Breathing and Heartrate Monitoring System using IR-UWB Radar

Muhammad Salman Raheel[1,*], James Coyte[1], Faisel Tubbal[1], Raad Raad[1], Philip Ogunbona[2], Christopher Patterson[3], Dana Perlman[4]
[1]School of Electrical, Computer and Telecommunications Engineering,
[2]School of Computing and Information Technology,
[3]School of Nursing,
[4]School of Education,
University of Wollongong, Australia
{*raheel, jacoyte, faisel, raad, philipo, cpatters, dperlman}@uow.edu.au

***Abstract* — This paper provides a feasibility study of estimating the heartrate and the breathing rate, using the waveform spectrum recorded by impulse radio ultra wideband (IR-UWB) radar. An algorithm is proposed that helps to separate the heartrate signal from the breathing signal. Furthermore, a Kalman filter is introduced that helps to reduce the noise factor from the obtained waveforms. The simulation result shows that the proposed algorithm can effectively estimate the breathing rate up to 97-99% and the heartrate above 90 % accuracy as compared to the traditional clinical equipment such as electrocardiograph (ECG).**

Keywords— vital signs; IR-UWB radar; heartrate; breathing rate; Kalman filter

I. INTRODUCTION

In recent years, the commercialization of Ultra-Wide Band (UWB) technology to operate at frequencies between 3.1 GHz to 10.6 GHz has stimulated great interest in wireless communication systems; particularly in RF tagging or identification [1] and in radar sensor applications [2]. These UWB wireless systems are focused to transmit or receive sub-nanoseconds pulses without the carrier signal such as in Impulse Radio (IR) UWB and sometimes use the modulated short pulses with the carrier. Recent studies show that such systems are built on a simple CMOS circuitry; hence consume less power, have low system complexity and high data rates [3]. Such advantages of UWB technology has recently driven the attention of researches to use it for medical applications [4-5], such as in medical imaging and for healthcare monitoring system specifically vital signs.

To date, the health professionals; such as doctors and nurses use clinical methods to measure vital signs [6]. This include, for example, the attachment of sensing devices to the patient body such as pulse oximeter for measuring the heartrate, or a nasal cannula for breathing rate [7]. Other traditional monitoring systems include; Poly-sonography (PSG), in which number of wearable sensors are connected through wires [8]. These sensors include: electroencephalography (EEG) that tracks the electrical brain activity, electrooculography (EOG) electrodes to measure the movement of eye, electromyography (EMG) electrodes for recording muscle activity, electrocardiography (ECG) electrodes for measuring the electrical heart activity, Although, these systems provide continuous real time monitoring of patient well-being but at the expense of high cost and complexity. Moreover, the continuous use of such devices cause allergies or rashes to the patients with sensitive skins [9].

Hence, the main challenge arises is to design a non-invasive vital sign monitoring system that allows monitoring the patient's vital signs without any attachments. The capability of UWB sensors to identify macro and micro movements inside the human body (e.g. heartbeat and respiration) makes it suitable to use for monitoring vital signs. On the other hand, Microwave Doppler radar [10] technique is also used for non-invasive detection of vital signs. However, this technique finds difficulty in penetrating through walls or obstacles as compared to UWB radars [11].

This paper provides the feasibility study of estimating the heartrate and breathing rate of a person using an IR-UWB radar. It has been investigated in [12], that at rest, the heart displaces chest by 0.08 mm whereas the breathing causes a displacement from 1 mm to several millimetres. Hence, the breathing rate signal has higher magnitude as compared to the heartrate signal. Furthermore, the heartrate becomes difficult to detect if the breathing harmonics or intermodulation product of breathing rate and heartrate falls within the heartrate frequency range. Therefore, the overall objective of this work is to propose an algorithm that can effectively detect the breathing rate and heartrate of a person within the range of an IR-UWB radar.

The paper is organized as follows. Section 2 discusses the related work. Section 3 explains the measurement setup and Section 4 explains the proposed algorithm. The simulations results are shown and discussed in Section 5. Finally, Section 6 provides the conclusion and future recommendations.

