Contact-Free Vital Sign Estimation Using Ultra-Wide Band Radar

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***Abstract*—This study presents an ultra-wideband (UWB) radar solution for contact-free sensing and estimating human vital signs. The proposed solution uses radio frequency (RF) signals to estimate even the tiniest chest movements, including those induced by breathing and the heartbeat. Our algorithm calculates heart rate (HR) and breathing rate (BR) based on signal processing techniques. Our algorithm is validated by comparing its results against the data obtained from a medical-grade wearable sensor. In our study, the correlation between the reference sensor and radar sensor yields 98.2% accuracy in breathing rate estimation. Additionally, we measured the root mean square error (RMSE) between the reference sensor and radar sensor and found it to be 1.36.**

***Index Terms*—Non-Contact, UWB radar, FFT, Vital Sign, RMSE.**

I. Introduction

Vital signs are measured continuously and non-invasively to obtain basic parameters of a patient's health status. Breathing and heartbeat signals are significant bio-signals that not only give information about patients' physical health but also help various public health systems manage their everyday operations [1]. The resting heart rate can indicate coronary heart disease and has strong links to non-cardiovascular disorders, including stroke and sudden death [2]. For example, a higher resting heart rate is associated with heart failure, while a decrease in a patient's respiratory rate may suggest the development of hypoxia [3].

Current contact-based techniques, such as belt sensors placed around the patient's abdomen to monitor breathing rate [4] and electrocardiogram (ECG) signals to measure heart rate [5], are routinely used to diagnose heart and breathing rates. However, these wearable devices are still constraining and inconvenient in scenarios where unobtrusive and ubiquitous respiration monitoring is desired. An ultra-wideband (UWB) radar is one of the most widely used non-contact vital sign monitoring methods. An ultra-wideband (UWB) radar [6] has advantages over a microwave doppler radar, such as a reduced risk of exposure to the human body, less power consumption, and an improved signal-to-noise (SNR) ratio [7].

Recently, there has been a growing trend of employing UWB radars for contact-free vital sign estimation. These vital signs are measured in a non-contact manner by detecting changes in the time of flight of narrow pulses emitted by the radar and backscattered from the human chest. Moreover, these UWB signals can also be used to localise and infer human gait patterns [8]. Radar-based monitoring techniques, however, are susceptible to low signal-to-noise (SNR) ratios and clutter effects, as noted in state-of-the-art studies [9–11]. This study examines how distance affects the accuracy of radar-based vital sign estimation systems. An empirical study is conducted using a single subject to test the system's efficacy, and the output is validated using a medical-grade device.

This paper is organised as follows: section II provides an overview of UWB radar technology and describes the experimental setup. In Section III, we discuss our experimental results and highlight the future research directions in Section IV.

II. Experimental Design

A. Overview of UWB Technology

A portable ultra-wideband (UWB) radar developed by Vayyar Imaging Ltd [12] is used in this work, namely the Walabot radar. It transmits frequency-modulated continuous wave (FMCW) chirps and collects received signals by a 2D antenna array. It is a programmable 3D sensor that looks into an object using radio frequency (RF) technology with a frequency range of 3.3 - 10 GHz proving a massive bandwidth of 7 GHz and has VYYR2401-A3 System-on-Chip integrated circuits that generate and record the signals. The radar is powered by simply connecting a USB wire to the host device, which is also used to send data between the radar and the host device using the Cypress controller. The given frequency range is good enough to detect direct distance within 10 meters based on the gradient of FMCW chirp. The average transmit power is about -16 dBm (25 microwatts). These power levels do not have any health issues whatsoever [13].

B. Radar Specifications

Following Table. I shows the radar specifications for the vital sign experimental setup.

TABLE I: Radar Specifications

Model	Walabot Developer
No of Tx/Rx	5/8
Power Supply	5v
Current Consumption	0.4 - 0.9A
Frequency Range	3.3 - 10 GHz
API	Python
Communication Protocol	USB 2.0/3.0
Distance Range	0 - 10 meters

C. Data Collection Setup

The experiment was performed from three different distances (55cm, 60cm and 65cm), as shown in Table. II. Overall data collection setup is shown in Fig. 1. The experiment was conducted for 10 minutes with a sampling frequency of 4Hz. The radar and the host device were linked together via a USB cable. When the radar receives power from the PC, we send the initial configuration to the radar through python programming, indicating that it is ready to capture chest movement caused by breathing. As shown in Fig. 2, the raw data is collected and saved to a .csv file for future pre-processing. Advanced signal processing techniques were applied to extract and estimate the breathing rate (BR), heart rate (HR) and heart rate variability (HRV).

