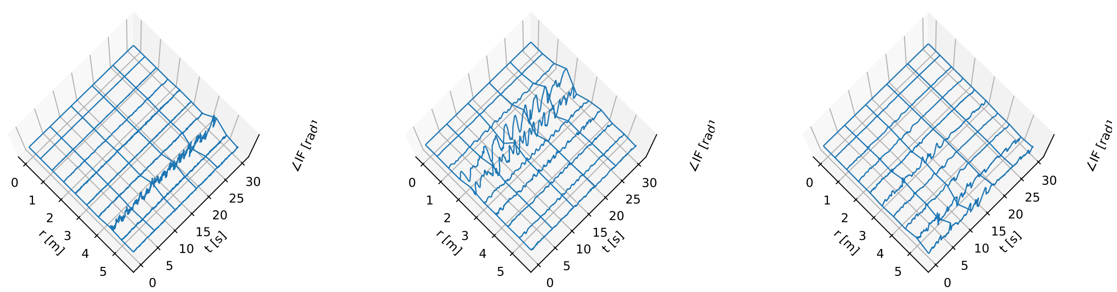
In order to better access and evaluate the results, Figure 14 depicts the frequency spectrum of the phase signals. The comparison is done between the no-obstacle experiment and the ones proposed in this chapter. When needed, frequency spectrum of the phase is evaluated both in the prior range and in the range corresponding to the greater phase signal strength.

The major positive observation from Figure 14 is that, for the wood obstacle, the frequency spectrum profile matches considerably the one obtained from the experiment without any obstacle. It indicates that a matching profile algorithm (including the previously proposed quality factor ν) is expected to accept their correspondence, leading to a correct identification of living human subject through wood obstacles.

However, it is noticeable that the whole frequency spectrum of the IF signal phase is attenuated in 6 dB after inserting an wood obstacle between radar and target, which is an unforeseen result. Due to reflection and absorption, only the IF signal strength, measured by its absolute value, was expected to be attenuated, as stated by the Friis Transmission Equation.

Differently from the results obtained with the wood obstacle, it is not as clear if we can or not detect the presence of a person behind a glass or masonry wall by simply comparing the results presented in Figures 14f and 14c to Figure 14a. A better approach is to, for each obstacle material, compare the results obtained having a person in the target position with the same experiment placing an inanimate object at the prior position.

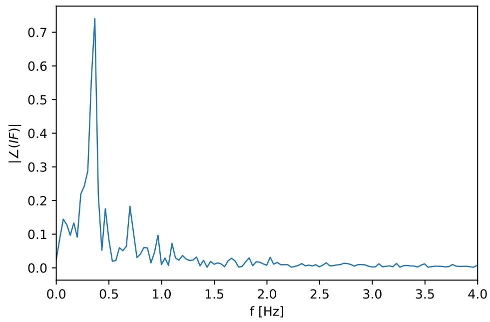
For instance, Figure 15 shows the time series of the through-glass experiment having



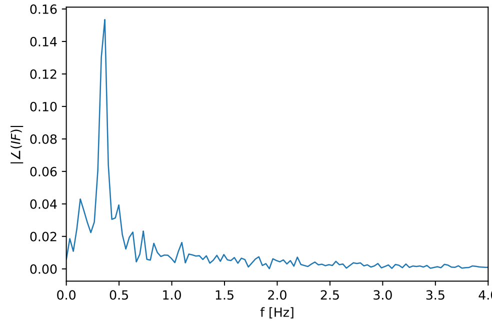
(a) Masonry wall. (b) Wood plank. (c) Glass.

Figure 13: Time series of FMCW IF signal phase for detection of person through obstacles of different materials.

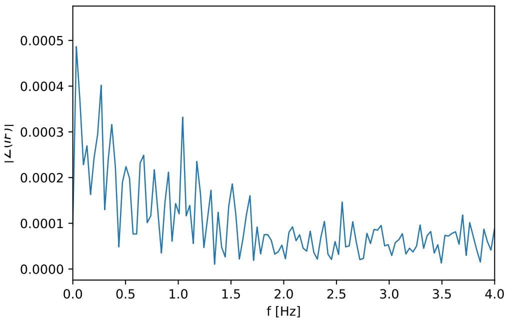
at the target position a person (Figure 15a) and a wood plank (Figure 15b).



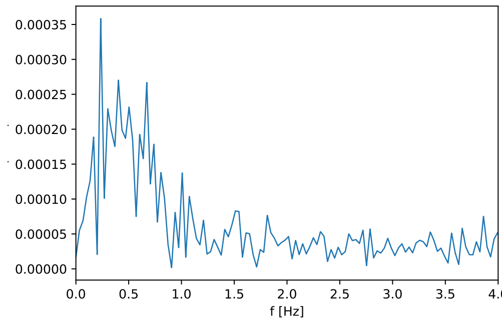
(a) No obstacle.



