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An Ultra-Wide Band Radar Based Noncontact Device for Real-time Apnea Detection

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An Ultra-Wide Band Radar Based Noncontact Device for Real-time Apnea Detection

by

Tian Tian

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of the

WORCESTER POLYTECHNIC INSTITUTE

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APPROVED:

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Abstract

This thesis presents a real-time noncontact system that can monitor an infant’s respiration and detect apnea when it occurs. For infants, bedside monitoring of respiratory signals using non-contact sensors is desirable at the hospital and for in-home care. Traditional approach employs acoustic sensors which can hardly detect infant breathing due to low SNR. In this thesis, a novel method is introduced by using a ultra-wideband (UWB) radar that obtains breathing signal from an infant’s weak chest vibration. Furthermore, advanced signal processing techniques are proposed to monitor the breathing signal and to detect apnea. Since an infant may move in the crib, a location algorithm is applied periodically to track the current location of the infant’s chest. An apnea warning is issued when the respiration is absent for a pre-defined period of time.
Acknowledgements

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Chapter 1

Introduction

1.1 Apnea

Apnea is a potentially serious disorder in which breathing is interrupted for 10 seconds or more. Apnea usually happens during sleep. There are three kinds of apnea: obstructive apnea, which is caused by an obstruction of the airway; central apnea, which is caused by the part of the brain that controls breathing not properly maintaining the breathing process; and mixed apnea, which is a combination of the two.

Central apnea is the most common type of sleep apnea in babies because the respiratory center in the brain is immature. In adults and children over one year old, obstructive apnea is the most common type. Any baby can have sleep apnea, but it’s much more common in babies who were born prematurely. In babies born to moms up to 37 weeks pregnant, it’s called apnea of prematurity. In babies born to moms past 37 weeks pregnant, it’s called apnea of infancy. The more premature a baby is, the more likely he/she is to suffer from apnea. Apnea can be fatal in infants. As a baby’s breathing stops, the oxygen levels in his/her blood fall and the levels
of carbon dioxide increase. An infant might suffer a severe drop in heart rate. In
general, a heart rate of 120-160 is normal for a premature baby and 80-140 for a full
term baby. When the infant’s heart rate drop below 80, this is called bradycardia.
Apnea is not rare among new born infants, so monitoring an infant’s respiration
information and warning the nurse in neonatal intensive-care unit (NICU) can be
life-saving. Usually the apnea warning should be reported if the infant does not
begin to breath again in 15 to 20 seconds[1, 2].

To monitor and identify apnea, a basic method is to monitor human’s respiration,
then identify the period where no breathing signal appeared. Currently most devices
used to monitor human’s respiration are based on contact sensors – pressure sensors
set under the mattress or wrapped around the chest and air flow detection sensors
set near the nose. Most contact sensors need to be attached to infant’s body or nose.
This would cause infant feel uncomfortable and may drop off while infant’s moving.
In this thesis, a non-contact technology based on Ultra-Wide-Band (UWB) radar is
developed to monitor the breathing of infant.

1.2 Radar System

1.2.1 Basic Radar System

RADAR, an acronym for Radio Detection And Ranging, is an object-detection
system that uses electromagnetic waves to determine the range, altitude, direction,
or speed of objects [3]. The simplest form of a radar system consists of a transmitter,
receiver and antenna, which is illustrated in Fig.1.1. The transmitter generates
electromagnetic wave broadcasted by the antenna. Part of the electromagnetic wave
is reflected when the wave is incident on a target. The reflected wave is collected by
the antenna and then passed to the receiver to extract the range, direction and/or
velocity information of the target.

Figure 1.1: A basic radar system

1.2.2 Radar Range Equation

Radar range equation is a fundamental determinant of radar performance. It describes the physical dependences of the transmit power [4]:

\[ P_{\text{RX}}^{\text{in}} = \frac{P_{\text{TX}} G_{A,\text{TX}} G_{A,\text{RX}} \lambda^2 \sigma}{(4\pi)^3 R^4 L_A^2 L_{sys}^2} \]

where \( P_{\text{RX}}^{\text{in}} \) is the power at the input of the receiver, \( P_{\text{TX}} \) is the power at the output of the transmitter, \( G_{A,\text{TX}} \) is the transmit antenna gain, \( G_{A,\text{RX}} \) is the receive antenna gain, \( \lambda \) is the wavelength of the carrier frequency, \( \sigma \) is the Radar Cross Section (RCS) of the target, and \( R \) is the range to the target. The radar channel
includes the environment surrounding the radar, i.e. the target and any interfering reflectors. \( L^A_{ch} \) is the additional channel loss, such as atmospheric attenuation due to oxygen or water vapor. And \( L^A_{sys} \) is the system loss, such as sampling loss.