II. RELATED WORK

As discussed earlier, the non-invasive vital sign monitoring system using the UWB radar has gained high attention during the last few years due to its high spatial resolution and low power consumption. Hence, numbers of research are carried forward [13-19] to estimate the heartrate and breathing rates. Osberger et al. [13], propose a continuous wavelet transform (CWT) algorithm accompanied with a background subtraction filter to detect the respiration movement of a hidden person using an UWB pulse radar system. The simulation result shows that the proposed system can able to detect the respiration signal up to the distance of 5 meters and behind the walls. However, the authors do not consider the breathing rate.

Similarly Venkatesh et al. in [14], discussed the use of IR-UWB signals to detect the chest cavity motion. They propose signal-processing algorithms suitable for the estimation of breathing and heartbeat rates, even within the presence of obstacles. However, the proposed solution does not consider the breathing and heartrate harmonics, which introduces noise factor due to false peaks in the signal. Moreover, there are several other scenarios wherein patients are monitored using UWB radars for heartrate, cardiac and motion activities such as in post-operative chambers. Immoreev et al. in [15] proposed an algorithm to restore and analyze quadrature signals arising from back and forth of patients' thorax and heart. However, the drawback of this contribution is lack of detailed description of algorithm used to obtain the reported results.

Lazaro et al. in [4] provides a mathematical model for estimating the heartrate and breathing rate using IR-UWB sensors. Furthermore, the authors' use Bessel functions and Fourier transform to obtain the breathing harmonics and the intermodulation products of breathing and heartrate. Moreover, in order to improve heart rate detection, a filter is designed that cancels out the breathing harmonics. The simulation results indicate higher accuracy of breathing rate estimation. However, the proposed system is not able to handle random body movements during a one-time measurement.

Multipath impulse response of the human body and breathing noise can lead to inaccurate estimation of the breathing rate. Therefore, Kang et al. [16], propose a reliable method to estimate breathing rate using an IR-UWB radar that incorporates multipath impulse response. They use an energy detector to extract the respiration signal reflected from the human body to reduce multipath effect. Then, a noise subspace method is used to estimate the respiration rate. However, they used sample autocorrelation function to estimate the breathing rate autocorrelation. Experiment result shows that the proposed method is more reliable as compared to the conventional method.

Similarly, Nguyen et al. in [17] suggest a harmonic path algorithm to estimate breathing and heartrate. The algorithm first finds the peaks with power above the selected threshold, computes a pairwise frequency distance, and only retains the peaks with pairwise distance between the heart ranges. In addition, the peaks with equal pairwise distances form a contiguous path and then average inter-peak distance is calculated over the path. Then, a harmonic path test (nodes with multiple frequencies to each other) is performed to ascertain if a path is to be discarded. The simulation result shows improvement in estimating the heartrate and breathing rate under harmonics interference.

Moreover, Khan et al. in [18] propose an approximation algorithm to estimate the breathing and heartrate. In a pre-processing phase, an averaging filter is used to remove clutter from the received signal. The breathing frequency is then estimated based on maximum peak locations of the spectrum. Furthermore, a notch filter is used to remove breathing harmonics. This allows heartrate to be estimated from the resulting signal; selecting more than one peak in the heart frequency range (1Hz-3Hz).

In a follow up work [19] Khan et al. added a movement detection method based on autocorrelation concept to the algorithm presented in [18]. The simulation result shows that the proposed algorithm provides stability in estimating the heartrate and breathing rate values. However, it cannot estimate the vital signs during the motion and waits until the object comes to rest. In this paper, we consider a similar approach as discussed in [19] to estimate the heartrate and breathing rate of the body.