D. Data Pre-Processing

As shown in Fig.3, the raw data must be processed using advanced signal processing techniques to estimate the desired vital signals (i.e., HR and BR). The acquired raw radar data was passed through a second-order Butterworth bandpass filter with a cut-off frequency of 0.08 - 4Hz to remove higher and lower frequencies. The filtered signal shows heartbeat and breathing signals, as shown in Fig. 4. To extract pure breathing signals from the filtered signals, the filter's cut-off frequency was set to 0.16 - 0.5Hz, and for heart rate signals, it was adjusted to 0.8 - 2Hz. The fast fourier transform (FFT) technique was used to build a spectrum for identifying peaks in the frequency domain, and the most extended peak of that spectrum identified the breathing rate or heart rate. We employed the signal interpolation approach after FFT to smooth down the peaks and interpolate data points for the heart rate FFT spectrum.

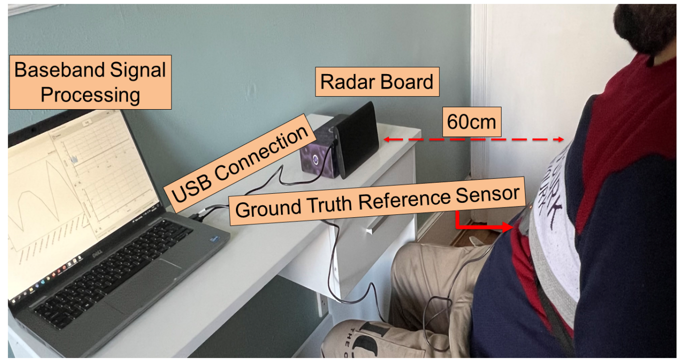

Fig. 1: Experimental Setup

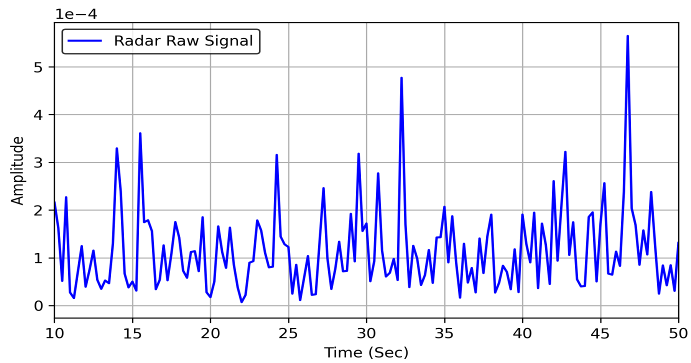

Fig. 2: Raw Radar Data

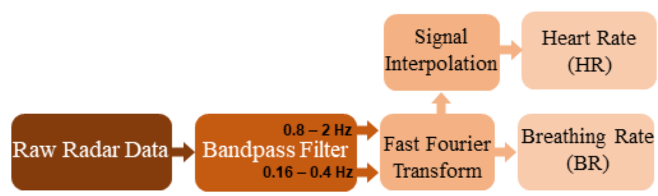

Fig. 3: Radar Signal Processing Steps

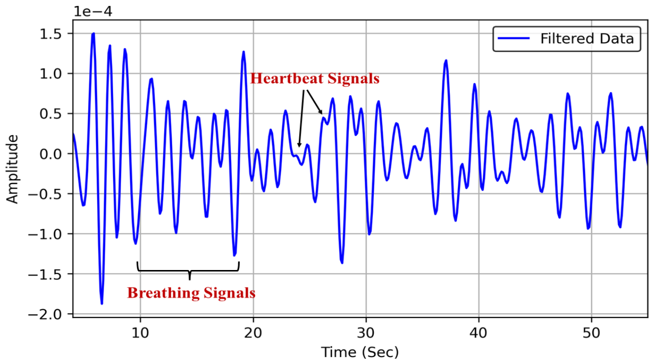

Fig. 4: Filtered Signal

III. Experimental Results

In this section, we can explain the results and the estimation of BR and HR by validating the respiration belt as a reference.

A. Breathing Rate

The frequency-based method determined the target by checking whether the frequency of range bins falls in the breathing frequency of 0.1 - 0.5Hz, which is susceptible to the environment noise [14]. This frequency range equals 6 - 30 breathing rates per minute (Brpm). The bandpass filter and FFT technique were applied to filtered data to obtain breathing frequency. The experiment was conducted from three different distances, as shown in Table. II.The FFT spectrum for normal BR is shown in Fig. 5a, where it can be observed that peak indicates 0.27 Hz, which is equal to 16.2 Brpm, which falls in the range of normal breathing.

TABLE II: Experimental Results

Distance	Frequency (Hz)	Brpm
55 cm	0.2	12
60 cm	0.27	16.2
65 cm	0.25	15

B. Heart Rate

The human's body heart rate (HR) ranges from 60 - 240 beats per minute (BPM), which equates to 1 - 4Hz [15]. Applying a second-order butterworth bandpass filter with a cut-off frequency of 1 - 2Hz on the filtered signal containing heartbeat data, as shown in Fig. 4, which removes lower frequency below 1Hz and higher frequency above 2Hz. The FFT method was employed to construct the spectrum with distinct frequency peaks. Among these spectrums, the frequency ranges of greatest interest were picked, and the peak with the maximum magnitude was most likely chosen as the HR estimation, as shown in Fig. 5b, that falls in the HR as mentioned above range.