The maximum range of radar can be derived from the radar range equation:

\[
R_{\text{max}} = \left( \frac{P_{TX} G_{A,TX} G_{A,RX} \lambda^2 \sigma}{(4\pi)^3 L^A_{ch} L^A_{sys} S_{\text{min}}} \right)^{1/4}
\]

where \( R_{\text{max}} \) is the maximum target range and \( S^\text{in}_{\text{min}} \) is the minimum detectable power at the input of the receiver. By increasing transmit power and/or decreasing the minimum detectable received power, the maximum range of the radar can be increased.

### 1.2.3 Radar Cross Section

Radar cross section (RCS) is a measure of the electromagnetic energy intercepted and radiated at the same wavelength by any object. The RCS of an object is a complex combination of multiple factors: size, shape, material, edges, wavelength, and polarization. There are seven basic scattering mechanisms [5]:

1. Reentrant Structures. Reentrant structures include cavities in a target, such as intake ducts, exhaust ducts, and cockpits on airplanes. Reentrant structures tend to be metallic and produce large echoes.

2. Specular Scatterers. Specular reflections result from surfaces that are perpendicular to the radar’s line-of-sight. The echo in the specular direction tends to be large but falls off quickly as the angle-of-incidence varies from 90°.

3. Traveling-Wave Echoes. It is common for a surface wave to develop on a target if the angle of incidence is small (i.e. the line-of-sight is nearly parallel to the target). The surface wave will travel along the surface of the target and can
be reflected from discontinuities toward the rear of the target. The resulting echo is called a traveling-wave echo and is common on targets such as airplanes and missiles. Traveling-wave echoes can be nearly as large as specular echoes.

(4) Diffraction. Tips, edges, and corners tend to diffract the radar signal but normally result in less significant echoes than specular reflections.

(5) Surface Discontinuities. Discontinuities such as seams, rivets, and gaps can result in diffractive echoes; the effects of surface discontinuities tend to be small.

(6) Creeping Waves. Creeping waves are the result of surface waves that follow the curvature of the target and are launched back toward the radar.

(7) Interactions. Interaction echoes result when the radar signal is reflected back toward the radar after bouncing off two or more target surfaces.

1.2.4 Antenna Direction

Antenna can be directional or omnidirectional. Directional antennas radiate energy more effectively in some directions than in others while omnidirectional antennas radiate energy uniformly in one plane and are directional in perpendicular planes [6].

1.2.5 Ultra Wideband Radar System

Ultra wideband (UWB) radar is a radar system using the ultra wideband waveforms, which is different from the traditional radar system which transmits continuous waveforms with a specific carrier frequency. An UWB signal should have bandwidths of greater than 500MHz or a fractional bandwidth larger than 20 percent at all times of transmission [7]. Bandwidth is defined as the frequency range in which the nonzero or above a small threshold signal energy spread. Use $f_H$ and $f_L$ to denote
the upper and lower limit of this frequency range, then the fractional bandwidth is defined as [8, 9]:

\[
\text{FractionBandwidth} = \frac{2(f_H - f_l)}{f_H + f_l}
\]

Fig.1.2 illustrates a simple narrowband signal in time domain and frequency domain.

![Diagram](image)

Figure 1.2: A narrow band signal in (a) time domain and in (b) frequency domain

And Fig.1.3 illustrates a simple UWB pulse in time domain and frequency domain.
The UWB radar works by sending out pulses under a Pulse Repetition Frequency (PRF) and collecting the return signal of each pulse. The pulse repetition frequency is typically in the range from 1 to 50 MHz. The PRF is limited by the range ambiguities. It is assumed that the reflected signal is received before the next pulse is transmitted. So the unambiguous pulse repetition interval (PRI) respect to the range R is:

\[ PRI > = \frac{2R}{c} \]

where \( c \) is the light speed and \( R \) is the range.

