Real-Time Non-Contact Infant Respiratory Monitoring Using UWB Radar

Xinming Huang[1,2], Ling Sun[1], Tian Tian[2], Zeyan Huang[2], Edward Clancy[2]

[1]School of Electronics and Information, Nantong University, Nantong, China 226019
[2]Department of Electrical and Computer Engineering, Worcester Polytechnic Institute, MA 01609, USA
xhuang@wpi.edu

Abstract: This paper presents a real-time system that can monitor an infant's respiration and detect apnea when it occurs. For infants, bedside monitoring of respiratory signals using noncontact 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 paper, a novel method is introduced by using 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.

Keywords: Respiratory monitoring; Apnea; UWB radar; Localization

1 Introduction

Apnea is a term for suspension of external breathing. During apnea, there is no movement of the respiration muscles and the lung volume remains unchanged. Apnea especially sleep 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. Traditional approaches to monitor neonatal apnea include wrapping a band around a baby's chest, putting a sensor beneath an infant's mattress, or analyzing chemical content of an infant's expiration [1]. Such approaches may cause neonatals as well as their parents nervous and are sometimes rejected by parents.

In this paper, a non-contact approach to detect an infant's breathing signal is proposed by using an ultra-wideband (UWB) radar [2]. UWB radar has been proved for better performance than other techniques such as receiver signal strength (RSS) and ultrasound for indoor localization [3]. The most important feature of UWB radar is the high spatial resolution which is suitable for detecting human's vital signs such as respiration [4]. Moreover, detecting infant apnea and informing a nurse when it occurs is a critical application that may save lives. This paper focuses on developing a real-time hardware prototype in conjunction with advanced signal processing algorithms that can track an infant's position, acquire and identify an infant's breathing signal, and trigger the alarm when an apnea occurs.

Related work includes infant position tracking [5], breathing monitoring [6] [7] [8], two dimensional power spectrum density and band pass filter [9] for localization and signal processing.

2 Methods

In this paper, UWB radar captures the signal and then transfers raw data to an embedded processor through USB interface. All signal processing algorithms are executed on the embedded processor to track an infant's location and to monitor its respiration at real-time.

2.1 UWB radar

UWB radar is a technology for transmitting information spread over a large bandwidth (usually larger than 500MHz), while providing a low-power density and reducing interference. The UWB pulses are short and spread their energy over a broad frequency range. The nature of UWB radar makes it more power-efficient than other continuous wave radars.

In particular, the Time Domain's PulsON400 UWB radar board is chosen for this research [10]. Figure 1(a) is the radiation signal waveform which achieves a bandwidth of 2.2 GHz and is transmitted periodically as a UWB pulse. Figure 1(b) shows that the signal power spectrum meets FCC regulation. After each pulse transmission, the receiver captures the comeback wave that is collected as one scan data shown in Figure 2 [10] [11]. The scan time after each pulse transmission determines the detection range of the radar.

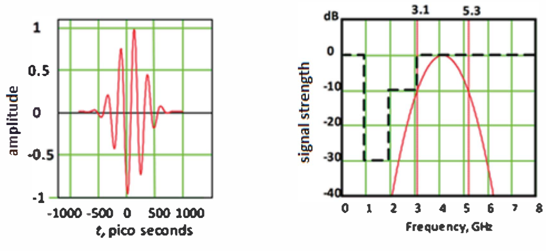

Figure 1 (a) Pulse transmitted by the radar **(b)** Transmit signal power spectrum

The radar system uses coherent transmissions to

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maintain the same phase of each transmitted pulse. The received signal power of many coherent pulses is 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 Figure 3 [10] [11].

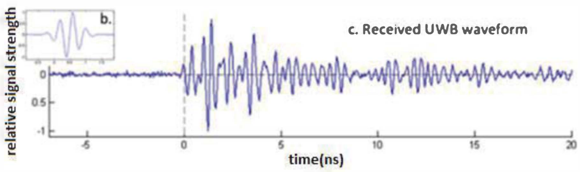

Figure 2 Comeback waveform sensed by the radar receiver

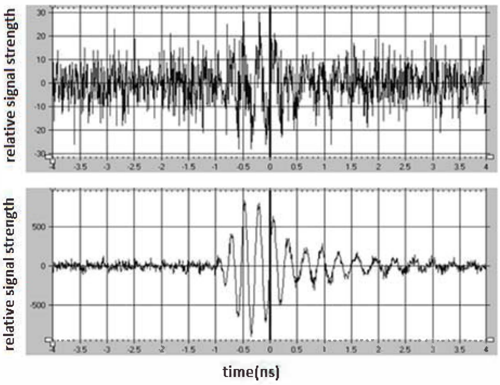

Figure 3 Received signal with different integrated ratio (16:1 means 16 received pulses are summed to form one scan and 512:1 means 512 received pulses are summed).

