Indoor Positioning and Life Detection using Asynchronous Multiple Frequency Shift Keying Radar System

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Approved by

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I, Zhenyi LIU, declare that this thesis titled, 'Indoor Positioning and Life Detection using Asynchronous Multiple Frequency Shift Keying Radar System ' and the work presented in it are my own. I confirm that:

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"Your time is limited, so don't waste it living someone else's life. Don't be trapped by dogma, which is living with the results of other people's thinking. Don't let the noise of others' opinions drown out your own inner voice. Most important have the courage to follow your heart and intuition. They somehow already know what you truly want to become. Everything else is secondary. Stay Hungry. Stay Foolish. I have always wished that for myself. And now, I wish that for you."

- Steven P. Jobs
(Commencement speech at Stanford University, June 12, 2005)

Ulsan National Institute of Science and Technology

Abstract

School of Electrical Engineering

Master of Science in Electrical Engineering

Indoor Positioning and Life Detection using Asynchronous Multiple Frequency Shift Keying Radar System

by Zhenyi LIU

Indoor positioning and life detection using radio frequency has been widely researched, however, to achieve both indoor positioning and life detection has been a very challenging task until now. By careful design of the waveform and a novel detection algorithm, asynchronous multiple frequency shift keying(A-MFSK) is proposed to solve this task for the first time in this thesis, which can operate between a multiple frequency shift keying(MFSK) mode and a single tone continuous wave(CW) mode, providing a possibility of A-MFSK for this task. Detailed explanation about the detection algorithm is given. Simulations and measurements results of both modes demonstrate that A-MFSK has the capability of indoor positioning and life detection.

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Last but not the least, I would like to thank my parents and my loved ones, during two years of studying abroad, I don't have enough time to company them, I am very thankful for their understanding, patience and support during my two years master research. I could not accomplish this without them.

Contents

List of Figures

Abbreviations

CW	**C**ontinuous **W**aveform
GPS	**G**loble **P**ositioning **S**ystem
RF	**R**adio **F**requency
LO	**L**ocal **O**scillator
HPF	**H**igh **P**ass**F**ilter
DSP	**D**igital **S**ignal **P**rocessing
FMCW	**F**requency **M**odulation **C**ontinuous **W**aveform
SFCW	**S**tepped **F**requency **C**ontinuous **W**aveform
AMFSK	**A**synchronous **M**ultiple **F**requency **S**hift **K**eying
ADC	**A**nalog to **D**igital **C**onverter
VCO	**V**oltage **C**ontrolled **O**scillator
PLL	**P**hase **l**ocked **l**oop
FFT	**F**ast **F**ourier **T**ransform
LNA	**L**ow **N**oise **A**mplifier
DDS	**D**irect **D**igital **S**ynthesizer
I/Q	**I**nphase / **Q**uadrature

Dedicated to my parents and my loved ones

Chapter 1

Introduction

1.1 Background

Indoor positioning technique was firstly raised around 1990 by Olivetti research laboratory, Cambridge, UK [1]. At that time, a badge needed to be attached to the persons and transmits IR signal every fifteen seconds, meanwhile, special sensors are needed to fix at different places in the buildings for detection. This is obviously not a good solution for indoor positioning but a good try at least, since no one wants a extra device attached to their body. As cellphones become widespread, people uses cellphones instead of badges firstly attached on the persons as an evolution of initial idea. Thus the first kind of indoor positioning technique is brought: active approach that requires a device attached to the targets and special sensors are used to receive the signals. In contrast to active approach, passive approach technique doesn't require extra devices attached to targets and that brings lots of benefits to people. Some main technologies like ultrasound, laser sensor, electric field, etc., which are used as passive approach. Both active and passive approaches has its pros and cons, active approach can provide more accurate location information of interested targets, while passive approach has lower cost and less restrictive since its device-free for targets. Different approaches are chosen depends on different applications. Current indoor positioning systems including active and passive approaches are shown in Figure 1.1.

In Figure 1.1, laser tracker, ultrasound system, RF radar and W-LAN belong to passive approach that transmit signal and received the echo signal from targets, different accuracy are listed. i-GPS, AGPS and GSM belong to active approach,

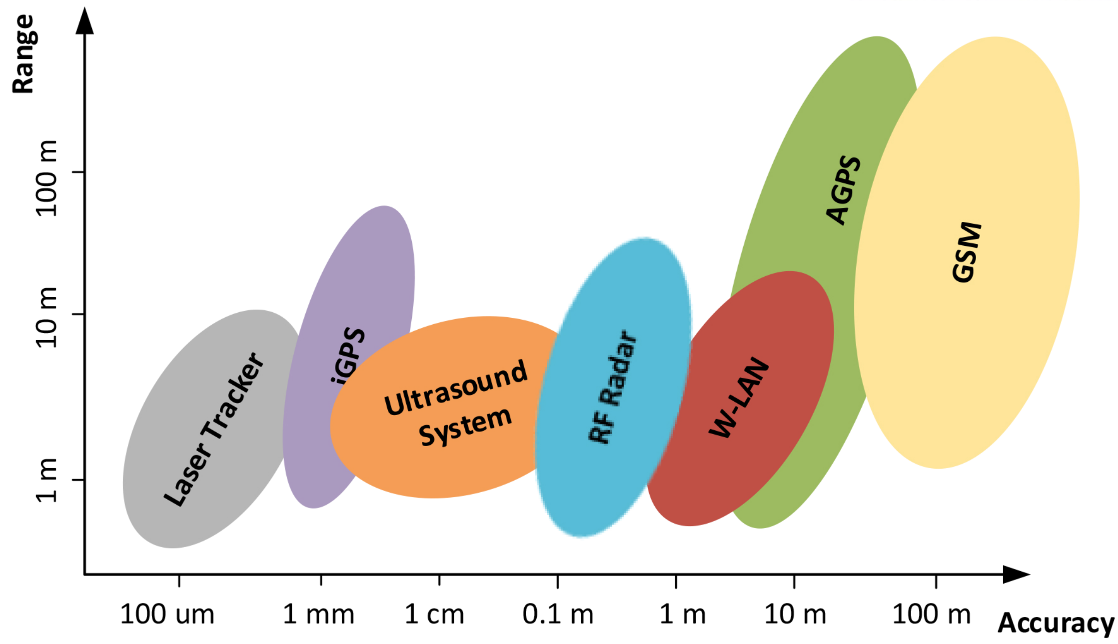


FIGURE 1.1: current positioning system

which means a device like a cellphone needs to communicate with receiver, thus location can be determined.

Life detection is fundamentally based on the vital signs. Vital signs include body temperature, blood pressure, heartbeat rate and respiration rate. In early research, sensors need to be attached to the person, thus vital signs can be collected and monitored constantly. Until now, the latest wearable device still utilizes the similar technique to collect the pulse (heartbeat) for health purpose. This is the contact approach, while the non-contact approach is also proven to be necessary in some cases. Non-contact approach is still in research stage. The mainstream technique utilizes RF radar.

As shown in the figure 1.2, in the crossing coordinate, the early stage of research are contact and active approach, like the badge or tag approach at very first, nowadays, badge-like methods are still being used, ankle bracelet GPS tracking device is used to track the persons who are released on bail but still remain as suspects. Cellphones are also used as communication devices for locating people. To get rid of the clumsy device like ankle bracelet tracking device or keep the ability of locating people even their cellphone went off or dead. Passive and non-contact approach provides the key to our requirements for remotely indoor positioning and life detection.

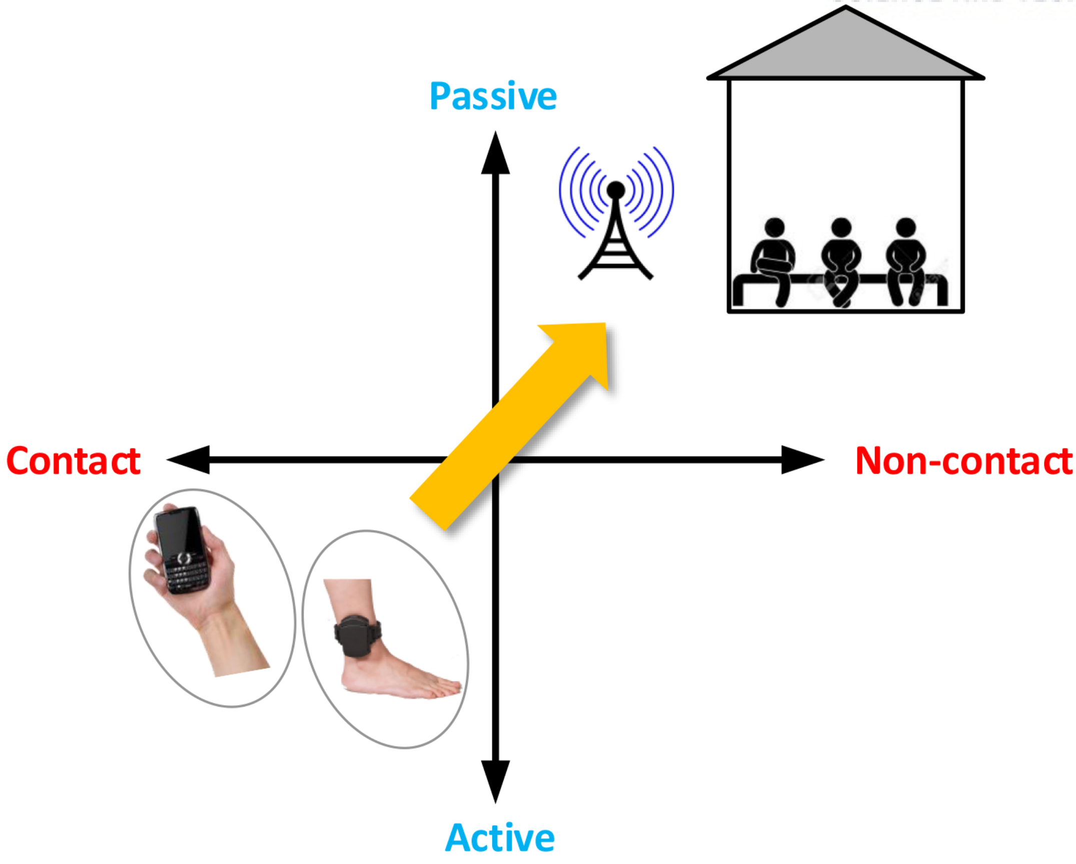


FIGURE 1.2: Crossing coordinate

Radars are among the best radio-frequency/microwave devices for remote sensing and it is categorized into two groups, long range radars and short range radars. Long range radars are usually for national defense or security purpose, and also are used as for civilian scenarios such as meteorological/weather measurement tasks and many others. Short range radars are usually compact devices that used for outdoor and indoor applications, like automotive radar for blind spot detection, auto cruise control,road traffic surveillance or industrial scenarios for multiple purposes[2][3]. Indoor application draw more attention recently, they can provide a non-contact monitor both improving our life quality at home, in the office or in the shopping malls and also like elder-care, patient monitoring, positioning and navigation, security(intruder detection), real-time health care, monitoring of sleeping infants.

Among all the indoor or outdoor application, a scenario shown in the figure1.3 is concerned in this thesis. One possible emergency scenario of a fire disaster is shown, where survivors may be stuck on different floors of the building. To rescue survivors in timely a manner, the vital signs of victims should be assessed quickly and the location of victims should be located quickly. With life detection and indoor positioning, firefighters can rescue more survivors.