So the PRF is limited as:

\[ PRF <= \frac{c}{2R} \]
A Time Domain’s PulseON 410 Monostatic UWB Radar (Fig.1.4) is employed as the radar device to detect the infant’s respiration in this thesis. In a monostatic setup, separate transmit and receive antennas are used and are put close together. For first order approximations, the two antennas can be assumed to be co-located.

The PulseON 410 Radar board uses an omnidirectional antenna. For the purpose of monitoring human being’s respiration, the omnidirectional antenna can deal with the situation that the target moves to another angle of the antenna by collecting the reflected signal from all directions, while the directional antenna would lose the target if it moves to another angle of the antenna. In this case, the return waveform after each pulse being sent out is composited by reflected signals from the surroundings. A simple return waveform is illustrated in Fig.1.5. And Fig.1.6 shows a real return waveform of the PulseON 410 Radar set in a room and surrounded by
Figure 1.5: Simple UWB return waveform
Figure 1.6: A return waveform of PulseON 410 UWB Radar

The operation range of PulseON410 Radar can reach hundreds of meters and the PRF is 10 MHz [10]. For the purpose of monitoring infant’s respiration in hospital, a range of few meters is enough. In this thesis the radar’s range is set to 4.32 m.

The radar system uses coherent transmissions to maintain the same phase of each transmitted pulse. The received signal power of many coherent pulses are summed. Since the received signal power is proportional to the square of the received signal, summation leads to signal power increases along with the square of the number of pulses while the incoherent noise is only summed linearly. Due to this coherent signal processing technique, a very high SNR can be achieved at high integrated ratio as illustrating in Fig.1.7 [11, 10].
1.3 IRB Approval

An institutional review board (IRB) is a committee that has been formally designated to approve, monitor, and review biomedical and behavioral research involving humans. A key goal of IRBs is to protect human subjects from physical or psychological harm, which they attempt to do by reviewing research protocols and related materials. In this thesis, all data collected from human and the methods used for
data collecting are IRB approved. A collaborative institutional training initiative (CITI) test completion report was added in the IRB list of Department of Neurology of University of Massachusetts Worcester and the report is showed in Appendix A.
Chapter 2

Method

2.1 System Block Diagram

Following diagram illustrates how the radar’s data get processed and the breathing signal get extracted.

![Figure 2.1: Breathing detection system diagram](image)

Figure 2.1: Breathing detection system diagram
2.2 Background Clutter Remove

The UWB Radar works by sending out a number of UWB pulses (the specific number is determined by the integrated ratio) and collecting the return waveforms. The return waveforms collected after pulses being sent out are summed by the coherent processing, to form one set of data, which is called one scan. The maximum pulse repetition frequency of the PulseON410 is 10 MHz. For a coherent processing with integration ratio of 1024, it takes about 0.0001 second to send out and collect 1024 pulses return waveform to form one scan. This time is very short compared with the time of one breath of human (varies from 1 to 5 seconds). So it is reasonable to assume that there is no target movement during one scan. The signal strength is denoted as \( r(\tau) \), where \( \tau \) is the travel time of the pulse. In other words, the signal strength at different time \( \tau \) represents the signal strength returned from different distance. The time of this dimension is called fast time. In practice, each scan data from the radar is the sample of \( r(\tau) \):

\[
R(n) = r(nT_f)
\]

where \( T_f = 61\,\text{ps} \) is the PulseON410 UWB Radar’s sample rate on each return waveform of a pulse. So the distance between each sample point is:

\[
d = T_f \cdot c/2 = 0.009m
\]

where \( c \) is the light speed in vacuum and \( c = 299,792,458\,m/s \). The detection range is set to 4.32 meters (the radar will only receive and store the return waveform of each pulse between 0 to 4.32 m), which is 480 sample points, so \( n = 0,1,2...479 \). This detection range is enough for the purpose of this thesis because the radar is...
set within 2 meters of the target to capture a strong breathing signal.

Recording the scans by time $t$ with the sample rate $f_s = 20$ Hz. So every 0.05 second one scan is recorded. Put these scans in a 2-D matrix along the time as $R(m, n) = r(mT_s, nT_f)$, where $m = 0, 1, 2...$ and $T_s = 0.05s$. The time $t = mT_s$ is called slow time. Each row of the matrix is one scan and each column of the matrix is the signal on the same location of different scans.