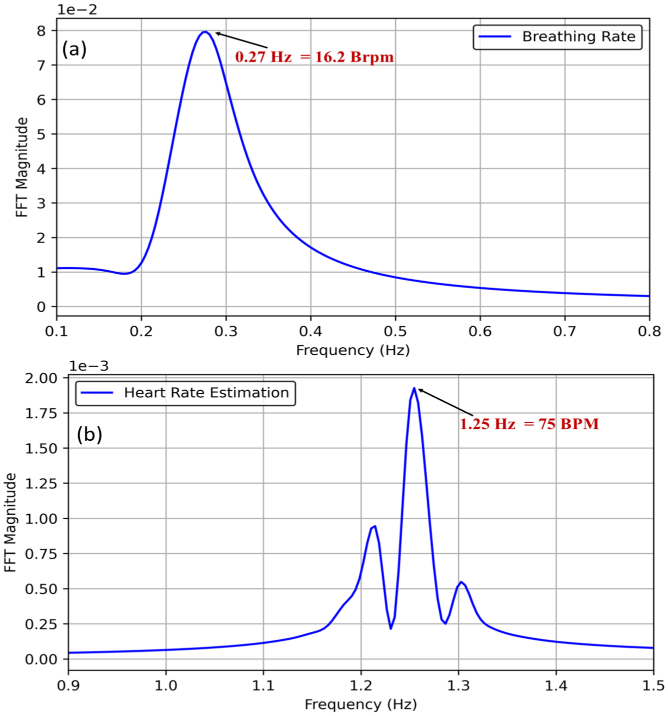

Fig. 5: (a) Normal Breathing Rate (Brpm) and (b) Heart Rate (BPM)

C. Validation

Vernier's medical-grade breathing belt, worn across the abdomen during data collection, validated our findings from the radar sensor. Fig. 6 depicts the comparison result between the radar sensor and the wearable belt, and the outcomes from the respiration belt and radar are shown in Table. III, which was collected at various distances. The FFT technique was also used on the filtered data from the respiration belt, and the highest magnitude among the different frequency spectrums shows the respiration rate as shown in Fig. 7.

TABLE III: Comparison Between Radar and Ground Truth (Brpm's)

Distance	Radar Sensor	Ground Truth
55 cm	12	13.8
60 cm	16.2	18
65 cm	15	17

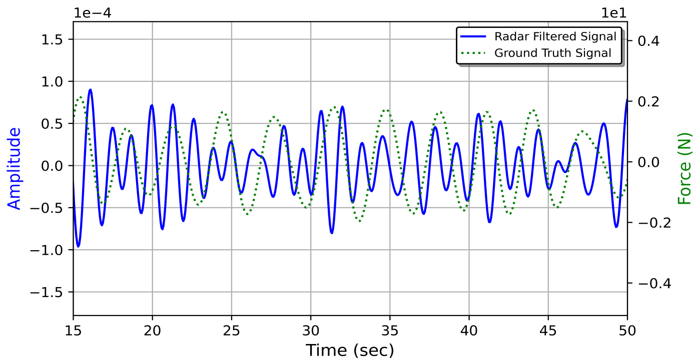

Fig. 6: Validation Between Radar and Belt

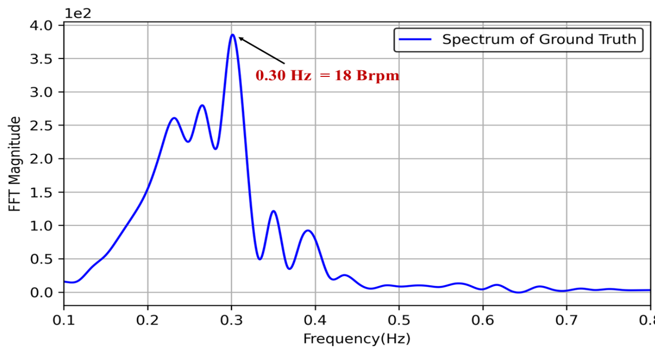

Fig. 7: Respiration Rate from Ground Truth

IV. Conclusion

In this study, we demonstrate how the FMCW chirps emitted by a UWB radar may be used to monitor a subject's breathing and heart rate from a single radar board. The radar is sensitive enough to pick up on chest movement caused by electromagnetic (EM) waves. To estimate BR and HR, signal processing techniques were used to process the radar's raw data. The results from the medical-grade wearable sensor were compared with radar results for validation. According to the correlation, the radar sensor monitors the respiratory rate non-invasively with an accuracy of 98.2%. The root means square error (RMSE) between the radar sensor and the breathing belt was 1.36. Radar sensors can be used in a non-invasive manner for a variety of medical purposes, including but not limited to sleep monitoring, primary care, and emergencies.

In the near future, numerous participants' vital signs will be monitored in real-time from various radar angles and participant postures. Additionally, we'll build a multimodal environment using the gaze application and vital sign monitoring to evaluate people's levels of fatigue or stress.

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