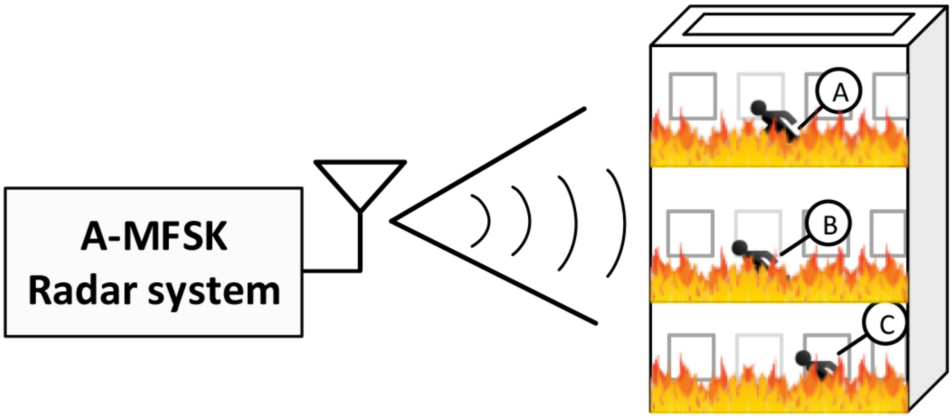


FIGURE 1.3: Possible Scenario

It is no doubt that in these indoor applications or the possible scenario mentioned above,short range radars have huge competitiveness with optical devices such as visible and infrared cameras and transducers[4]. Even though radars and cameras can complement each other, radars have some advantages over optical devices due to their intrinsic nature, which can be very useful for our purpose here, such as range measurement, small displacement detection,or through-the-wall seeing capability.

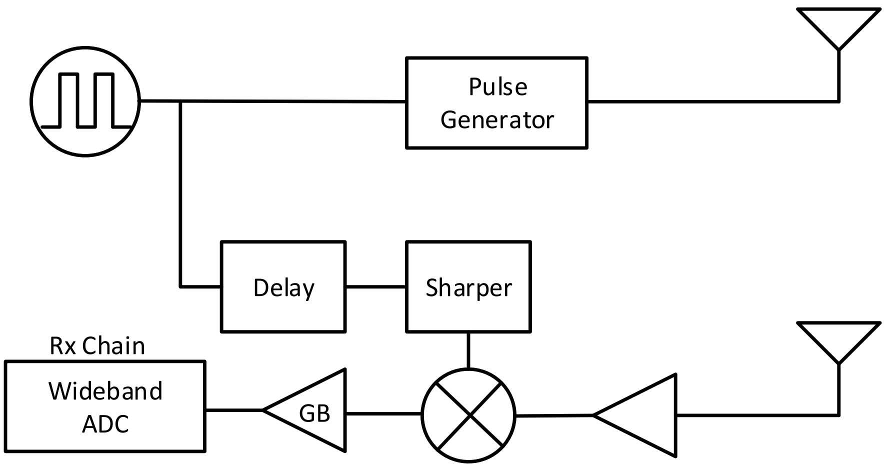


FIGURE 1.4: UWB radar structure

One example of widely used radar is given here, impulse radio ultra wide band(UWB) radars are the short pulse variants of traditional pulse radar systems as shown in figure 1.4[5]. This kind of radar transmits short range pulses, which are generated by pulse generator with a repetitive frequency. The receiver captures the signal reflected by the target and amplifies it with a low-noise-amplifier(LNA). Then a correlation between the received pulses and the delayed replica of the transmitted pulses is performed. The correlated signal is sampled by a wideband analog to digital converter(ADC). UWB radar has a very spatial resolution that enables it detect the small movements through wall[6]. Furthermore, the bandwidth of UWB radar spreads a very large spectrum range, which makes UWB radars robust to interference and the multipath effect[7]. UWB shows very promising performance on detection of small movements in human body like chest wall movement, however, utilizing an ultra wide bandwidth, requires high performance ADCs to handle the signals, thus increase the cost.

1.2 Summary

Indoor positioning and life detection is a very challenging task for current technique, different researches have been conducted and reviewed. From active and contact approach to passive and non-contact approach, more comfortable and convenient devices are developed for human, among all of them, radars are the most dominate technique that is used today, and one example of UWB radar is introduced, however due to the ultra wide bandwidth, high performance ADCs have to be used, cost increase then. In the next chapter, three main radar techniques that used for indoor positioning and life detection are reviewed.

Chapter 2

Previous Approaches

2.1 Introduction

In this chapter, three stat-of-the-art RF radar techniques will be introduced: Single tone continuous waveform radar, step frequency continuous wave radar and hybrid FMCW-interferometry radar, the common part among them is that they are all used as health monitoring. Details are given at each section.

2.2 Single tone Continuous Waveform Radar

Interferometry radar, which has been widely used in various applications such as nondestructive characterization of material and plasma diagnostics [8, 9], and it's known for its high accuracy and fast operation of displacement measurement due to the fact that the displacement is resolved within a fraction of a wavelength of the operating frequency. Optical interferometers like laser-interferometers, have been reported by previous works [10–12]. Single tone continuous waveform(CW) radar belongs to millimeter-wave interferometry. These radar devices transmits a continuous unmodulated signal with single tone and receives the echo signal returned from target. The waveform is ideal for a precise measurement of the Doppler frequency,thus the small displacement measurement is possible, detailed analysis is given as below.

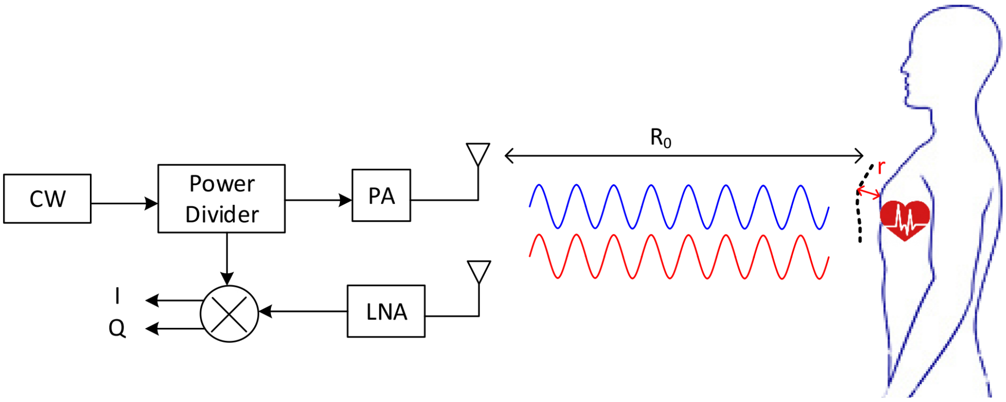


FIGURE 2.1: Interferometry radar structure

2.2.1 Detection Theory

Single tone Continuous waveform shows as below, which transmits a constant frequency of microwave, and received the echo signal with a beat frequency caused by the moving targets due to Doppler principle.

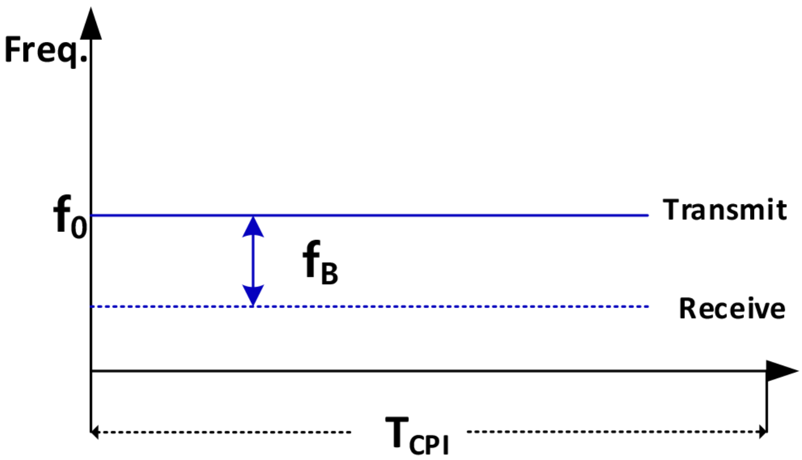


FIGURE 2.2: Single tone waveform

CW radar transmits an unmodulated signal:

$$T(t) = cos(2\pi ft + \phi(t)) \tag{2.1}$$

with operating frequency f and phase noise $\phi(t)$. The distance between human body and radar is R, and the chestwall displacement caused by respiration of heartbeat is $r(t)$. Received signal is :

$$R(t) = cos[2\pi f(t - \frac{2R_0 + 2r(t)}{c})) + \Phi(t - \frac{2R_0}{c})] \tag{2.2}$$

where c is the speed of light, the received signal will cause phase difference. After received the signal, down-converting process is applied to resolve baseband signal, the down converted complex baseband signal with beat frequency is expressed as:

$$B(t) = exp[-j2\pi(\frac{2}{\lambda}v_r t + \frac{2}{\lambda}R_0)] \tag{2.3}$$

From the equation above, f_B is shown in the baseband signal, which is proportional to the radial velocity of the moving target. However the phase of the baseband consists a constant term proportional to the target range R_0:

$$\phi = 4\pi\frac{R_0}{\lambda} \tag{2.4}$$

So the target range is not resolvable by using single tone continuous waveform. The radar device implements a homodyne quadrature architecture, and thus the two output, in-phase(I) signal and quadrature(Q) signal are extracted. There is an issue that when the LO and received signal are either in-phase or 180° out of phase the null detection point occurs. The variable part of phase is only dependent on the distance to the target R_0, the null detection point occurs with a target distance every $\lambda/4$ from the radar. If the null points remain unsolved, it will result in a poor signal and can also yield wrong measurements results. In the reported literature, a quadrature receiver is proposed to avoid these null detection points, which implements two receiver chains with LO phases 90° apart to make sure that there is always at least one output not in the null detection point [13]. As it is known that quadrature channel imbalance and dc offset issues exist in the direct conversion receivers of radar and communication systems[14]. Imbalance errors can be corrected by Gram-Schmidt procedure[15]. Whereas all dc offset is not desirable. Simplest solution for dc offsets is to remove them by using a HPF(High-pass-filter). However, several modulation methods, such as phase modulation, contains critical dc information, which must be distinguished from the unwanted signal dc offset caused by imperfection in circuit components and reflections from stationary targets. Since the dc information component coming from the target position in Doppler radar is normally several orders of magnitude larger than the amplitude of the baseband signal related to the heartbeat or respiration activities, which makes it impractical to simply digitize the full signal with reasonable resolution. The baseband signal can be shown as below,heart and respiration motion is given by x(t) and y(t),

$$B_I(t) = sin[\theta + \frac{4\pi x(t)}{\lambda} + \frac{4\pi y(t)}{\lambda} + \delta\phi(t)] \tag{2.5}$$

$$B_Q(t) = cos[\theta + \frac{4\pi x(t)}{\lambda} + \frac{4\pi y(t)}{\lambda} + \delta\phi(t)] \tag{2.6}$$

Assuming that the x(t) is much smaller than $\lambda/4\pi$, due to the small angle approximation, and they can be simplified as sinusoidal waves of frequency f_1 and f_2 with θ, and integer multiple of π, then the Q channel signal can be expanded as below:

$$\begin{aligned} B_Q(t) = 1 - \frac{1}{2}[(A^2 + B^2) - A^2 cos4\pi f_1 t - B^2 cos4\pi f_2 t - \\ 2AB(cos2\pi(f_1 + f_2)t - cos2\pi(f_1 - f_2)t) + \\ 2\delta\pi(t)(2Asin2\pi f_1 t + 2Bsin2\pi f_2 t + \delta\pi(t))] \end{aligned} \tag{2.7}$$

As we can see in the equation, there is a significant dc component output, and the output is no longer proportional to displacement. The squared terms result in signal distortion either by doubling the signal frequency or by mixing the heart and respiration rates, while the linear terms are multiplied by the residual phase noise, thus degrading the SNR. So dc offset compensation techniques needs to be implemented and dc offset needs to be removed for the further calculation.

The two output channels of a quadrature receiver shows as below,

$$B_I(t) = sin(\frac{4\pi r}{\lambda} + \theta) + DC_I \tag{2.8}$$

$$B_Q(t) = cos(\frac{4\pi r}{\lambda} + \theta) + DC_Q \tag{2.9}$$

where $\phi = 4\pi R_0/\lambda$ represents the constant phase caused by original distance between target and radar, it will remain unchanged during the displacement measurement, λ is wavelength of operating frequency, DC_I and DC_Q are the dc levels of the I/Q channel respectively. before arctangent demodulation is performed, the dc off set has to be removed from the I/Q signal. From equation 2.8 and 2.9, the outputs of I and Q signals both contain a constant phase delay caused by the original distance between target and radar. By applying the arctangent operation to the I/Q signals, accurate phase demodulation can always be obtained regardless of the target's position[16].