The background clutter is the signal coming from all surroundings other than the target. As discussed before, the received signal strength of each distance is the sum of reflected waves of all objects on this distance. Because the surroundings are static, by subtracting the average signal strength of each distance, the background clutter can be attenuated.

### 2.3 Fourier Transform

Fourier Transform is widely used in many areas of engineering and science [12, 13]. In signal processing, Fourier Transform is a very important and useful method to analyze the frequency feature of the signal.

For a signal $x(t)$, if there is a period $T > 0$ which let:

$$x(t) = x(t + T)$$

for all $t$, this signal $x(t)$ is defined as periodic signal.

To represent any periodic signal $x(t)$ as the sum of simple sines and cosines signal:

$$x(t) = \sum_{-\infty}^{+\infty} c_n e^{j\frac{2\pi nt}{T}}$$
And this set of the sum of sines and cosines are called Fourier Series. The coefficients in the series can be solved as:

$$c_n = \frac{1}{T} \int_{-T/2}^{T/2} e^{-j\frac{2\pi nt}{T}} x(t) dt$$

A rectangular waveform can be decomposed into such kind of set as illustrated in Fig.2.2. Each sinusoid is a frequency component of the original signal.

![Figure 2.2: A rectangular waveform being decomposed into a combination of sinusoids](image)

By extend the period $T$ to infinity, $T \to \infty$, the general Fourier Transform can be derived [14]:

$$X(f) = \int_{-\infty}^{+\infty} x(t)e^{-2\pi jft} dt$$

$X(f)$ is the frequency spectrum of the signal $x(t)$. Or $X(f)$ is the signal’s
representation in frequency domain and $x(t)$ is the signal’s representation in time domain.

In practice, a continuous signal has to be sampled into digital signal (a sequence of numbers) with an analog-to-digital convertor (ADC) in order to be processed by computer. Sampling a continuous signal $x(t)$ every $T$ seconds: $x_s(n) = x(nT) \quad n = 1, 2, 3,...$

$T$ is the sampling interval and $f_s$ is the sampling frequency or sampling rate, where $f_s = 1/T$.

As Fourier Transform is used to process the continuous signal, the Discrete-Time Fourier Transform (DTFT) is used to process this sampled discrete digital signal. The Discrete-time Fourier Transform is defined as:

$$X(f) = \sum_{n=-\infty}^{\infty} x_s(n)e^{-2\pi j f T n}$$

The DTFT is also a continuous function of frequency, so $X(f)$ need to be sampled into discrete. The sampling of DTFT is the Discrete Fourier Transform (DFT). $X(f)$ is a periodic function with $\frac{1}{T}$ period ($e^{j\omega}$ is periodic). The N-point DFT is to calculate N samples of one cycle of $X(f)$:

$$X(k) = \sum_{n=-\infty}^{\infty} x_s(n)e^{-2\pi j k n/N}$$

where $k = 0, 1, 2 \ldots N-1$.

### 2.4 Bandpass Filter

As discussed in the previous section, the received signal is the combination of all possible kind of signals coming from different signal sources in different frequency
range, including useful signals and noise. Filter is an important tool which is employed in this situation and distinguish the useful signal from the noise. The filter works by attenuating or even eliminating signals in some prescribed frequency range and strengthen signals in other frequency range. Then the useful signal is kept.

The digital filter performs mathematical operations on the sampled, discrete-time signal to get the desired signal while the analog filter, which is an electronic circuit, is used to process continuous-time analog signal.

Fig.2.3 illustrates a typical bandpass filter’s frequency response $|H(z)|$. For the frequency range $f < F_L$ and $f > F_H$, there is $|H(z)|^2 < 0.5$. $F_L$ is the lower cut-off frequency and $F_H$ is the higher cut-off frequency. And the frequency range from $F_L$ to $F_H$ is the passband.