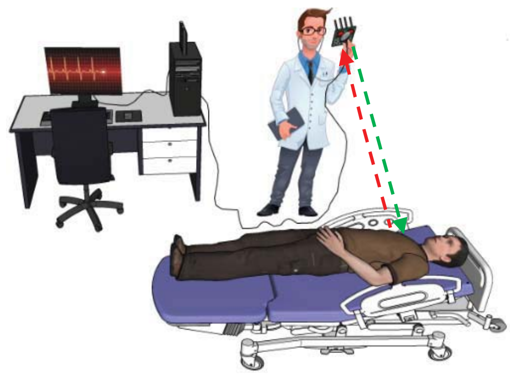

Figure 1. IR-UWB radar experimental setup

III. Measurement Setup

The basic measurement setup for the proposed monitoring system is shown in Figure 1. The IR-UWB radar is connected to a desktop machine using a USB interface to receive the raw impulse data reflected from the human body. The MATLAB software is used for algorithm design and signal processing of the received signal. This measurement setup uses a Xethru® X4M03 module [20], which consists of a pair of X4A02 directional patch antennas with integrated Wi-Fi filter, Xethru X4 radar SOC and Atmel®SAMS70 microcontroller for controlling X4 SOC and to communicate with external devices. The radar operates within the range of 5.9-10.3 GHz with a 65-degree patch aperture in both axes. The range of the radar is programmable up to 10m, however, for testing purposes the range is considered for the data reception within the 3m distance from a radar and a human body.

IV. Proposed Algorithm

The flow chart of the proposed algorithm is shown in Figure 2. Initially, the raw impulse data is acquired after reflection from a human body as shown in Figure 3. As discussed earlier, the frequency with higher magnitudes correspond to respiration rate while those with lower magnitude values correspond to heartrate. In the next stage, the the slow time and fast time matrix are extracted from the buffered values. The slow time matrix helps to identify the frequency of the UWB radar or a time between each pulse, whereas the fast time matrix identifies the distance of a human body from the radar. Afterwards, a loopback filter is used to remove the unwanted clutter from the slow time and fast time matrix as discussed in [21], where the background substraction parameter α is set at 0.96. The value of α is chosen based on the radar waveform and it is considered as a reasonable value to remove unwanted information without losing the useful information. In the next step, the algorithm compute the variance along the slow time axis for each row in the fast time matrix. This helps to identifies the chest displacement of a person, which is required to estimate the breathing rate. Moreover, a 40 dB Chebyshev is applied to attenuate the upper and lower ends of the respiration signal in the time domain in order to reduce the effects of spectral leakage [22]. Similarly, an adaptive Kalman filter is used that helps to remove any unwanted additive noise due to surroundings or