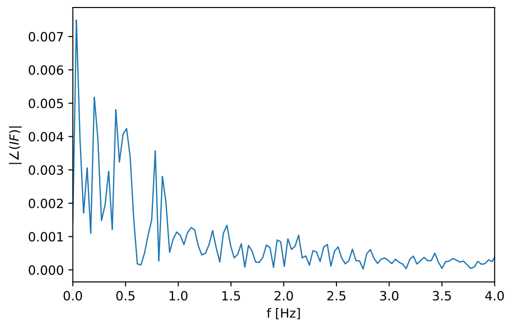
(b) Wood plate.



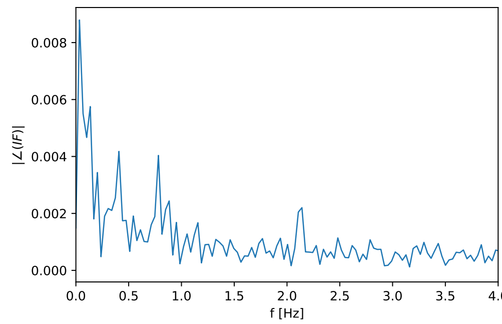
(c) Masonry wall.



(d) Masonry wall @ peak phase signal.

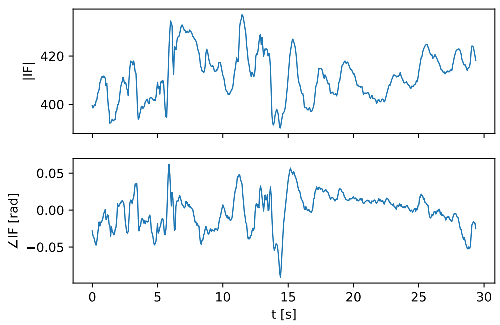


(e) Glass.

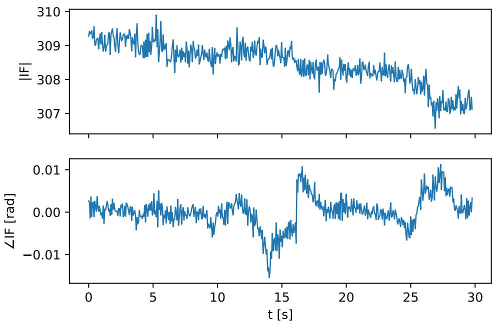


(f) Glass @ peak phase signal.

Figure 14: Frequency spectrum analysis of IF phase of FMCW radar aiming to human target through different obstacles.



(a) Person at target position.



(b) Wood plank in target position.

Figure 15: Time evolution of properties of IF signal from FMCW radar pointing at different targets through 8mm-thick glass obstacle.

Even if the amplitude of the signal at Figure 15a is orders of magnitudes smaller than one observed for the experiments without any obstacle (Figure 7a), both its time series and frequency spectrum are distinguishable from the results from an inanimate object as target. It means that, if the right metric is used for comparing the signals, a person can be identified even if its frequency spectrum profile does not match the ideal case.

5.3 Statistical analysis of experiments

For evaluating this aspect, Table 3 shows the main statistics about the quality factor ν, previously defined, over the multiple repetitions of each test. The experiments were performed either placing a person or an inanimate object at the target distance from the radar.

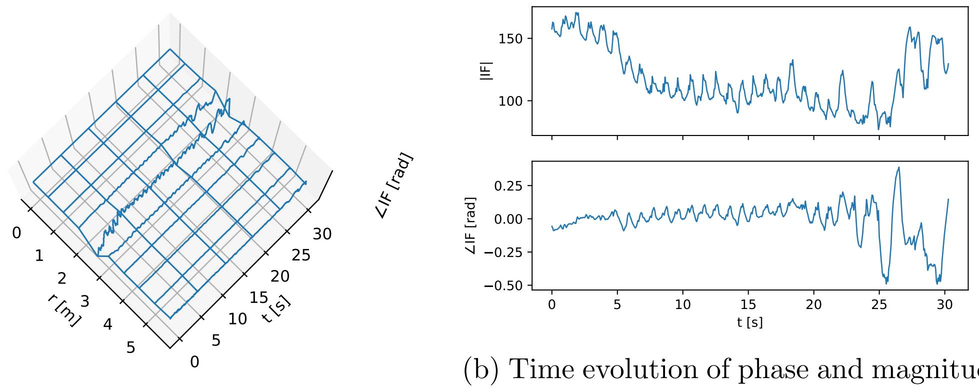
Table 3: Comparison of statistics from quality factor ν for experiments on IF phase of FMCW radar with different obstacle materials and target objects. IF signal evaluated at prior distance from target.