![Figure 2.3: A typical bandpass filter frequency response](image)

The average resting respiration rate by age are [15, 16]:

18
<table>
<thead>
<tr>
<th>Age</th>
<th>Respiration rate (Breaths/minute)</th>
<th>Respiration rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birth to 6 weeks</td>
<td>30-60 Breaths</td>
<td>0.5-1 Hz</td>
</tr>
<tr>
<td>6 months</td>
<td>25-40 Breaths</td>
<td>0.42-0.67 Hz</td>
</tr>
<tr>
<td>3 years</td>
<td>20-30 Breaths</td>
<td>0.33-0.5 Hz</td>
</tr>
<tr>
<td>6 years</td>
<td>18-25 Breaths</td>
<td>0.3-0.42 Hz</td>
</tr>
<tr>
<td>10 years</td>
<td>12-15 Breaths</td>
<td>0.2-0.25 Hz</td>
</tr>
<tr>
<td>Adults</td>
<td>16-20 Breaths</td>
<td>0.27-0.33 Hz</td>
</tr>
<tr>
<td>Elderly</td>
<td>10-30 Breaths</td>
<td>0.17-0.5 Hz</td>
</tr>
</tbody>
</table>

Table 2.1: Respiration rate by age

For the targets from 6 months to elderly, the respiration rate is from 0.17 to 0.67 Hz.

Butterworth filter is a type of filter which has a very flat frequency response in the passband [17] and is commonly used in motion analysis. It was first described by the British engineer and physicist Stephen Butterworth in his paper in 1930. Butterworth showed that a low pass filter could be designed whose cutoff frequency was normalized to 1 radian per second and whose frequency response (gain) was [17]:

\[ G(\omega) = \sqrt{\frac{1}{1 + \omega^{2n}}} \]

where \( \omega \) is the angular frequency in radians per second and \( n \) is the number of poles in the filter.

Fig. 2.4 illustrates different butterworth bandpass filters with different order N.
Based on the respiration rate in Table 2.1, a 4th order Butterworth bandpass digital filter with lower cut-off frequency $F_L = 0.15$ Hz and higher cut-off frequency $F_H = 0.8$ Hz is designed using Matlab and a set of filter’s coefficients is obtained. The signal is filtered on discrete time using the difference equation:

$$y(n) = a_1 x(n) + a_2 x(n-1) + \ldots + a_N x(n-N+1) - b_1 y(n-1) - b_2 y(n-2) - \ldots - b_M y(n-M)$$

where $a_n$ and $b_n$ is the coefficients of the designed filter.

### 2.5 Target Localization

There are tens of sample locations that may show some levels of object movement. This step is to find the specific location where respiration activity is the strongest. After removing the background clutter and passing through the band pass filter, the
breathing signal at chest position is significantly stronger than the interference. In addition, the signal energy reaches its maximum value at the breathing frequency. Therefore, we employ the method of power spectrum density (PSD) analysis to find the location with the highest SNR. The comparison of PSD among signals from different locations is shown in Fig. 2.5.

Figure 2.5: PSD comparison of location where breathing signal appears and locations where no breathing signal appears

### 2.6 Dynamic Peak Detection

Peak detection algorithm aims to identify each peak from the time-domain signal after filtering. To implement peak detection algorithm, an empirical threshold is set below which any peaks can be treated as noise. In a typical peak detection system, the threshold is usually proportional to the variance itself. With a fixed threshold, the peak detector works by scanning each datum sequentially. The peak detector
keeps scanning datum until it detects a value that is greater than the threshold. It then compares the value with the very next datum. If the next datum has a smaller value, then a single peak is detected. If not, the peak detector will repeat this procedure on the next datum.

For the purpose of apnea detection, non-peak periods are meaningful. The goal is to identify a period of time when apnea happens, during which no evident peaks above the threshold can be found. To accomplish it, a dynamic threshold is applied and it is proportional to the reciprocal of signal variance. This is due to the fact that signal strength may change significantly through time. A dynamic threshold is used to adjust the current threshold to be within the same scale of signal strength. This method is to automatically generate a relatively high threshold when there are no obvious peaks in the signal, which indicates the target has stopped breathing. The dynamic threshold makes the software program more robust for identifying apnea. That is, when there are no obvious peaks above the current threshold, the threshold starts to increase. The threshold becomes higher, which helps to eliminate the noise. If no peak above threshold is detected for an extended period of time such as 10 seconds, an alarm is set off.

2.7 Reference Data Collection

To verify the processed signal from the radar is breathing signal, a reference signal which can directly represent the breathing signal is collected with the radar’s data together. The air flow will make a big noise when the target breathes out, so the sound recording of the air flow coming from a human’s noise can be used as a reference signal for the breathing signal. A little microphone is attached under the target’s nose and the sound data is collected using Matlab while the radar is
tracking the chest movement when target is breathing. Fig. 2.6 illustrates one sound recording while breathing, each breathing can be very clearly found in the recording.