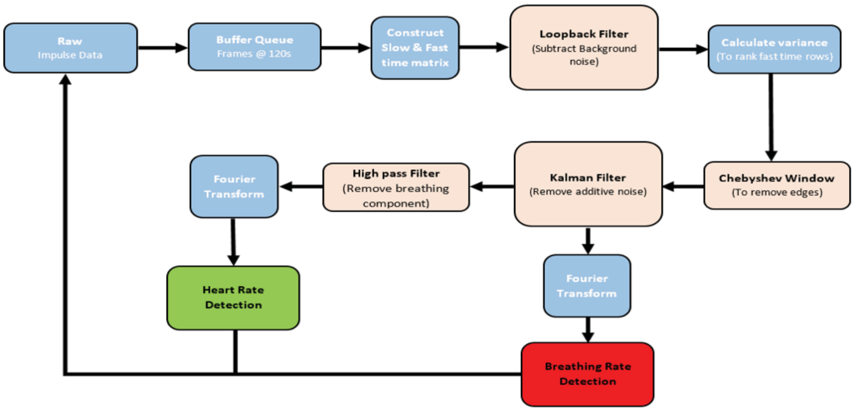

Figure 2. Proposed Algorithm

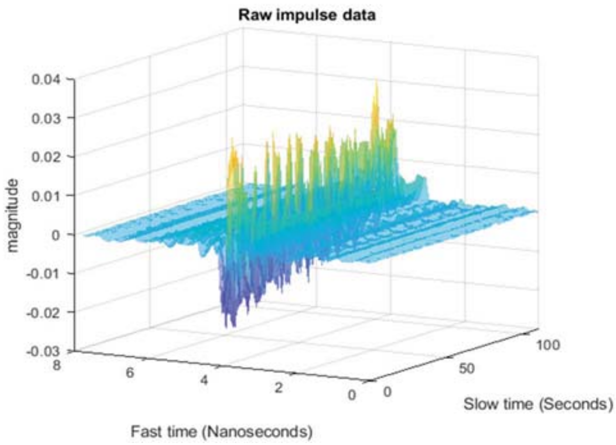

Figure 3. Raw Impulse Data

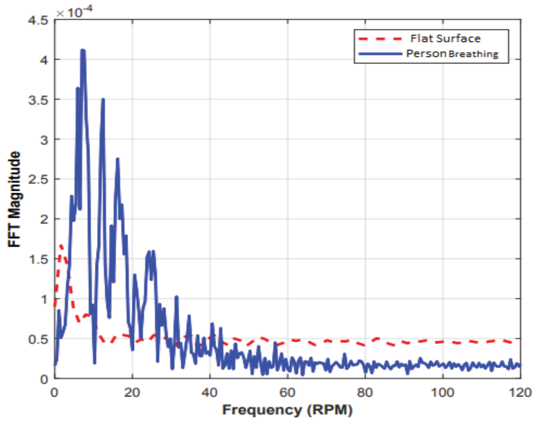

Figure 4. UWB Radar Setup Testing

through any possible vibrations. Subsequently, the frequency response of the time domain signal is calculated to identify the highest peak, which estimates the breathing rate frequency. Whereas, in the case of heart rate detection, the waveform received after the Kalman filter is again passed through a highpass filter which is set to around 0.5 Hz. This allows to filter out the breathing signal from the heartrate signal. Finally, the FFT is done on the signal received from highpass filter and an approximate value of heartrate is detected.

V. Experimental Results and Discussions

We evaluate the performance of the proposed algorithm based on vital sign measurement of a person aged between 25-30 years, sitting on a chair (at rest position) within the 3m range of an UWB radar. Before, we start recording the actual measurements; an initial testing is performed to validate if the radar is working appropriately. To do this, we obtain the FFT response of the radar signal transmitted and reflected back through a wall ceiling as well as from a person as shown in Figure 4. The result shows that if the signal is reflected from the flat surface the FFT response is almost negligible as the actual transmitted signal is received in the inverted state. However, if the signal reflects from the person, it has higher peaks of FFT magnitude due to the chest displacement and the received signal is the addition of transmitted and the displacement signal. This result can also help to identify alive person within the range during disaster recovery. Figure 5 (Upper plot) shows the signals extracted from the slow time fast time matrix with the largest variance, which contained the periodic motion caused by contraction and relaxation of heart and lungs. Figure 5 (lower plot) Kalman filter smoothing of the respiration rate signal with the local maximum peaks highlighted on the stem plot. Similarly, Figure 6 shows the waveform of the reflected oscillations caused by the test subject's pulse rate and the red waveform shows the average heart rate, obtained after passing through a high pass filter.

Finally, Table 1 summarizes the experimental results and validate that our proposed algorithm can effectively obtain the breathing rate up to 97-99% and the heartrate above 90 % accuracy as compared to the traditional clinical equipment such as electrocardiograph (ECG).

Table 1. Accuracy of proposed algorithm for heart & breathing rate estimation compared to the existing ECG

Breathing Patterns	Breathing rate			Heartrate		
	IR-UWB Radar (Cycles Per Minute)	Invasive Device (Cycles Per Minute)	Error Ratio	IR-UWB Radar (Cycles Per Minute)	Invasive Device (Cycles Per Minute)	Error Ratio
Deep	6.95	7	1%	60	64	6.25%
Normal	8.16	8	1.7%	72	78	7.6%
Fast	13.56	14	3%	80	89	9%