The displacement can be resolved by arctangent demodulation:

$$r = \arctan\left(\frac{B_I(t) - DC_I}{B_Q(t) - DC_Q}\right) \cdot \frac{\lambda}{4\pi} \tag{2.10}$$

which relates to the detected phase and wavelength of operating frequency. It can be seen from equation 2.10 that the phase change is proportional to r/λ. It means higher frequency results in high sensitivity of a small movement measurement.

2.2.2 Discussion

As the interest in wireless health care increases in the microwave community, researchers have contributed to other advancements in biomedical interferometry radar system. For instance, the phase cancellation by range correlation in conventional interferometry radars with a free running oscillator is degraded as the range to the target increases, but an inject locking radar system front end can partially resolve the issue [17]. Injection-locking radar system show advantages in anti-clutter and anti-interference. When used to monitor human vital signals, injection-locking radars can be implemented so as to effectively cancel random body movement and improve accuracy.

Even though radar provides high resolution of displacement measurement and speed measurement, however, due to its periodical phase proportional to range R and single frequency, there is no range resolution, which means multi-targets can not be resolved. CW radar provides high accuracy for vital signs monitoring but highly ambiguous for location measurement. These waveform is suitable for the kind of application that needs the human target located at a certain known place and continuously monitor the vital signs. But it is not suitable for the application for rescuing, which the target location is requisite.

2.3 Step frequency Continuous Waveform Radar system

A contactless health-monitoring system is proposed enabling fall detection and tagless localization [18], which is using step frequency as fig.2.3. Unlike the conventional step frequency, in this case, the waveform consists of a single tone, $f_{ISM} = 5.8GHz$ at ISM band, alternated with a stepped frequency CW(SFCW) waveform with 40 steps(bursts) working in the UWB band. Stepped frequency generates a synthetic ultra wide bandwidth. Each tone lasts 1 s and is used to continuously detect the speed of a person using Doppler effect, whereas the SFCW is used to detect the location of target's absolute distance. SFCW consists of 40 steps of constant CW pulses, the offset from pulse by pulse is 25 MHz. Each pulse is T=50 μs, resulting in a burst duration of 2 ms, total band is 1 GHz, positioned from 6 GHz to 7GHz, enabling a smallest resolution of 15 cm. The reason why a single tone is inserted before a SFCW are: 1, SFCW has a drawback of detecting the target velocity(will be addressed in the later part); 2, Due to Doppler effect, single tone continuous waveform shows great results on velocity detection. T_{CPI} is set to 1.002s.

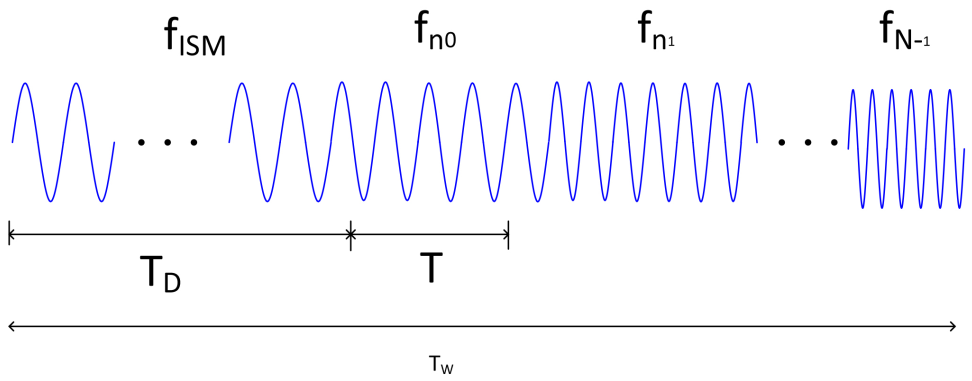


FIGURE 2.3: Step frequency waveform

2.3.1 Detection theory

Initial amplitudes is not considered, the transmitted signal is written as

$$T_s(t) = cos[2\pi f_{ISM} t + \phi_{ISM}(t)] \quad (0 \leq t \leq T_D) \tag{2.11}$$

$$T_{SFCW}(t) = cos[2\pi(f_0 + n\Delta f)t + \phi(t)] \quad (T_D < t \leq T_W) \tag{2.12}$$

Where $0 \leq n < N$, target is located at a distance R away, the received signal is expressed as below:

$$R_s(t) = cos[2\pi f_{ISM}(t - \frac{2R}{c}) + \phi_{ISM}(t - \frac{2R}{c})] \tag{2.13}$$

and

$$R_{SFCW}(t) = cos[2\pi(f_0 + n\Delta f)(t - \frac{2R}{c}) + \phi_n(t - \frac{2R}{c})] \tag{2.14}$$

After go through the I/Q mixer, the output can be modeled as the product of the received signal with a copy of the transmitted signal. And it is given as, with a quadrature sampling:

$$e^{-j\phi_i} = I(t) + jQ(t) \tag{2.15}$$

where,in case of single tone,

$$\phi_i = \phi_s = 2\pi f_{ISM}\frac{2R}{c} + \Theta_{ISM} + \Delta\phi_{ISM}(t) \tag{2.16}$$

in the case of Stepped frequency,

$$\phi_i = \phi_s = 2\pi(f_0 + n\Delta f)\frac{2R_n}{c} + \theta_n + \Delta\phi_n(t) \tag{2.17}$$

where

$$\Delta\phi(t) = \phi(t) - \phi(t - \frac{2R}{c}) \tag{2.18}$$

is the residual phase noise. θ is the additional phase difference between the mixer and the antenna. when the target is moving, the rang equals:

$$R = R_{ISM} + v(t)t \quad (0 \leq t \leq T_D) \tag{2.19}$$

$$R_n = R_0 + v(t_n)nT \quad (T_D < t \leq T_W) \tag{2.20}$$

R_{ISM} defines the range to target at time $t = 0$,while R_0 defines the range to target at time $t = T_D$. Apply the range of moving target to the phase of 2.10 and 2.11,

$$\phi_s = 2\pi f ISM \frac{2R_{ISM}}{c} + 2\pi \frac{2f_{ISM}v(t)}{c} t + \theta_{ISM} \tag{2.21}$$

and

$$\phi_n = \frac{4\pi f_0 R_0}{c} + 2\pi \frac{\Delta f}{T} \frac{2R_0}{c} nT + 2\pi \frac{2v(t_n f_0)}{c} nT + 2\pi \frac{2v(t_n n\Delta f)}{c} nT + \theta_n \tag{2.22}$$

In the equation 2.22, when detecting stationary targets, only first two terms are valid. As the second terms implies, the range resolution is divided by n, so it provides a good range resolution. However, the third term represents frequency shift due to the motion of the target, the DSP processor will mistake the frequency step as a Doppler frequency shift due to the velocity caused by range. The fourth term of equation represents the changes in the frequency of each pulse with the targets motion, thus causing the frequency spread over the dwell, which results in some negative effects, including loss of range resolution, range accuracy and signal to noise ratio.

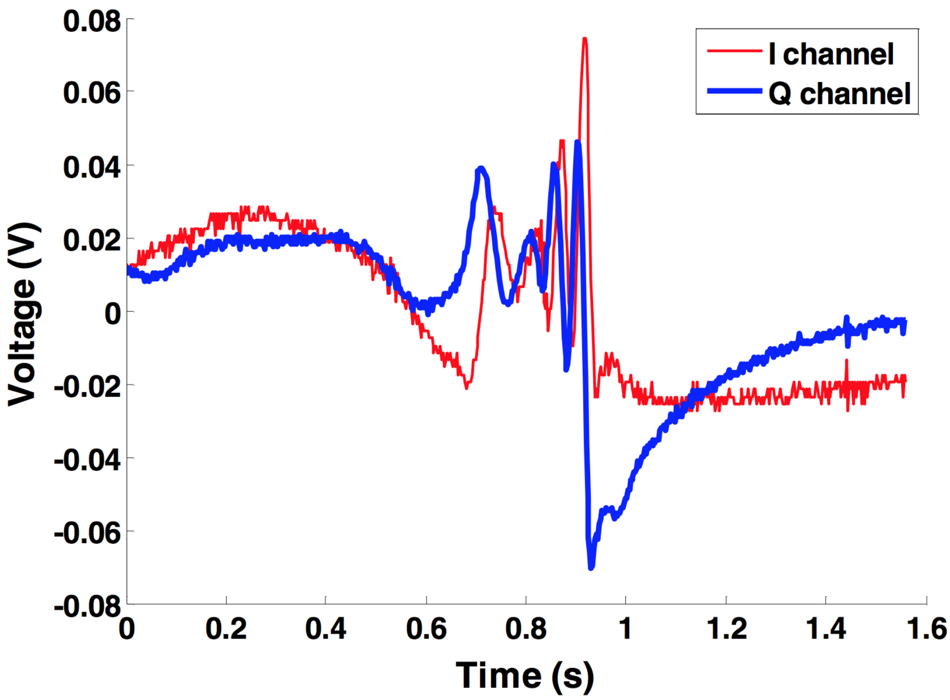


FIGURE 2.4: Fall event

The key to distinguish between normal movement and a fall relies on the different speed changes. During a fall, the speed continuously increase until a sudden stop, whereas during a normal walk or a movement, the Doppler signals experiences a controlled movement. More precisely, during a walk, the speed remains constant over time. As shown in the figure 2.4 and 2.5, during a walking and a fall movement, corresponding I/Q signals are shown, respectively. The frequency of the signal is proportional to the velocity of the person during the movement. Thus, the different pattern of movement can be distinguished.

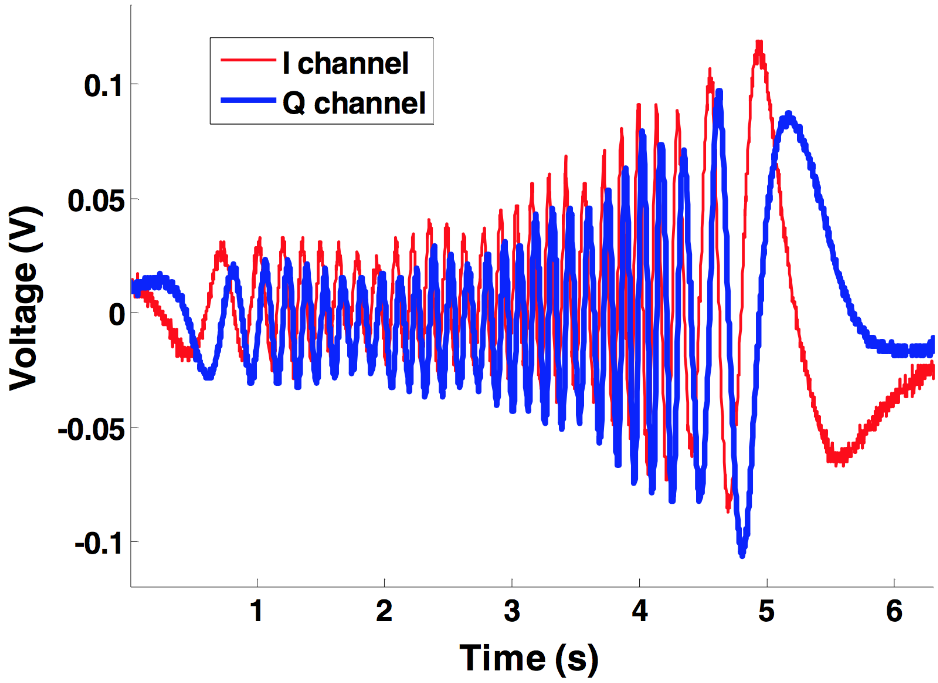


Figure 2.5: normal movement

2.3.2 Discussion

As implies as aforementioned, the stepped frequency is able to locate the multi-targets, and by carefully design, it can detect the fall event, the key relies on the different changes in a speed experienced during a fall or a normal movement.Since during a fall, the speed will continuously increase until an abruptly stops. This waveform have a improvement compared with CW radar and ultra wide band radar, but it still has a distance from our requirements of indoor positioning and life detection because it can not resolve the monitoring of vital signs. And the moving target will bring Doppler error to the results.