2.2 Mathematical models

Typically, the frequency range of the breathing signal is between 0.25 and 1 Hz. For relaxed human beings, respiration can cause chest movement from 0.1mm to several millimeters. When a pulsed signal is transmitted to a human target, it will be reflected due to the high reflectivity of the body. The distance between human chest and antenna is denoted by s_0. The distance varies due to the respiration motion [12].

Here d_r and f_r are the respiration chest movement amplitude and frequency respectively. The total distance is:

$$s(t) = s_0 + d(t) = s_0 + d_r \sin(2\pi f_r t) \quad (1)$$

According to radar transmission theory, the received signal includes echoes from different channels with different delay variations due to respiration. The normalized received pulse is denoted by $p(t)$. The total received signal can be represented by:

$$r(t,\tau) = \sum_k A_k p(\tau - \tau_k) + Ap(\tau - \tau_d(t)) \quad (2)$$

where A_k , A are the amplitudes of each echo from other channels and human body. τ_k, τ_d are the time delay of each echo from other channels and human body. τ_d is determined by antenna distance $s(t)$:

$$\tau_d(t) = \frac{2s(t)}{c} = \tau_0 + \tau_r \quad (3)$$

where c is the light velocity. UWB radar captures the received signal into a 2-D M × N matrix, denoted by $R[m,n]$:

$$R[m,n] = r(\tau = mT_f, t = nT_s) \quad (4)$$

The row vectors record one time pulse reflected from different range, denoted by m, which represents $\tau = mT_f$ (fast time). The column vectors record received signals at different time at each location, denoted by n, which represents $t = nT_s$ (slow time).

In a static environment, the clutter from the background can be considered DC component and can be removed easily by subtracting the mean from the matrix, in both rows and columns. After subtraction, there will be only one received signal remained:

$$r(t,\tau) = Ap(\tau - \tau_d(t)) \quad (5)$$

The Fourier transform of $r(t,\tau)$ is:

$$R(f,\tau) = A\sum_{i=-\infty}^{\infty} G_i(\tau)\delta(f - if_r) \quad (6)$$

where the functions $G_i(\tau)$ can be computed using Bessel functions:

$$G_i(\tau) = \int_{-\infty}^{+\infty} P(v)\, J_i(\beta_r v) e^{(j2\pi v(\tau-\tau_0))} dv \quad (7)$$

where $P(v)$ is the Fourier transform (in fast-index) of the received pulse.
It can be proved that $G_i(\tau)$ is maximized at $\tau = \tau_0$:

$$U_i \equiv G_i(\tau_0) = \int_{-\infty}^{+\infty} P(v)\, J_i(\beta_r v) dv \quad (8)$$

where $\beta_r = 2\pi d_r$.
Consequently,

$$R(f,\tau_0) = A\sum_{i=-\infty}^{\infty} U_i\, \delta(f - if_r) \quad (9)$$

From the equation, we can know that the spectrum of received signal after DC component removal consists of a series of delta function at every harmonics of respiration frequency if_r. The amplitude of each delta function is controlled by U_i: Therefore the respiration signal is included in the received signal matrix and can be obtained by processing the slow time signal.

2.3 Band pass filter

The main purpose of the band pass filter is to attenuate signals that are unrelated to respiration. A filter is designed to pass frequencies within a certain range and attenuate frequencies outside that range. A Butterworth type band pass filter is utilized to make frequency response as flat as possible in the pass band. It is also referred to as a maximally flat magnitude filter, which is ideal for our design. Before implementing the band pass filter, the received signal is subtracted by the mean value of the original signal to eliminate random background clutter.

Table I Respiration rate by age

Age	Respiration Rate (breaths/minute)	Respiration Rate (Hz)
Birth to 1 year	30-60	0.5-1
1-3 years	24-40	0.4-0.67
3-6 years	22-34	0.37-0.57
6-12 years	18-30	0.3-0.5
12-18 years	12-16	0.2-0.27

For the band pass filter design, frequency information of our target should be predetermined. In our case, we are primarily interested in respiration speed of 15 to 60 breaths per minute that is 0.25 Hz to 1 Hz in frequency domain. Correspondingly, the band pass frequency of the filter is set to 0.2 Hz to 1.1 Hz empirically. Table I shows typical breathing rates for children at different ages and adult.

2.4 Respiratory monitoring and apnea detection

For respiratory monitoring, we need to find the exact location of the breathing object and its breathing frequency. Therefore, we propose a peak detection algorithm using power-spectrum density (PSD) analysis, which reveals the signal with the highest SNR. For continuous monitoring, we need to keep track of the object since an infant may move in the incubator or crib. Therefore, the peak detection algorithm needs to be executed periodically to track the object. Once we locate the breathing location, the received time-domain signal at that location is record and display as the de facto breathing signal on the monitoring screen. Certainly, the breathing signal data can also be transferred to the doctor's office through computer network at real-time.