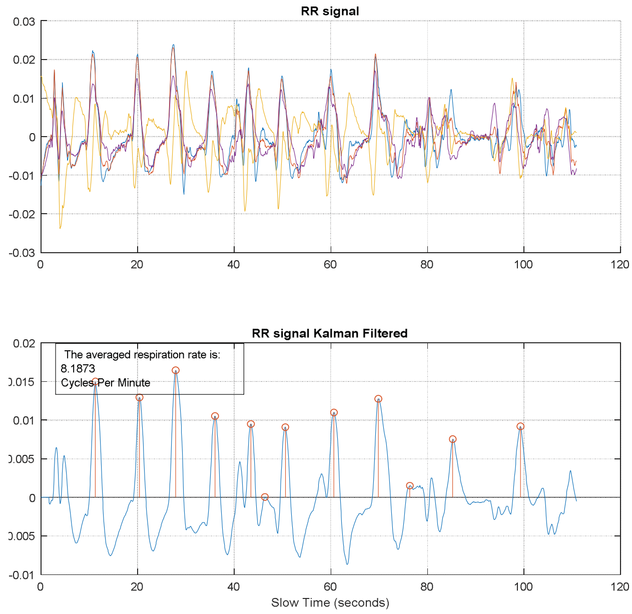

Figure 5. UWB Radar Setup Testing

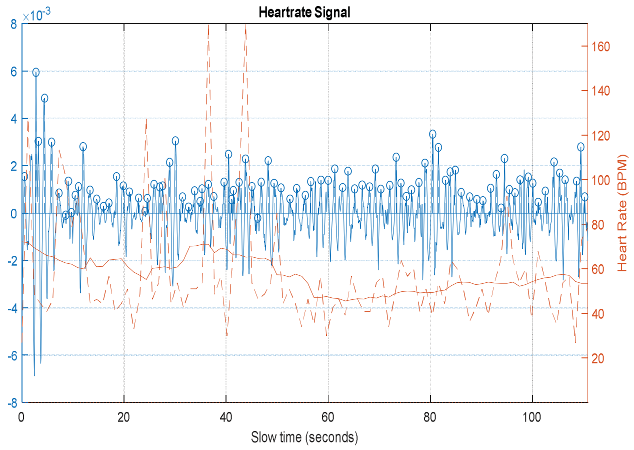

Figure 6. Average Heart rate vs the heart oscillation signal

VI. Conclusion and Future Work

This paper provides a feasibility study of continuous non-invasive vital signs monitoring system; particularly the heartrate and the breathing rate, using the waveform spectrum recorded by impulse radio ultra wideband (IR-UWB) radar. Furthermore, an algorithm is presented to separate the heartrate signal from the breathing signal and calculate their respective frequencies. The simulation result shows that the proposed algorithm can effectively estimate the breathing rate up to 97-99% under different scenarios and the heartrate above 90% as compared to the values obtained using an invasive device. Hence, the device can be used as a non-invasive method for patient monitoring. In the future, we consider testing our proposed system under different scenarios; such as; if a person is not facing the device or there is a continuous additive noise. Furthermore, we aim to improve the heartrate monitoring accuracy by designing a better adaptive filter.

References

[1] Y. Ma, N. Selby, and F. Adib, "Minding the billions: Ultra-wideband localization for deployed RFID tags," in Proc. ACM Mobile Computing and Networking, Snowbird, UT, pp. 248–260, Oct 2017

[2] A. Lazaro, A. Ramos, D. Girbau and R. Villarino, "A Novel UWB RFID Tag Using Active Frequency Selective Surface," IEEE Transactions on Antennas and Propagation, vol. 61, no. 3, pp. 1155-1165, March 2013

[3] Fontana, R. J., Recent system applications of short-pulse ultra-wideband (UWB) technology," IEEE Trans. on Microwave Theory and Tech., Vol. 52, No. 9, 2087-2104, 2004

[4] A. Lazaro, D. Girbau, and R. Villarino, "Analysis of vital signs monitoring using an ir-UWB radar," Progress In Electromagnetics Research, Vol. 100, 265-284, 2010

[5] Bilich, C. G., \Bio-medical sensing using ultra wideband communications and radar technology: A feasibility study," IEEE Pervasive Health Conference and Workshops, 1-9, Nov. 2006

[6] Y. Cho, S. J. Julier, N. Marquardt, and N. Bianchi-Berthouze, "Robust tracking of respiratory rate in high-dynamic range scenes using mobile thermal imaging," Biomedical Opt. Express, vol. 8, pp. 4480-4503, Oct. 2017

[7] M. Folke, Cernerud, M. Ekström, and B. Hök, "Critical review of non-invasive respiratory monitoring in medical care," Medical and Biological Engineering and Computing, vol. 41, pp. 377-383, 2003