2.4 Hybrid FMCW-interferometry

Different approaches and different waveform are tried in researches, in this part a Hybrid FMCW-interferometry Radar is introduced. The waveform is shown as fig.2.6. The radar system is operating in the 5.8 GHz ISM band with a 160 MHz bandwidth, the system combined two kinds of waveform: Frequency Modulation Continuous Waveform(FMCW) and Interferometry Radar. FMCW radar is used to locate human, Interferometry radar is used to vital sign detection[19].

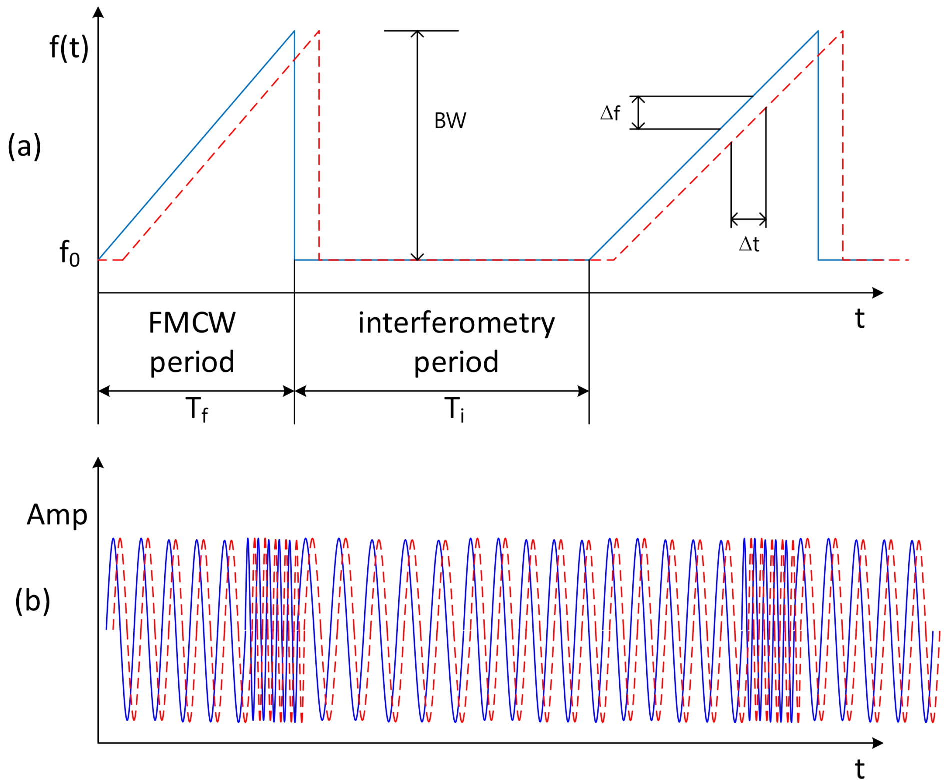


FIGURE 2.6: Hybrid FMCW-interferometry radar waveform

2.4.1 Detection theory

As shown in Figure 2.6, the initial phase of the transmitted signal for each time interval is properly controlled by the radar. Moreover, if there are no phase mismatches at the Rx stage, the coherence of the over- all system is guaranteed [62]. This phase maintenance allows for obtaining the phase/Doppler history of the illuminated target during the so-called coherent processing interval(CPI), which can encompass thousands of waveform periods. This important feature is attained in the radar prototype to be presented here through the sharing of clocks at the transmission and acquisition stages.

The one chirp transmitted complex signal can be expressed as:

$$S_T(t) = exp(j(2\pi f_c t + \pi\gamma t^2 + \phi)) \tag{2.23}$$

where $\gamma = BW/T_f$ is the chirp rate. Then the received signal is obtained after the round-trip time of flight. The distance between radar and target is assumed as R_τ,and it will remain constant during one chirp period since T_f is very short compared with the target movement speed. The Received signal can be expressed as:

$$S_R(t) = \delta S_T(t - \frac{2R_\tau}{c}) \tag{2.24}$$

where δ is the amplitude of the received signal normalized to the transmitted signal. The mixing of a replica of the transmitted signal with the received one is known as de-chirping, and results in the beat signal that can be expressed as:

$$S_b(t) = S_{T(t)} \times S_R^*(t) = \delta exp(j(f_b t + p_b + \phi)) \tag{2.25}$$

$$f_b = \frac{2\gamma R_\tau}{c} \tag{2.26}$$

$$p_b = \frac{2\pi R_\tau}{c} \tag{2.27}$$

where f_b is the beat frequency that is proportional to the distance information, p_b is the phase history, and ϕ is the residual phase. With beat frequency, the location information can be estimated.However, because of the limited bandwidth, FMCW only can not meet the requirement of vital signs(Respiration and heartbeat) monitoring. Thus, the interferometry radar is combined with FMCW to solve the vital signs monitoring.The detection theory of interferometry radar is presented at section 2.21.

2.4.2 Discussion

A hybrid radar that integrates the FMCW mode and interferometry mode is introduced, FMCW mode is used to resolve the target location, interferometry mode is used to resolve the small displacement. The advantages of two kind of waveform is made fully used of. Through this design, both indoor positioning and life detection is achieved by using two kinds of waveform: FMCW and Single tone CW. However, this will increase the complexity of system and processing speed.

2.5 Summary

In this chapter, three waveform are introduced briefly, detection theory of each is given to have deeper analysis of each pros and cons. Single tone CW provides highly accurate small displacements measurement which can be used to detect the heartbeat and chest wall movement. However, due to the limitation of waveform, target range is not detectable. SFCW inserts a single tone at its head, thus, highly velocity estimation can be achieved by Doppler principle, however, there is still need relatively higher bandwidth even though with a low instantaneous bandwidth, and the velocity detection error of SFCW is still remained. At last, a hybrid waveform is introduced, which takes advantages of two kinds of waveform, but with two kinds of waveform, circuit complexity and DSP processing speed is unsatisfactory. In next chapter, with the addressed drawbacks, to overcome these problems, a novel radar system that can meet the strict requirement of both indoor positioning and life detection is proposed and introduced.

Chapter 3

Proposed approach

3.1 Introduction

In last chapter, three common waveform are introduced, single tone continuous waveform can only detect the small displacement, range resolution is ambiguous, step frequency provides target location but high accuracy life detection uses ultra wide bandwidth which increases the cost and complexity of system, whereas the hybrid FMCW and interferometry radar has to use two kinds of waveform which increase the difficulty of radar system. Respect of different drawbacks, they still can not solve indoor positioning and life detection perfectly. Thus, in this chapter, a novel waveform with a specially designed algorithms is proposed for resolve the task of both indoor positioning and life detection and rigorous analysis will be given.

3.2 Proposed Waveform and Detection theory

3.2.1 Proposed Approach

As it is aforementioned in chapter 2.1, interferometry radar, i.e., single tone continuous wave(CW) radar is used to monitor small displacements, as it has very high resolution due to the fact that the displacement is resolved using the differences in the phases of the received waves, which is within a fraction of a wavelength of the operating frequency. Life detection is based on the small displacements of the chest wall caused by respiration and heart beat, which can be precisely detected by CW radar system.

MFSK transmits a variation of FSK that uses more than two frequencies, and M represents multiple levels. In contrast to FMCW, MFSK provides unambiguous range and velocity information simultaneously even in multi-target situations without any ghost targets [20]. By comparing the ambiguity function between FMCW and MFSK, it is noticeable that MFSK suffers from less clutter interference due to the stepped frequency used by MFSK[21].

As shown in figure.2, the proposed waveform of asynchronous multiple frequency shift keying is depicted. To meet the requirements of indoor positioning and life detection, Asynchronous MFSK(A-MFSK) waveform is proposed. A-MFSK can be modeled as a MFSK and a CW. Detailed analysis is given below.

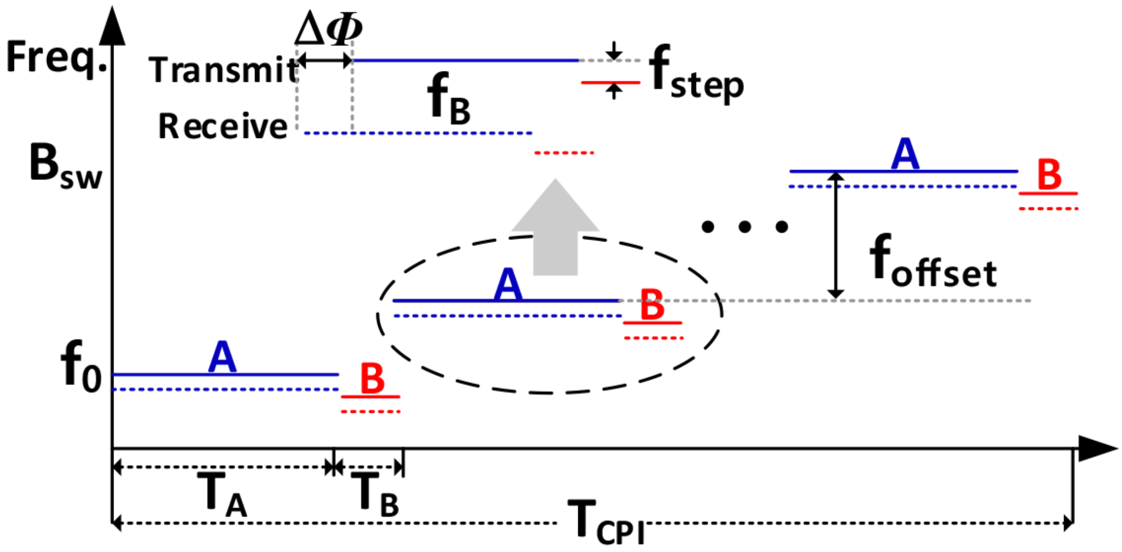


FIGURE 3.1: AMFSK waveform

The n^{th}received signal of A-MFSK can be modeled as a two-step signal:

$$Step_A(t) = cos2\pi(f_0 + (n-1)\cdot f_{offset})\cdot(t - \frac{2R}{c}) \quad (3.1)$$

$$Step_B(t) = cos2\pi(f_0 - f_{step} + (n-1)\cdot f_{offset})\cdot(t - \frac{2R}{c}) \quad (3.2)$$

For step A, $t \leq T_A$, and step B $T_A \leq t \leq T_B$. Steps A and Steps B are transmitted with a f_{step} difference, then they are shifted by f_{offset} from level by level $n-1$ times, n ranges from 1 to 16. Range R can be written as $R_0 + V \cdot (n-1) \cdot (T_A + T_B)$ in the moving targets situations, R_0 denotes original range. c denotes the speed of light. When A-MFSK operates in MFSK mode, both steps A and B are used to resolve range and velocity information. Dechirping process or deramping is implemented since the AMFSK follows the same pattern of LFMCW as a chirp frequency modulation as it is seen from the whole period. Dechirping process directly reference the received the signal, high frequency of transmitted signal and received signal mix with each other, then a low frequency baseband signal is obtained. Dechirping process can simplify the ADC architecture, which provides a significant relaxation of the hardware complexity for the entire AMFSK architecture and drastically diminishes its cost. Named as beat frequency f_B and phase difference $\Delta\phi$ are written using received signals [20],

$$f_B = -\frac{2}{\lambda} \cdot V - \frac{2}{c} \cdot \frac{B_{sw}}{T_{CPI}} \cdot R_0 \tag{3.3}$$

$$\Delta\phi = 2\pi((T_A + T_B) \cdot \frac{2}{\lambda} \cdot V - f_{step} \cdot \frac{2}{c} \cdot R_0) \tag{3.4}$$

f_B depends on both range R_0 and velocity V. λ is the wavelength of operating frequency. Operating frequency is chosen as 24.05 GHz. B_{sw} denotes sweep bandwidth, 200 MHz bandwidth is used in this design. With the equations (3.3) and (3.4), the only unknown items, range R_0 and velocity V, can be resolved simultaneously as below(3.5)(3.6). The maximum range for MFSK can reach 150m when $2R/c < 1ms$. 75 cm range resolution and 7.8 cm/s velocity resolution can be achieved.