For apnea detection, it is to identify a period of time when breathing signal is absent. During infant apnea, no evident signal peaks above the threshold are detected. We propose a parameter called dynamic threshold that 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 apnea detection more robust. If there are not many peaks above the current threshold, the threshold starts to increase gradually. The higher threshold helps to eliminate the artificial noise. If no peak above threshold is detected for an extended period of time such as 10 seconds, an alarm is set off. Our experimental results show that this dynamic threshold method can reduce the false alarm rate.

3 Experimental results

In this section, we present the measurement results using an experimental platform with PulsON400 UWB radar. The radar is connected to a Raspberry Pi embedded processor through USB interface. Figure 4 shows the hardware setup. The radar acquires the raw data and the embedded processor serves as the controller. The detailed steps of the experiment are described as follows.

The radar is placed about 1 meter away from an infant. Obstacles in between are permitted except for metal material, since metal can absorb electromagnetic wave. In our experiment, the range of the UWB radar system is set to 4.8 meters. The spatial resolution is 1 cm.

Figure 4 Experimental setup with UWB radar and an embedded processor

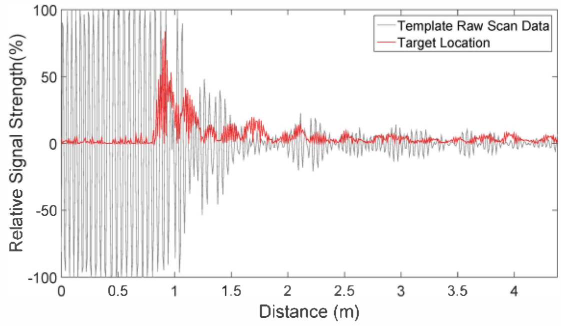

Figure 5 An example of the raw data acquired by the UWB radar from one scan

The original data is obtained from the UWB radar receiver, which are samples of the received signal strength in real-time. Figure 5 shows an example of the received signal at different locations from one scan.

Next, we record the signal for 60 seconds at each target position. So the acquired signals can be sorted into a two-dimensional (2D) matrix as described in Section 2.2. At first, the mean value is removed from the signal. Then a band pass filter is applied to attenuate unrelated information. Only signals between 0.25 to 1.0 Hz are retained. Figure 6 shows an example of the filter signal, which indicates possible respiration activities at the distance of about 1 meter from the radar.

In order to find the exact location and the frequency of the breathing signal, we employ PSD analysis to find the peak with highest SNR. Figure 7 shows that the PSD of the breathing signal at the location of 0.97 meter from the radar and its frequency is about 0.67 Hz.

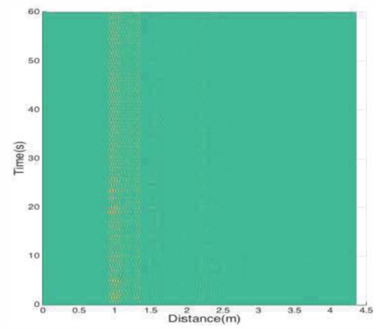

Figure 6 Two-dimensional signal plot after background removal and band pass filter

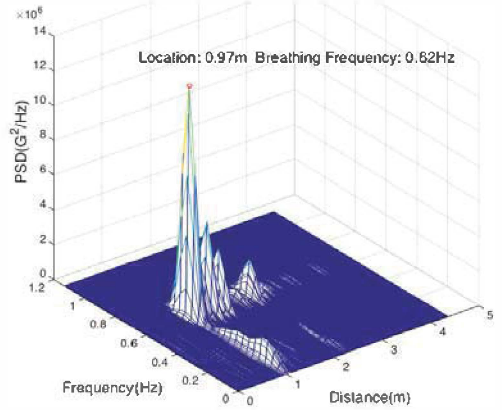

Figure 7 Location and frequency are determined by PSD

Once we identify the location, the time-domain signal can be captured and displayed. Figure 8 show the normal breathing activity of an infant at the identified location. As mentioned in Section 2.4, we propose an adaptive threshold to detect apnea. If we directly use the amplitude and frequency of the time-domain signal as criteria of apnea, it would result many false alarms since the breathing signal captured by the radar can be very volatile. The adaptive threshold increases gradually when signal is weak, but it declines quickly if a strong signal is detected. As shown in Figure 8, the threshold value is close to zero when breathing is normal. Figure 9 shows an apnea is detected if no breathing signal is above the threshold value for about 15 seconds.