![Breathing sound recording](image)

**Figure 2.6: Breathing sound recording**

After a shaping filter, the breathing peak is easy to identify as showing in Fig. 2.7.
Figure 2.7: Breathing sound recording (processed)
Chapter 3

Device Setup and Data Collection

3.1 Device Set Up

The Time Domain’s PulseON410 Radar board receives control command and sends the scan data through the USB serial port. So a device which can run a serial port communication driver and store the data is required to operate the PulseON 410 Radar board. A credit-card sized computer board Raspberry Pi is employed as the device connected with the radar board which can run a driver program to control the radar and store the data. The Raspberry Pi board runs a C program to control the Radar board, generate synchronizing signal and store the data. The synchronizing is used to synchronize the radar’s data with other possible breathing monitoring devices’ data if needed. Set the C program to be executed automatically after the Raspberry Pi board booting up, connect the PulseON410 Radar and the Raspberry Pi board together to build a standalone easy use device that can be accepted by the hospital of UMass Memorial Medical Center to collect the data at its NICU.
3.2 Synchronizing Signal

Synchronizing signal is used to synchronize the radar’s scan with other respiration monitoring devices provided by the hospital so that the radar’s data can be compared and analyzed with other data. The synchronizing signal is generated every 30 seconds by the driver program running on the Raspberry Pi board and output through the General Purpose Input/Output (GPIO) port as a digital signal, then collected by the data acquisition card of UMass Memorial Medical Center. The data acquisition card will collect all devices data and synchronize them. While each sync signal is being generated, the radar’s scan data at this time are recorded with a synchronized stamp. The synchronizing signal is encoded with 14 bits. First 3 bits are encoded as ‘010’ to indicate synchronize start. The next 8 bits indicate the
index of the synchronize signal. The index starts from 1 and increase by 1 after a sync signal being sent out. The index is denoted by an 8-bit MSB binary number. The last 3 bits are encoded as ‘010’ to indicate the end of the sync signal. The GPIO port on the Raspberry Pi board can output a ‘High’ (5V) or ‘Low’ (Ground) level. For the start and end sign, ‘High’ is used to denote ‘1’ and ‘Low’ is used to denote ‘0’. For the 8-bit index binary number, a transit from ‘High’ to ‘Low’ or from ‘Low’ to ‘High’ is used to denote ‘0’, non-transit is used to denote ‘1’. The fifth synchronizing signal is illustrated in Fig. 3.2.

![Figure 3.2: The fifth sync signal](image)

There are 256 combinations (8 bits) synchronizing signal indexes and the synchronizing signal is generated per 30 seconds, so the repeat index will not appear until 128 minutes, which is enough for one set data whose length is determined as 60 minutes. A set of one-hour data is enough for analysis.
Chapter 4

Results

4.1 Raw Data

The data were collected in laboratory AK209 at WPI (a typical graduate school’s laboratory with complex surroundings). The radar was set about 1 meter away from the target (human). The sample rate in slow time was set to 20 Hz and the reference signal was collected together. A 2-D plot of the data matrix R(m,n) is shown in Fig.4.1. The different colors denote different signal strength.
4.2 Processed Data

After background clutter removal as discussed in Section 2.2 and passing data through the bandpass filter as discussed in the Section 2.4, the 2-D plot of the data matrix is shown in Fig. 4.2.
By verifying with the reference signal, the clearly periodical color changing between 1 to 1.4 meter is the breathing signal. As discussed in Section 2.5, the Power Spectral Density (PSD) is used to calculate the breathing frequency and the location (the fast time) with the strongest breathing signal. The 3-D plot of the PSD computed along slow time on all locations is illustrated in Fig. 4.3. By using the PSD, the strongest breathing signal can be found on the location of 1.4 m and the breathing frequency is 0.23 Hz.
Set the n in $R(m,n)$ to 155, which is corresponding to the distance of 1.4 m, and extract the breathing signal. The result is compared with the breathing signal collected by the microphone and illustrated in Fig. 4.4.
Figure 4.4: Breathing signal collected by (up) radar and by (down) microphone

Following results illustrate the performance of the device by detecting different respiration rates. A software metronome was used to provide a stable rate and the person who was monitored exhaled and inhaled following this fixed rate.