Obstacle	$\nu_{@\ person}$	$\nu_{@\ inanimate\ object}$
None	0.181 ± 0.046	0.054 ± 0.031
Wood	0.136 ± 0.035	0.021 ± 0.003
Masonry wall	0.056 ± 0.011	0.068 ± 0.014
Glass	0.108 ± 0.028	0.055 ± 0.014

At first, one may notice that there is a meaningful difference between the quality factor measured with and without obstacles for the human target. In spite of that, an one-tail t-test for evaluating the null hypothesis of same mean quality factor for human and inanimate object behind obstacle gives a P value of 0.02% for the wood obstacle and 3.8% for glass obstacle. In other others, the statistical likelihood that those tests represent a meaningful difference in system behaviour is 99.98% and 96.2% respectively. Nevertheless, for the evaluated setup the results obtained with masonry obstacle did not provide any result that could lead to the detection of a person behind the wall.

5.4 Apnea identification through obstacle

We notice that the statistical meaningfulness of the results are present in spite of the major attenuation of the phase signal detected by processing the IF signal. This introduces the questions of whether the evaluated signal is in fact caused by the breathing of the person or if the attenuation was capable of suppressing it. In order to evaluate it, the apnea-breathing experiment was performed again for the detection of breathing through an wood obstacle and the result is presented in Figure 16.



(a) Time-range-phase plot.

(b) Time evolution of phase and magnitude at prior distance.

Figure 16: Slow-time IF phase signal of FMCW radar pointing at human subject behind wood obstacle. Subject induces apnea and then resumes breathing during test.

In this experiment it can be seen that the phase signal has a relatively low amplitude until $t = 23\ s$, and after that the amplitude of the signal increases, besides having a change in frequency. This time instant coincides with the subject resuming its breathing. Take note that, after a long time of induced apnea, the breathing is intense and quick paced, reason for the non-uniform profile observed in the last seconds of Figure 16b.

Such a result shows that the proposed processing scheme is capable of detecting a living person behind a wall while not detecting other similar objects, such as a body without vital signs.

5.5 Chapter final considerations

In this chapter it has been presented the results from applying a novel FMCW radar signal processing strategy for detecting people through obstacles. While previous works had already proven its effectiveness for measuring vital signs of humans with sub-millimeter accuracy, we have proven its applicability in a new field.

It has been achieved by first observing that, working with the 24 GHz base frequency, the signal strength would not provide meaningful results for the task of people identification. It dues to the relatively high reflectance of building materials to the base frequency of the used radar.

Nevertheless, by analyzing the phase of the FMCW IF signal much more meaningful results were obtained. It has been shown that, in spite of the low signal strength, the previously proposed quality factor ν (that measures the relative frequency spectrum density of the IF phase in the expected human RR range) was enough to distinguish the presence from the absence of a person behind a wood and glass obstacles with statistical meaningfulness. The same results were not observed for masonry obstacle, though, which might be correlated to the frequency base-band used.

Finally, one simple experiment has shown that the proposed setup is able of distinguishing a breathing person from a body without this vital sign.

6 DISCUSSION

At the light of the experimental results presented so far, this chapter discusses the applicability and effectiveness of FMCW radars and of the proposed signal processing strategy for the detection of buried victims. It is important to take a step back from the data and to point out the strengths and limitations of the experiments performed, so that future studies can be assertive their research directions.

6.1 About the radar properties for the task

One of the most important characteristics of a radar systems is its base frequency of operation. This is the factor that dictates which materials the EM will -mostly- penetrate and by which it will -mostly- be reflected. This dues to transmittance and reflectance being material properties that significantly vary with the frequency of the EM wave, as illustrated by the classic Newton's Prisme Experiment. As a rule of thumb, the longer the wavelength, the less it penetrate in most materials, as briefly discussed in [32], [51].

When it comes to continuous-wave radars, the wavelength (inversely proportional to the frequency) has also a major effect on the information one may extract from the signal, as illustrated in Equation 3.7. In general, the smaller the wavelength, the better the resolution one might get from CW radars. This is the reason why several researchers on vital sign monitoring with radars use frequencies of 66 GHz or 77 GHz [33], [35], [36]. Without such small wavelengths, intrinsic device noise and other effects could make it significantly harder to obtain details as heartbeat from the radar signal, specially with commercial mass-produced devices, as done some in some of these cases.