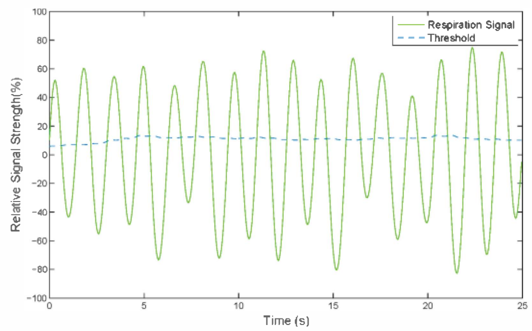

Figure 8 Normal breathing signal is displayed in time-domain

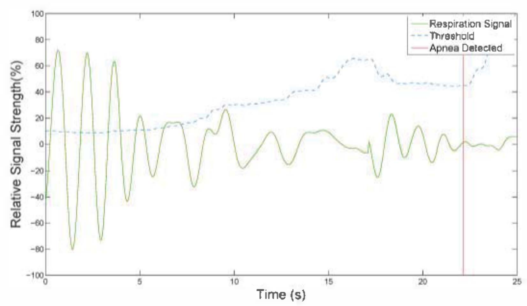

Figure 9 Apnea is reported if no breathing signal is above the threshold for 15 seconds

In practice, we have to consider the movement of an infant. If no breathing signal is detected above threshold for 10 seconds, the system will automatically execute the peak detection algorithm using the previous 10 seconds' data to relocate a breathing object. This is effectively to track the infant location. If a peak is detected at another location, the time domain signal of the updated location is applied and the threshold will quickly go down to zero. If no peak is detected and the breathing does not come back within the next 5 seconds, an apnea warning is reported to the nurse and interventions can be applied timely.

4 Conclusion

In this paper, we present a real-time respiratory monitoring and apnea detection system using non-contact UWB radar technology. The detailed algorithms are discussed such as signal filtering, target localization, peak detection, and apnea warning. Our preliminary results prove the feasibility of the proposed technique. The UWB radar is integrated with an embedded processor as a compact experimental platform. More data collection and validation are currently underway with the collaboration of the neonatal intensive care unit at a local hospital.

References

[1] B.-H. Chu, B. S. Kang, C. Chang, F. Ren, A. Goh, A. Sciullo, W. Wu, J. Lin, B. P. Gila, S. Pearton, J. Johnson, E. L. Piner, and K. Linthicum, "Wireless detection system for glucose and pH sensing in exhaled breath condensate using algan/gan high electron mobility transistors," IEEE Sensors Journal, vol. 10, no. 1, pp. 64–70, 2010.

[2] K. Ota, Y. Ota, M. Otsu, and A. Kajiwara, "Elderly-care motion sensor using UWB-IR," in IEEE Sensors Applications Symposium (SAS), pp. 159–162, 2011.

[3] M. Kuhn, C. Zhang, S. Lin, M. Mahfouz, and A. Fathy, "A system level design approach to uwb localization," in IEEE MTT-S International Microwave Symposium Digest (MTT '09), pp. 1409–1412, 2009.

[4] A. Lazaro, D. Girbau, R. Villarino, and A. Ramos, "Vital signs monitoring using impulse based uwb signal," in 41st European Microwave Conference (EuMC), pp. 135–138, 2011,

[5] N. Andre, S. Druart, P. Gerard, R. Pampin, L. Moreno-Hagelsieb, T. Kezai, L. Francis, D. Flandre, and J.-P. Raskin, "Miniaturized wireless sensing system for real-time breath activity recording," IEEE Sensors Journal, vol. 10, no. 1, pp. 178–184, 2010.

[6] J. Li, L. Liu, Z. Zeng, and F. Liu, "Simulation and signal processing of uwb radar for human detection in complex environment," in the 14th International Conference on Ground Penetrating Radar (GPR), pp. 209–213, 2012.

[7] T. Akiyama, T. Ikegami, and K. Takizawa, "A non-invasive detection of respiration by using ultra wideband signals," in the 15th International Symposium on Wireless Personal Multimedia Communications (WPMC), pp. 514–518, 2012.

[8] Y. Xu, S. Dai, S. Wu, Y. Dang, J. Chen, and G. Fang, "Novel detection method and parameters analysis of vital signal for ultra-wideband radar," in IEEE International Geoscience and Remote Sensing Symposium (IGARSS), pp. 1822–1825, 2011.

[9] A. Aoude, R. Kearney, K. Brown, H. Galiana, and C. Robles-Rubio, "Automated off-line respiratory event detection for the study of postoperative apnea in infants," IEEE Transactions on Biomedical Engineering, vol. 58, no. 6, pp. 1724–1733, 2011.

[10] T. Domain, "Time domain data sheet of PulsON 400," Time Domain, June 2012.

[11] ——, "Time domain ultra wideband (UWB) definition and advantages," Time Domain, June 2012.

[12] A. Lazaro, D. Girbau, and R. Villarino, "Analysis of vital signs monitoring using an ir-uwb radar," Progress In Electromagnetics Research, vol. 100, pp. 265–284, 2010.