$$R_0 = -\frac{c \times \Delta\phi}{4\pi f_{offset}} - vnT \tag{3.5}$$

$$v = \frac{f_{sweep} c \Delta\phi}{4\pi f_{offset}} - \frac{c f_B}{2} \tag{3.6}$$

If only step A is processed through the processor, within T_A, A-MFSK can be modeled as a single tone CW with a period of T_A, and the operating frequency uses $f_0+(n-1)\cdot f_{offset}$. It needs to be mentioned that strict clock synchronization between transmitter, receiver and processor is essential. The normalized baseband signal in I/Q channels can be represented as below [22],

$$B_I(t) = sin(\frac{4\pi r}{\lambda} + \theta) + DC_I \tag{3.7}$$

$$B_Q(t) = cos(\frac{4\pi r}{\lambda} + \theta) + DC_Q \tag{3.8}$$

where $\theta = 4\pi R_0/\lambda$, once original range R_0 for CW mode is obtained from the process of MFSK mode, it will remain constant during process of CW mode, thus θ remains unchanged for calculation. Circuit phase noise is not considered here. DC_I and DC_Q are the dc levels of the I/Q channels. Arctangent demodulation is employed to resolve the displacement because it is robust to null point detection issues[16]. Phase demodulation is needed to recover the phase. Thus the displacement r is:

$$r = \arctan\left(\frac{B_I(t) - DC_I}{B_Q(t) - DC_Q}\right) \cdot \frac{\lambda}{4\pi} \tag{3.9}$$

which relates to the measured phase and wavelength of operating frequency. Since the operating frequency is increasing from level by level, it only will result in higher sensitivity of phase detection, which means a small movement can cause a significant phase change that can be easily measured. The periodically phase changed between [-π,π] requires a phase unwrapping process to rebuild the actual displacement when displacement exceeds the range. The phase unwrapping process is a memory algorithm.

It should be noticed that AMFSK waveform is different from conventional MFSK that with synchronous steps. To achieve a relative longer time for the monitoring of vital signs, T_A is set as 2 ms, thus, vital signs can be checked every 2 ms. Since T_B only provides frequency shift for location information, it is set as 1 ms. By setting different time periods of step A and step B, both MFSK and CW features can be obtained. People can define different ratio between Step A and step B due to different application. In this case, long time and real time monitoring is not necessary for rescuing. If the system is used as a vital sign monitor for real

Parameters	Specifications
Carrier Frequency	24.05 GHz
Bandwidth	200 MHz
T_{CPI}	48 ms
T_A: T_B	2:1
T_A+ T_B	3 ms
f_{step}	2.5 MH
M	32
R_{max}	50m
δR	75 cm
δV	7.8cm/s

time detection and monitoring, the ratio between step A and B can be properly enlarged for adopting the higher monitoring accuracy. From the equation 3.4, the first term of the equation is not exist in FSK only situation, the phase difference solely depends on the frequency step between step A and B, since the R_max is set as 50m for this application, f_{step} should be smaller than 3 MHz with respect to an unambiguous phase angle, and it is set as 2.5 MHz. From the same equation, frequency offset can also be derived due to assure that the radar received signal can always be down-converted by the corresponding transmitted signal, thus, 32-ary A-MFSK is used, T_{CPI} becomes 48 ms, CPI represents coherent processing interval. Designed parameters specifications can be checked in the table as below.

3.2.2 Operation Algorithms

As introduced in the above section, AFMSK is operating at two modes: MFSK and CW. To effectively switch between two modes and correctly calculate the detection results, a novel algorithm is needed.

As shown in the flow chart of Figure.3, which is the overall operation algorithm. After the echo signal is received, baseband signal is obtained after down-convert. It needs to be mentioned that CW process needs the original range information to resolve the target displacement as (5) and (6), so it needs MFSK mode operate for the first T_{CPI}, whereas CW mode is idle. Once CW obtains the range information, it will operate with the constant phase brought by the original range within one T_{CPI}, because T_{CPI} is much faster than the speed of target's movement. After first T_{CPI}, signal goes to mode decision. Time information is extracted and compared with the T_{CPI}. If the time is less than T_{CPI}, the CW mode will be activated, then step A will operate as a single tone CW within T_A. Vital signs are monitored in this

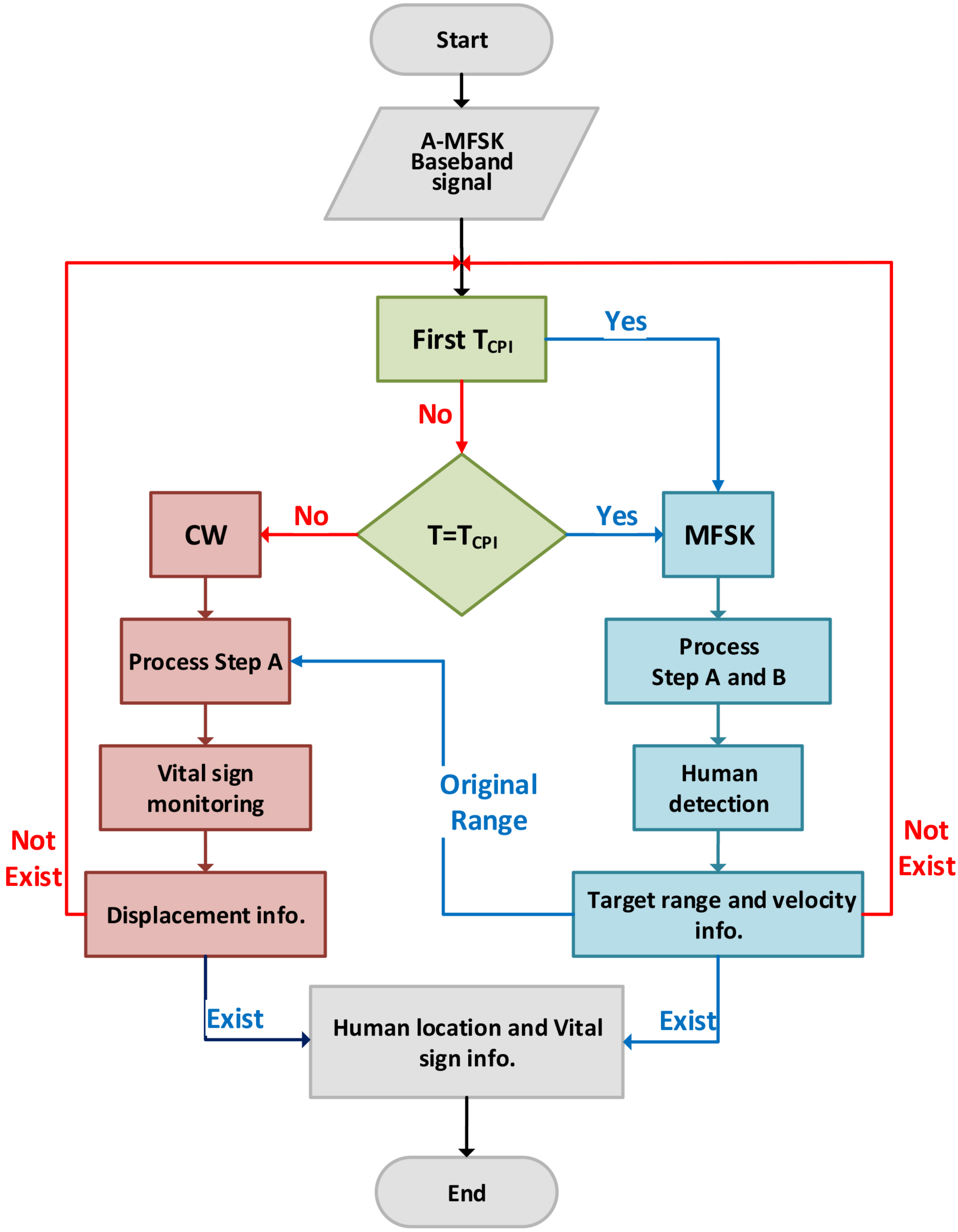


FIGURE 3.2: Operation Algorithm

mode using the displacement r from (7). In contrast, if the extracted time reaches T_{CPI}, the MFSK mode will be activated, then both steps A and B will be processed to obtain beat frequency and phase difference, then (3.3) and (3.4) are used to resolve the range and velocity information, and the range information is ready for the CW mode of next T_{CPI}. CW mode is designed to operate for a relative longer time compared with MFSK mode to monitor vital signs accurately, and it operates 16 times with a interval T_B, per T_{CPI}, whereas MFSK mode operates only once per T_{CPI} for location information.Since T_B is too short to have effect on the monitoring of vital signs, thus, the CW mode can be considered operating reliably. Consequently, an A-MFSK radar can be used for indoor positioning and life detection.

3.3 Summary and Discussion

In this chapter, we introduced a very novel idea for the indoor positioning and life detection application. By applying an asynchronous steps unlike the conventional MFSK, AMFSK can gain some interesting characters based on this. AMFSK contains asynchronous steps. During the period of steps A, step A mimics the operation of a single tone continuous waveform, thus resolved the small displacement ingeniously.By carefully choose the ratio of steps A and steps B, different purpose of vital sign monitoring can be achieved. And a novel algorithm guarantee that the waveform is feasible for this application. With a steps frequency, a low instantaneous bandwidth processing can alleviate the load of processor and also the dechirping process can reduce the complexity of ADC then the cost is reduced. By switching between MFSK and CW modes, both indoor positioning and life detection is achievable, thus provides a very comparable advantages with the conventional approaches. Without using an ultra wide bandwidth, life detection is possible and an ingenious method that only implements one kind of waveform, with special algorithm to make AMFS be capable of both indoor positioning and life detection at the same time.

Chapter 4

System Design and Experimental Results

4.1 AMFSK signal generator design

An A-MFSK signal generator is proposed in figure 3.3. There is a conventional PLL structure for tuning the frequency that can achieve high frequency and low power. A PLL consists four basic components: a phase detector that compares the phase of the input signal against the divided phase of the VCO, output a phase difference between the two inputs.To achieve a higher lock range, a charge pump is used, thus, both phase and frequency difference can be achieved. The output is then filtered by loop filter,the voltage difference is feed into VCO. Control voltage changes the frequency so as to reduce the phase and frequency difference between input signal and VCO. Once the input signal and VCO frequencies are equal, the lock condition is on. The PLL can generate a new frequency based on the reference frequency, retaining the stability, accuracy, and spectral purity of the original reference. Other than that, to achieve narrow channel frequency spacing resolution, fractional-N division technique like digital $\Delta\Sigma$-modulator is needed to generate a stream of integers that can interpolate a fraction number corresponding to the control input. As the figure 3.3 shows, the crucial part for this is design a modulation logic to control the frequency divider.

Regarding of modulation logic design, figure 3.3 and 3.4 should be seen together, since an asynchronous steps for FSK should be generated, the conventional MFSK control logic has to be redesigned totally[23]. In this design, the ratio constant is set according to the length ratio between steps A and B. If the length ratio between A and B is 2 to 1, then the ratio constant is set as 3. Firstly, the clock signal goes into a counter to obtain the number of pulses, then the pulses number is compared with ratio constant calculation.