Hence, there is a clear trade-off between maximum resolution and material penetration for selecting the base frequency of the radar. Whereas most of the literature on through-wall person detection studies mostly CW and UWB radars between 1 GHz and 10 GHz [38] [52] [53] [54], the present work opted for the 24 GHz band due to a few issues. In spite of the known penetration issues, 24 GHz and higher frequency systems are much easier to find in off-the-shelf devices due to their wide range of application in both industrial and automotive industries. It avoids possibly unnecessary development of custom-built hardware, possibly accelerating time to market of a possible product. Besides that, higher frequency radars normally can operate with smaller antennas -if not considering synthetic aperture radars-, making them easier to build and to embed in handheld or drone solutions for rescuing teams. Moreover, through a few academic search engines (ScienceDirect, Google Scholar and Elsevier) no publications were found evaluating the usage of above-10 GHz radars for detecting people through-obstacles, also making the experiments presented here meaningful.

6.2 About the signal processing strategy

The signal processing approach studied here has proven to be effective and to have useful properties. In Chapter 4, some literature results on vital sign detection were reproduced, whereas in Chapter 5 the results were extended to a new scenario: through-wall vital sign measurement and identification.

One important consequence of this approach that is also meaningful for first attendant teams in disaster sites is that it enables the estimation of the distance to the target. In the studied use-case, it gives the rescuing teams the information about how deep to dig to rescue someone.

As shown in Figure 13, when the IF signal strength is low the target distance can be extracted from the phase of the IF signal that best matches a RR profile. However, for strong signals the fact that the phase signal corresponding to the target's breathing may leak for multiple frequencies/ranges (see Figure 6) requires further investigation so that the range estimation can be done accurately.

Another positive observation of this project is that even for low signal strengths the detectability is still possible if an appropriate signal feature matching strategy is used. Two of the most common situations where victims may be buried are avalanches and landslides, usually caused by a combination of rain and unstable terrain. In both cases, water, with high EM absorbance, is a major component of the "obstacle" between the radar and the person. Due to the high attenuation of the wave this resilience to low signal strength can be extremely helpful.

Besides that, one comment must be made on the quality factor ν proposed for the identification of a person. Since it is based on the analysis of the Fourier spectrum of the signal, a finer resolution of its analysis is associated with a longer sampling in the time domain. This may pose a practical problem for the end users, since having to wait for thirty seconds for taking each spatial measurement in large areas may be too long when the clock is ticking for saving lives. Hence, a faster and more suitable approach for this detection also has to be investigated.

Another point that was not taken into consideration through this project that may differ in field scenarios is the noise induced by the placement and pointing of the radar. Whereas in our experiments the device was let fixed on a solid support, in the field it is expected to be either carried by people or drones searching for victims. Both of these carrying methods may introduce small displacements in the radar that have to be evaluated and eventually suppressed not to interfere on the measurements. This suppressing could be done either processing the signal (in the analog or digital domains) or using a mechanical stabilization system, such as a gyro-stabilized gimbal.

7 FINAL CONSIDERATIONS

This project has reviewed multiple technologies currently available for the detection of buried victims and has identified the most prominent research areas in the field. The study of radars for vital sign measurement and people detection through obstacles has received significant attention from the academia with promising results in the last decade. Among recent research, FMCW radars have been successfully applied for vital sign (e.g. heartbeat and breathing) monitoring.

In this project the use of a commercial 24 GHz FMCW radar was evaluated for detecting people through obstacles measuring their vital signs. For doing so, first the appropriate signal processing strategy has been reviewed. Then, some experiments on the recovery of respiratory fluctuation were successfully conducted, under the condition of the radar having a clear view from the target. For differentiating the signal corresponding to a breathing person from others, a quality factor has been proposed and verified to be able to distinguish each scenario.

Afterwards, the same vital sign recovery experiment was conducted introducing obstacles of different building materials (wood, masonry and glass) between the person and the radar. The tests have shown that, with statistical meaningfulness and using the proposed quality factor, people were successfully identified behind obstacles of wood and glass, but not behind a masonry wall. It has also been shown that the signal of a breathing person can be distinguished from the one obtained from someone inducing an apnea.

The results obtained here were promising, but there is still much research to be done before this technology is mature to start to save lives. The first point to be evaluated is the use of 10 GHz, 5 GHz and 2 GHz (or maybe even lower) base frequencies for detecting people through obstacles with FMCW radars.

Moreover, in future research the obstacles evaluated should also be more realistic with disaster scenario, including piles of debris, mud or ice, in order to evaluate the impact of reflection and absorption by multiple interfaces and materials. Concerning the target, the impact of multiple people in the field-of-view of the device and possible false-positive sources (e.g. leaking water, swinging beams, small animals, etc.) is also to be analyzed. Keeping in mind the application of these devices, it is important to evaluate new processing and feature matching strategies for identifying people with FMCW radars that allow real-time operation, as well as to identify the impact of manipulating the radar while its acquiring data.

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