Set the metronome’s rate to 0.15 Hz (6.67 seconds per breath) and let the target person breathe following this rate, the result is showed in Fig. 4.5.
Figure 4.5: Result of 0.15Hz

Set the metronome’s rate to 0.25 Hz (4 seconds per breath) and let the target person breathe following this rate, the result is showed in Fig. 4.6.
Figure 4.6: Result of 0.25Hz

Set the metronome’s rate to 0.35 Hz (2.86 seconds per breath) and let the target person breathe following this rate, the result is showed in Fig. 4.7.
Set the metronome’s rate to 0.45 Hz (2.22 seconds per breath) and let the target person breathe following this rate, the result is showed in Fig. 4.8.
Figure 4.8: Result of 0.45Hz

Set the metronome’s rate to 0.60 Hz (1.67 seconds per breath) and let the target person breathe following this rate, the result is showed in Fig. 4.9.
Figure 4.9: Result of 0.6Hz
4.3 Real-time monitoring

A real-time monitoring program including target presence detection, breathing signal localization, breathing signal peak detection and no breathing warning is developed using Matlab. Fig. 4.10 is the system block diagram, which illustrates how this real-time monitoring application works.

Figure 4.10: Real-time monitoring system block diagram

(1) Presence detection.

The application is in the presence detecting stage when it is started up.

Raw data acquired by the UWB radar is the signal strength reflected from the objects. When objects in surroundings move, the scanning result becomes different in time domain. Besides, reflected signal strength changes too. Regarding this feature, we can determine whether a target is in presence by evaluating the difference between current result and historical result.

Here comes the need for a template to be compared with, the template needs to be set up by recording one set of scan data when there is no target. After that, each scanned data is compared with the template. When there is a significant difference
between the current scan and the template in time domain, the system begins to capture breathing signal in frequency domain, and the real-time monitoring process is triggered. On the other hand, the environment may change little by little without triggering the alarm, which in a long time causes the original template inaccurate at all. So after a period of time, the template needs to be updated. The UWB radar keeps scanning if scanned signal resembles the template and the template is continuously updated by the newly scanned data.

![Figure 4.11: Target presence detection](image)

(a) Target is not present

(b) Target is present

Figure 4.11: Target presence detection
Once the target who will be monitored presents in the detection range, the monitoring programming will automatically go to the next stage, start the respiration monitoring.

(2) Breathing Signal Localization

Once the target presents, the application will start to keep collecting the data and store the most recent 10 seconds data. After the first 10 seconds data (200 scans for 20 Hz sample frequency) are collected, the breathing signal localization algorithm will be implemented on these data to identify the location where the strongest breathing signal appears.

(3) Real-time Monitoring and Peak Detection

After the localization step, a signal location is determined. The time-domain signal on this location is displayed and the peak detection algorithm is implemented on this location. Fig.4.12 illustrates the normal breathing activity of an adult at this location.

(4) Breathing Signal Relocate

In practice, target's movement, which would lead to the disappearance of the breathing signal on the previous location, has to be considered. To avoid the false alarm, if no peak is detected on this location for more than 10 seconds, the application will use the most recent 10 seconds data to locate the breathing signal again. If the breathing signal is found on a new location, the application will update the signal location and return to the real-time monitoring stage. If the breathing signal still does not come back in the next 5 seconds, an apnea warning is reported. Fig.4.13 shows an apnea is detected if no breathing signal peak is detected in 15 seconds.
Figure 4.12: Normal breathing signal displayed in time-domain

Figure 4.13: An apnea is detected in real-time monitoring
Chapter 5

Conclusion

In this thesis, a stand-alone device made up with a PulseON410 UWB Radar and a micro computer RaspberryPi is developed and used to collect breathing signal data wirelessly. The signal processing algorithm is developed to extract the breathing signal. The device is tested in the laboratory on an adult and the result is compared with the reference signal collected from a microphone. The device and algorithm is proved in the sense of collecting the right breathing signal in different frequencies. Then a real-time detection system used to monitor breathing and to detect apnea is developed using UWB radar technology and Matlab. The detailed algorithms are discussed for the functions of signal filtering, target localization, peak detection and apnea warning.


Appendix A

Collaborative Institutional Training Initiative (CITI) completion report

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<td>PHONE</td>
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**GROUP 1. BIOMEDICAL RESEARCH INVESTIGATORS AND KEY PERSONNEL**

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Director Office of Research Education
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