The ratio constant is set to limit the output of the clock signal, once the pulses number is beyond the limit, the output of the comparator will be as a control signal. Meanwhile, the output will feedback through a integer multiple ratio constant to constantly tracking the accumulation of the counter and be compared with. Thus the output are only ones and zeros. The clock signal for accumulator is also needed to be special designed. Normally, the clock signal behaves like the "clk"in figure 3.4,however it will generate error steps due to the register records the number every rising edge in this case, so a special design clock signal is needed. The desired clock signal should checks the rising edge following a time period ratio, it means after first rising edge is generate, there should be no more edge checking process until step B period arrives, and right after the step periods finishes the edge checking processing should start again. Based on this, between two pulses that corresponding to steps A and B should keep a empty period and normal space is kept between every two pulses. To achieve this, the two comparators are used,"clk"and "clk1" are used to be compared with 0 due to the double interpolation data type to define the rising and falling edge. As the "ctrl" signal keeps a constant two pulses at 0 levels, this character can be used to achieve a "clk1"signal for register. Because the output of two comparators are obtained based on the "ctrl" signal, a time delay is needed to synchronize the "clk1" and "ctrl" for the later part.

Then the operations goes to the multiplexers, step constant and inc constant is switched by "ctrl" signal, then start from min value, the step and offset of waveform can be achieved. When the "ctrl" becomes high, subtractor operates and FSK modulation achieves. The wholes process repeats until the maximum number "BW" is reached, then the reset circuit will generate a signal to clear the content of the accumulator and set the output to the min value again. The whole process of timing diagram is depicted in figure 3.4.

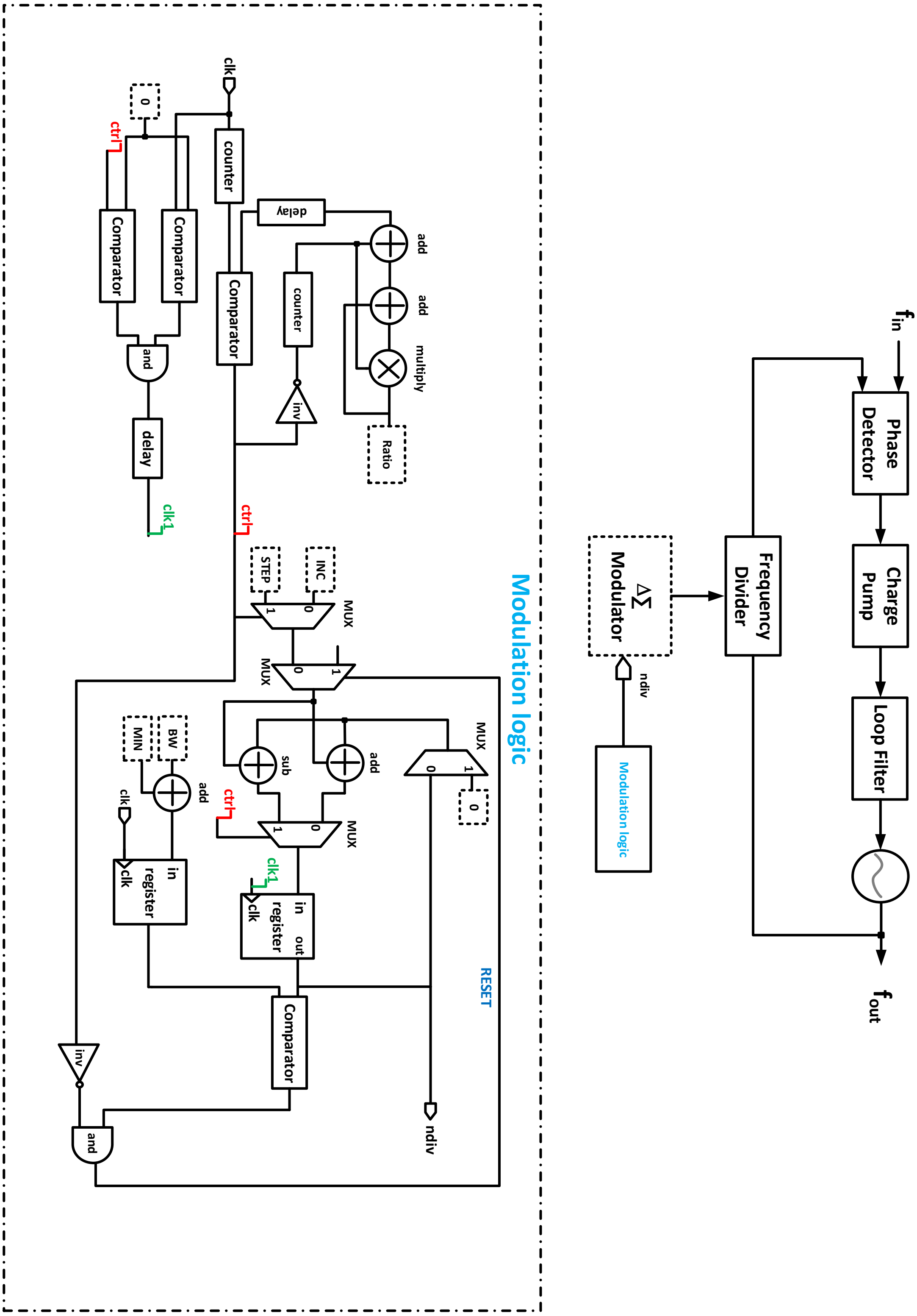


FIGURE 4.1: Signal generator

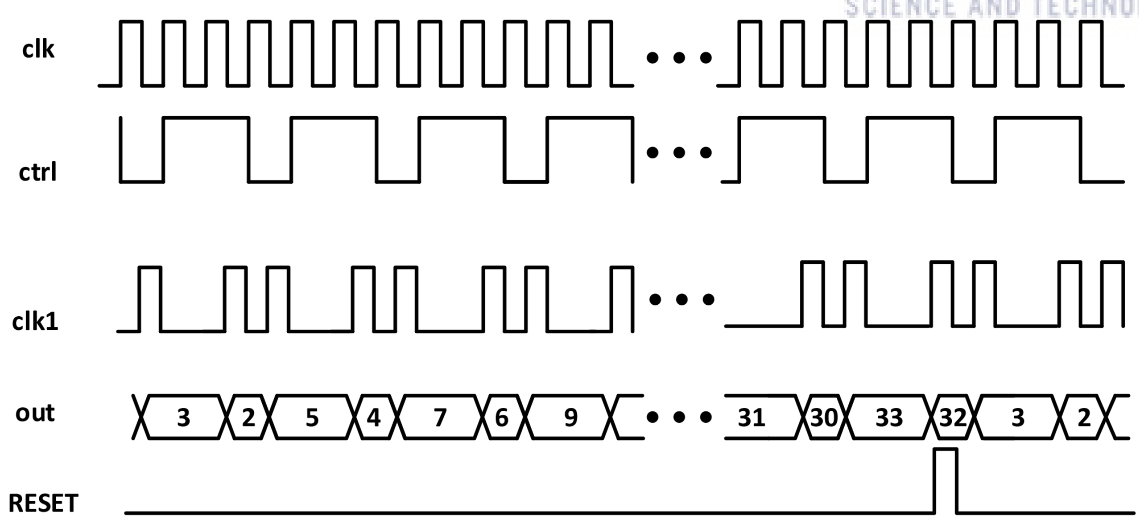


FIGURE 4.2: Timing diagram

4.2 Simulation Results

A novel detection approach for indoor positioning and life detection is proposed, simulation is conducted to verify the feasibility of the proposed approach, in figure 4.1, behavior simulation of AMFSK signal generation by CPPsim is shown. Cppsim is based on C++, providing speedy and flexible system level simulation of complex mixed signal circuits. The results shown the controlled voltage for PLL frequency tuning. The Results accurately demonstrated the feasibility of the designed signal generator. One T_{CPI} is shown, and a zoomed in view is given to show the ratio between Step A and B. As we can see, the Steps A lasts two times longer than Steps B, this feature gives a longer monitoring time on vital signs detection, better results can be expected intuitively.

By switching between two modes, simulation results of both modes are given. Simulations using MATLAB and Keysight ADS are carried out to verify the design of A-MFSK and its detection algorithm. When the MFSK mode is on, for signal steps A and B, whole period of signal is analyzed. FFT is applied to obtain frequency spectrum. To detect peaks, CFAR detector is used. The advantage of MFSK for multi-target detection is revealed, as shown in figure 4.2, three targets locates at 20 m, 21.5 m, 22.8 m as set in advance. This results provides the possibility when more than one victims needs to be located for rescuing.

For vital signs monitoring, according to medical researches, the respiration pattern is set as 1.6 mm oscillation amplitude to simulate a weak respiration, and its