[8] C. A. Kushida, M. R. Littner, T. Morgenthaler, C. A. Alessi, D. Bailey, J. Coleman, L. Friedman, M. Hirshkowitz, S. Kapen, M. Kramer, T. Lee-Chiong, D. L. Loube, J. Owens, J. P. Pance, and M. Wise, "Practice parameters for the indications for polysomnography and related procedures: an update for 2005,," Sleep, vol. 28, pp. 499-523, Apr. 2015

[9] Fitbit Acknowledges Latest Devices are Causing Rashes, Advises to "Give Your Wrist a Rest", [online]. Available: https://techcrunch.com/2015/02/11/fitbit-acknowledges-latest-devices-are-causing-rashes-advises-to-give-your-wrist-a-rest (accessed on 7 December 2017)

[10] Lubecke, O.B.; Ong, P.-W.; Lubecke, V.M. 10 GHz Doppler radar sensing of respiration and heart movement. In Proceedings of the IEEE 28th Annual Northeast Bioengineering Conference, Philadelphia, PA, USA, 20–21 April 2002

[11] Safaai-Jazi, A., S. M. Riad, A. Muqaubel, and A. Bayram, Report on through-the-wall propagation and material characterization," DARPA NETEX program, "Ultra-wideband propagation measurements and channel modeling," Nov. 2002

[12] Singh, M. and G. Ramachandran, Reconstruction of sequential cardiac in-plane displacement patterns on the chest wall by laser speckle interferometry," IEEE Trans. Biomed. Eng., Vol. 38, No. 5, 483-489, 1991

[13] Ossberger, G., T. Buchegger, E. Schimback, A. Stelzer, and R. Weigel, Non-invasive respiratory movement detection and monitoring of hidden humans using ultra wideband pulse radar," Proc. of the 2004 International Workshop on Ultra Wideband Systems Joint with Conference on Ultra Wideband Systems and Technologies, 395-399, Piscataway, NJ, USA, 2004

[14] Venkatesh, S., C. Anderson, N. V. Rivera, and R. M. Buehrer, Implementation and analysis of respiration-rate estimation using impulse-based UWB," 2005 IEEE Military Communications Conference (IEEE Milcom'05), Vol. 5, 3314-3320, Oct. 2005

[15] Immoreev, I. and T.-H. Tao, UWB radar for patient monitoring," Aerospace and Electronic Systems Magazine, No. 11, 18, 2008

[16] Jae-Mo Kang, Dong-Woo Lim, Jae-Hwan Lee, Changdon In, Hyung-Myung Kim, Sung-Chul Woo, Cheonsoo Kim, "Reliable estimation of respiration rate using UWB impulse radar", Microwave Conference Proceedings (APMC) 2013 Asia-Pacific, pp. 997-999, 2013

[17] V. Nguyen, A. Q. Javaid and M. A. Weitnauer, "Harmonic Path (HAPA) algorithm for non-contact vital signs monitoring with IR-UWB radar," 2013 IEEE Biomedical Circuits and Systems Conference (BioCAS), Rotterdam, 2013, pp. 146-149

[18] F. Khan, J. W. Choi and S. H. Cho, "Design issues in vital sign monitoring through IR UWB radar," IEEE International Symposium on Consumer Electronics (ISCE 2014), JeJu Island, 2014, pp. 1-2

[19] F. Khan, J. W. Choi and S. H. Cho, "Vital sign monitoring of a non-stationary human through IR-UWB radar," 2014 4th IEEE

International Conference on Network Infrastructure and Digital Content, Beijing, 2014, pp. 511-514

[20] Xethru by Novelda, Xetrhru X2 Impulse Radar Transceiver Datasheet. https://www.xethru.com/community/resources/x2-datasheet.24/, accessed 2017-12- 01

[21] Yim, D.H.; Cho, S.H. An Equidistance Multi-human Detection Algorithm Based on Noise Level Using Mono-static IR-UWB Radar System. In Proceedings of the 2014 International Conference on Future Communication, Information and Computer Science (FCICS 2014), Beijing, China, 22–23 May 2014

[22] Digital Signal Processing Committee of the IEEE Acoustics, Speech, and Signal Processing Society, eds. Programs for Digital Signal Processing. New York: IEEE Press, 1979, program 5.2.