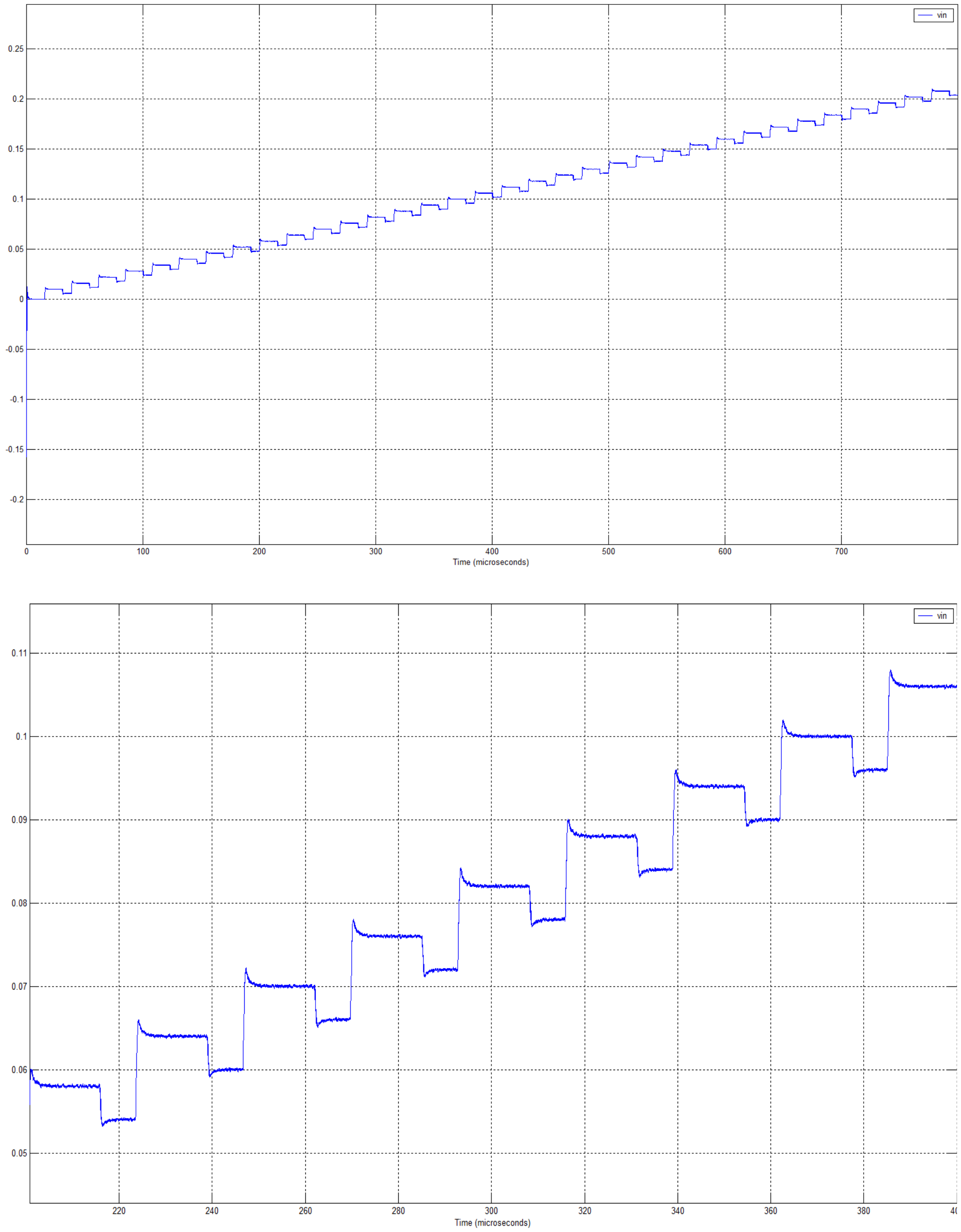


FIGURE 4.3: Simulated AMFSK Signal

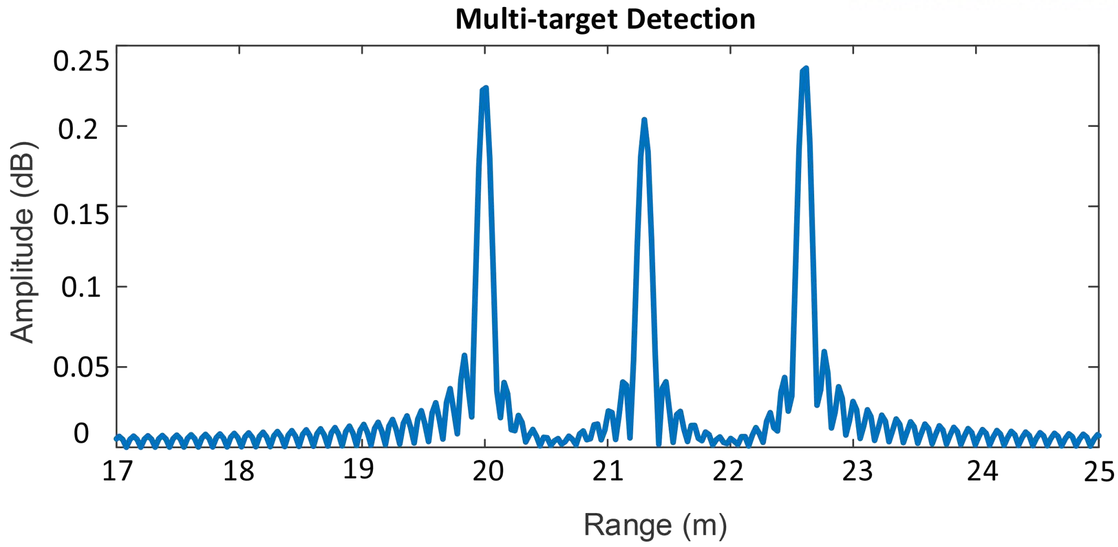


FIGURE 4.4: MFSK mode target detection

frequency is 0.3 Hz. The heartbeat pattern is set as 0.5 mm oscillation amplitude, and its frequency is 1.2 Hz. In this case, the null point elimination using RF phase shifter is used to provide an opportunity to always lock the radar system to the optimum point [24], and target phase needs to be unwrapped because the measurement phase always takes values between $-\pi$ and π. The harmonics order is set as 3 because harmonics caused by demodulation method and respiratory movement itself should be considered. Respiration and heartbeat is extracted as shown in figure.4.3.

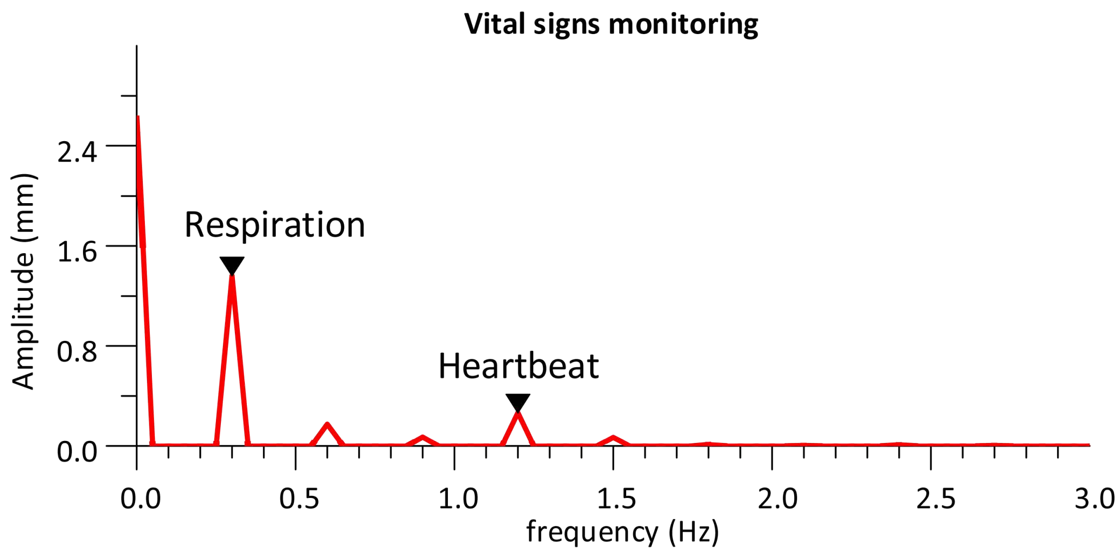


FIGURE 4.5: Respiration detection

4.3 Overall System Design

Hardware is implemented to further testify the proposed approach. As shown in the Figure 4.4, section A is a 6.5 cm $\times$ 6.5 cm micro strip antenna, which are low profile, conformable to planar and non planar surfaces, simple and inexpensive to manufacture using modern printed-circuit technology.section B is and 3.5cm $\times$ 3.9cm AMFSK signal generator which integrates a fractional -N PLL with a voltage controlled oscillator operates at 0.6 GHz, C contains DSP which process the acquired I/Q signals, and it is fabricated in a 10 cm$\times$8 cm PCB. A Simplified system architecture of AMFSK is depicted in figure4.5, a PLL and VCO is responsible to generate AMFSK waveform with special control logic aforementioned, and correctly synthesis of the baseband signal to be transmitted. After a upconversion with a carrier frequency, the signal, the transmitted signal is split into two, one serves as a local oscillator and the other is fed into a power amplifier to compensate for the free-space loss, by properly amplified and filtered, the signal will arrive at transmit antenna. Tx and Rx antenna provides 12° in the E-plane(Horizontal) and 25° in the H-plane(Vertical). Antenna pattern is given at figure 4.7. LNA is responsible for increase the Signal to Noise ratio of received signal, and it provides 4 dB typ. noise figure. After going through RF mixer, the signal is downconverted, filtered. High frequency band ADC is not needed here because AMFSK provides steps frequency, it means the total bandwidth is divided by the number of steps, and the ADC only needs to deal with instantaneous bandwidth that is much lower. This is also one of the benefits of AMFSK that it can alleviate the load of processor. BRENESAS Microprocessor R5F5621BDFB is used for DSP, which has 256KB flash memory and 64 KB RAM, with a 10 bit. The I/Q signal are then acquired and digitized by the ADC inside the microprocessor.

4.4 Measurement Results

A measurement test is conducted in a short range, a target is placed at 1 m from radar, as we could see from figure4.8, on the range map, the target is detected at 1 m in a slow time domain. Further test is conducted about I/Q signal, after ADC, I/Q signal outputs carrying the target information. As we can see in the figure 4.9, two situation are compared, with small displacement and without small displacement, the small displacement is usually under 1 mm, and in the test, the

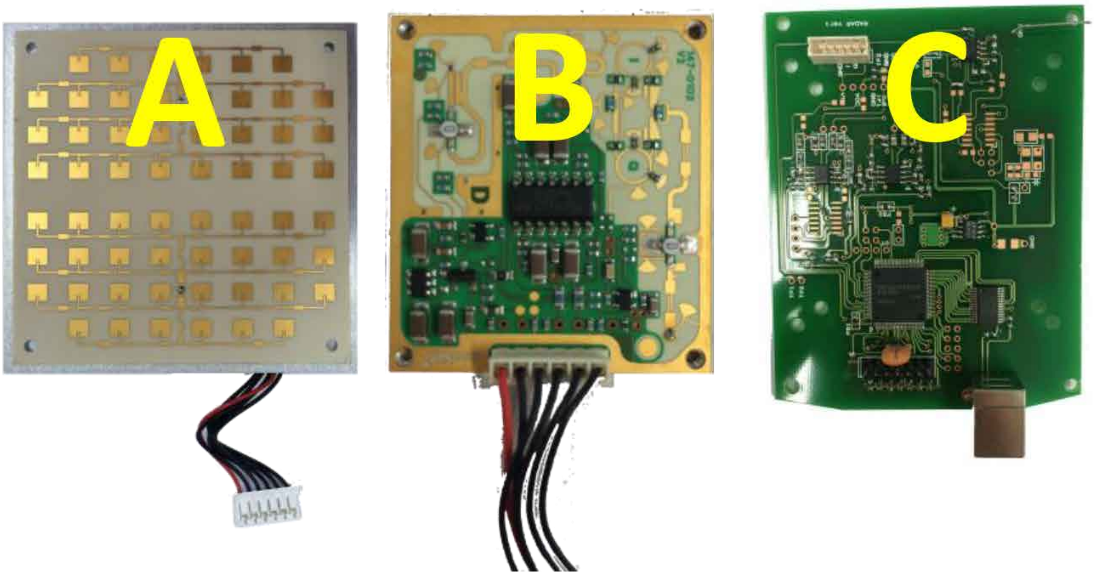


FIGURE 4.6: hardware implementation

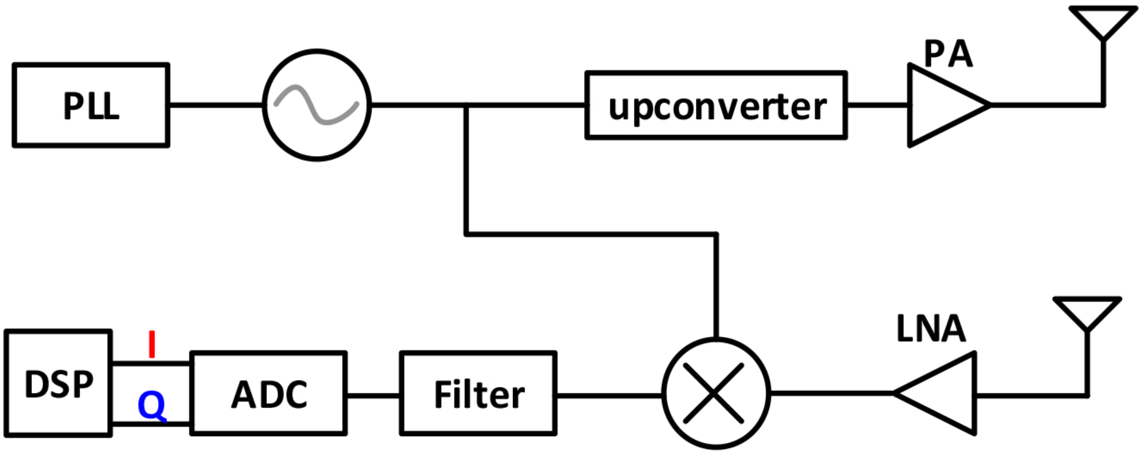
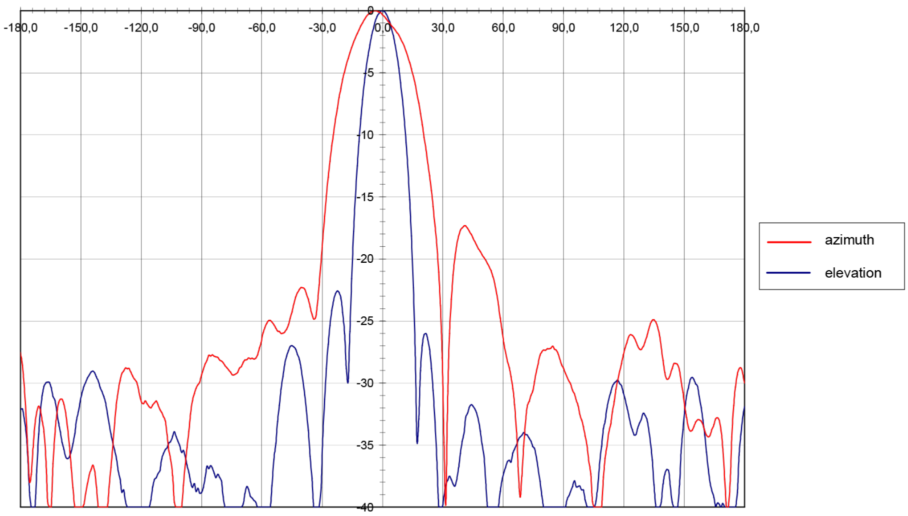


FIGURE 4.7: System structure

small displacement is from human chest wall movement during respiration. The I/Q signal with time domain shows different pattern depends on the existence of small displacement. And frequency spectrum shows different signal strength and respiration rate, a deep breath case causes higher power on the frequency domain compared with a normal breath. The last graph shows the unwrapped phase caused by displacement, as it shows, small displacement causes a large phase difference. Thus, respiration of human can be detected from the detection of small displacement, since human respiration pattern is periodical, a sudden movement caused by wind or natural power can be ignored. This feather provides

Parameter			Specification	Remark
Transmitter	Frequency range	RF	24.15±0.2GHz	
		IF	0.6±0.2GHz	
	Bandwidth		200 MHz	
	Output Power		+10 dBm typ.	
	LO frequency		24.75 GHz	
Receiver	Frequency range	RF	24.15±0.2 GHz	
		IF	0.6±0.2GHz	
	Bandwidth		200 MHz	
	LO frequency		24.75GHz	
	Dynamic range		70dB	
	Rx Input P1dB		-8 dBm	
	Noise Figure		4dB typ.	
Common	RF Port		HP-SMA(f)	
	BB Port		SMA(f)	
	Bias		5V/1300mA	

FIGURE 4.8: hardware Specifications



Parameter	Symbol	min	typ.	max.	units	comment
antenna pattern	horizontal		12		°	azimuth
	vertical		25		°	elevation
side lobe level	horizontal		-20		dB	azimuth
	vertical		-13		dB	elevation

FIGURE 4.9: Antenna Beam Pattern

the possibility of vital sign detection when a survived victim needs to be saved in a fire disaster.

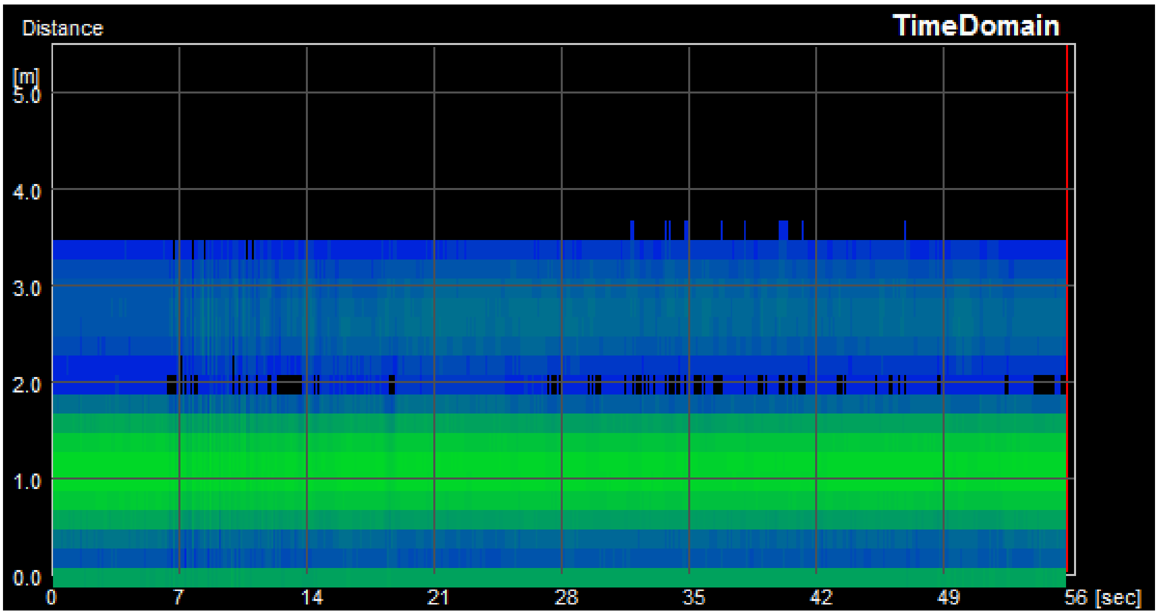


FIGURE 4.10: Target location

4.5 Summary

In this chapter, redesigned AMFSK signal generator is proposed, by properly designed the clock signal, AMFSK is generated by PLL. Simulation results are given, which provides good resolution in multi-target detection and vital signs detection, hardware design and measurement results demonstrated the feasibility of the proposed approach of AMFSK radar system for indoor positioning and life detection application.

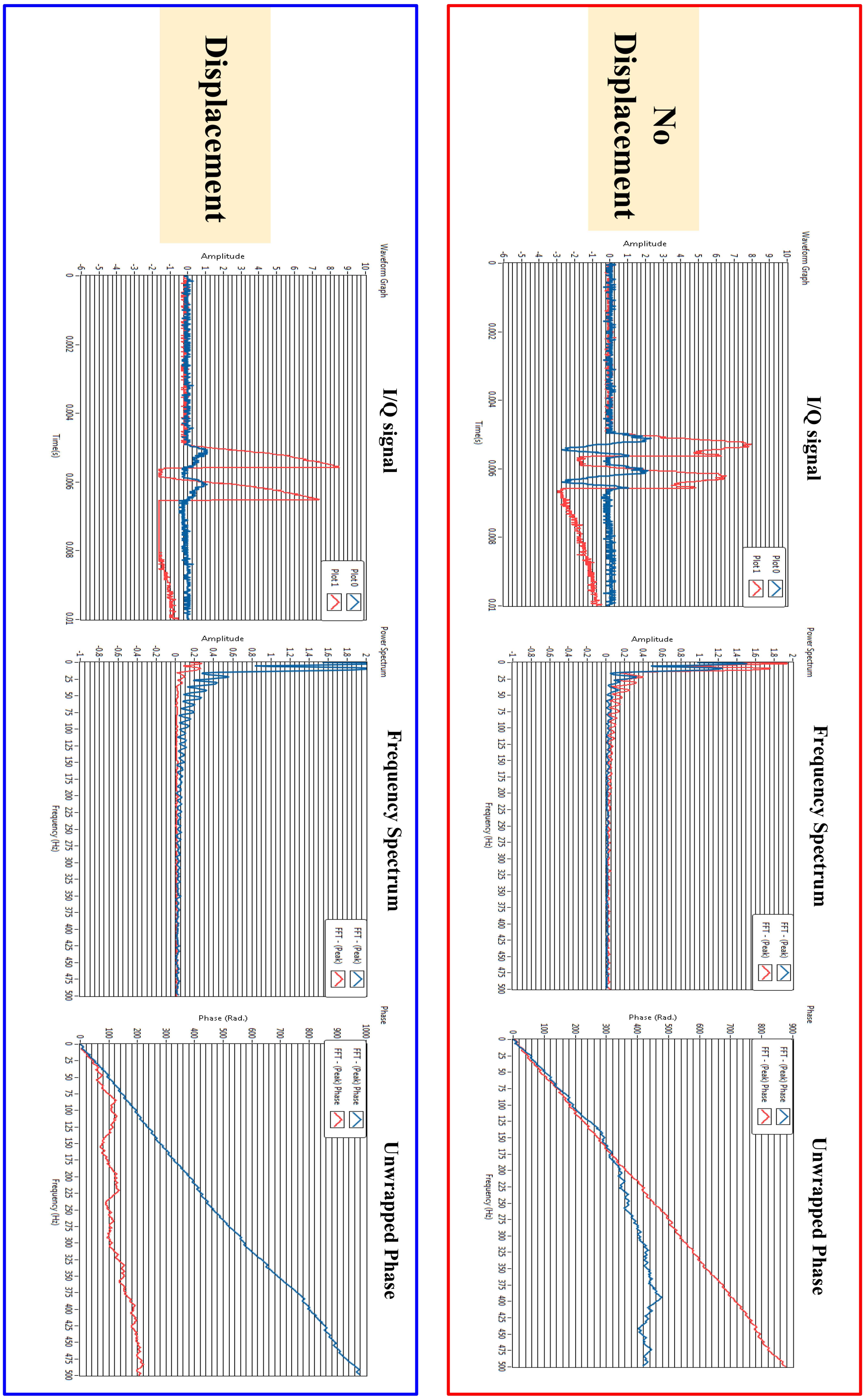


FIGURE 4.11: I/Q signal measurement

Chapter 5

Future works

Although AMFSK's feasibility of indoor positioning and life detection is proven until now, both respiration and heartbeat are detectable in simulation, however, due to complex environment, only respiration is detectable in practical by now, further improved hardware and algorithm need to developed based on the existing one. And there are lots of possibilities for the application of AMFSK.

FIGURE 5.1: Health monitoring

Based on the detected respiration pattern, more complex pattern recognition algorithms are expected, for example, some patients with respiration illness have abnormal respiration pattern, the abnormal pattern can be recognized remotely by radar device, there was several times of public health problem, the well known SARS happened at 2003, and as a rapidly spread and easily infected viral, government needed to control the entry of suspect patients, in this kind of cases, AMFSK radar can be a complementary method with existing thermal cameras when it is used as detector in crowd in public places like airport, and help timely locate the suspect patients, then prevent the widely spread of virus.

Smart home is one of the hottest trends these days. AMFSK radar can play a big role in this area due to its ability on both locating people and monitoring health state. As currently AMFSK AMFSK can only detect if there is constant phase shift by chest wall, and the location of monitored people. Thus the AMFSK needs to improve the ability of continuously and accurately monitoring human activities, like elder care or infant care, elders are usually leave without the care of their children, same case for the infant with a pair of busy parents, they need health monitoring in case of emergency accidents.

Chapter 6

Summary and Conclusion

The purpose of conducting this study is to provide an alternative and better approach for indoor positioning and life detection, especially like survivors rescuing in a fire disaster. As a technique with long history, radar technique is usually used as national defense, enemy troops surveillance,etc.for national security purpose and road traffic for civilian purpose. With a series of emerging application scenarios, radar technique can serve people through wider aspects, indoor positioning and life detection are widely researched and studied recently, since they can provide a location of human in a conceal situation, which is useful for rescuing in an emergency situation like earthquake and fire disaster.

People employed ultra wide band radar at first, because target range detection is not new for radar capability, life detection is crucial in this application. UWB radar provides fine resolution, so small displacement like chest wall movement is detectable. However, UWB radars need high performance ADC to process the signal which is not cost efficiency enough. To explore more cost efficiency approach, people tended to interferometry radar, which is a single tone continuous radar with a high resolution on small displacement either, with the pros, there comes the cons, since the periodic phase of signal, range detection is not available. Stepped frequency continuous waveform was proposed for this application, fall event detection is studied with the capability of indoor positioning. To take the merits of two kinds of radar, hybrid methods that combined two kinds of waveform is explored, FMCW-interferometry radar was proposed. Proposed SFCW needs ultra wide band, even though it can provide synthetic bandwidth which can alleviate the load of processor.

MFSK radar was firstly employed in automotive radar application in 2001 by rohling. MFSK shows some competitive merits than conventional FMCW and SFCW, as it's known that MFSK could provide multi-target detection capability without ghost targets that FMCW has and moving target detection without a Doppler shift error that happens on SFCW. With all these merits, in this study, MFSK is brought to solve indoor positioning and life detection problems, with special designed waveform: asynchronous MFSK and a novel detection algorithm. Designed detail and algorithm description are given in the contents. Simulation and measurement were conducted to testify the proposed idea. Results show the feasibility of proposed approach for both indoor positioning and life detection.

This work provides a novel and better approach for the challenging task of achieving both indoor positioning and life detection, as mentioned in the chapter of future works, more application scenarios can be developed and AMFSK is proven to be a promising technique with a flexible redesigned signal generator, it can meet different requirements of monitoring and detection.

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