Real-Time Visual Respiration Tracking with Radar Sensors

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Abstract. Wireless detection of respiration rate (RR) plays a significant role in many healthcare applications. Most of the solutions provide simple waveforms and display the number of estimated RR. In this paper, a visualiser's approach for the wireless respiration tracking with commercial radar sensor, Walabot, is proposed. Walabot provides a real-time 2D heatmap from the reflected signals, and an abstract graph is extracted from the heatmap to represent the respiratory motion intuitively. Since monitored objects' movements may cause inaccurate measurements, two optimisation algorithms are developed to enhance accuracy. A respiration waveform is then obtained, and the average RR is calculated. The data is collected for different scenarios of breathing speed, including normal, hold, and deep. The computed RR accuracy is compared with the manually counted RR during the data collection as a reference. Overall, the calculated RR has high average accuracy, and the performance of the visualiser is precise and consistent. This solution also has the potential to monitor respirations for multiple subjects or in a through-wall situation.

Keywords: Data visualization · Wireless monitoring · Respiration rate

1 Introduction

Physiological signal monitoring has received significant attention in recent decades, especially for health care purposes. Breathing waveform, as one of the important vital signals, has an essential role in early diagnosis for respiratory diseases such as lung disease (too fast breathing), apnoea (sudden stop) [10], unusual respiration (e.g., Biot's Breathing, Cheyne-Stokes respiration) [2,17], and other related diseases [12,16]. Therefore, the early investigation and treatment are proven to be highly effective [1,15].

There are many processes to measure and monitor breathing with various sources of signals like mechanical movement on the torso [14], or airflow pressure by oral or nasal cannula [8]; however, most of the monitoring devices output only processed waveforms and the estimated respiratory rate [5,7,18]. People with little knowledge of physiology might have difficulty understanding how the breathing in each second contributes to the final respiratory waveform.

M. Ur Rehman and A. Zoha (Eds.): BODYNETS 2021, LNICST 420, pp. 158–167, 2022.
https://doi.org/10.1007/978-3-030-95593-9_13

This paper proposes a solution which provides an abstract visualiser for breathing monitoring to indicate different respiratory processes (inhalation and exhalation) with a commercial wireless radar. The algorithm is image-based so that the mechanical movement caused in the respiratory process can be extracted. In Sect. 2, the radar sensor and the analysis processes are presented. Section 3 shows the experimental results and the comparison with the manually counted RR as a reference. The conclusion and potential applications will be discussed in the last section.

2 Methods

2.1 Sensor System

Walabot is a low-cost commodity ultra-wideband (UWB) radar-based device which generates 2D and 3D image frames from the reflected signals. Walabot operates in the frequency range of 3.3–10.3 GHz, which can cover 10 m detection range based on the Frequency-Modulated Continuous Wave (FMCW) chip's gradient. It contains a 2D antenna array to produce and receive radio frequency (RF) waves, and the reflected signals are processed by the VYYR2401 A3 System- on-Chip integrated circuit. Doppler, azimuth and elevation positions [11] of the moving objects are extracted from the processed signal in the form of 2D and 3D heatmap image [3].

2.2 Sensor Overview

Object distance and angle are calculated from the received RF signals by the 2D array of antenna in polar coordinates (Theta-Phi-R), Fig. 1. With the intensity of

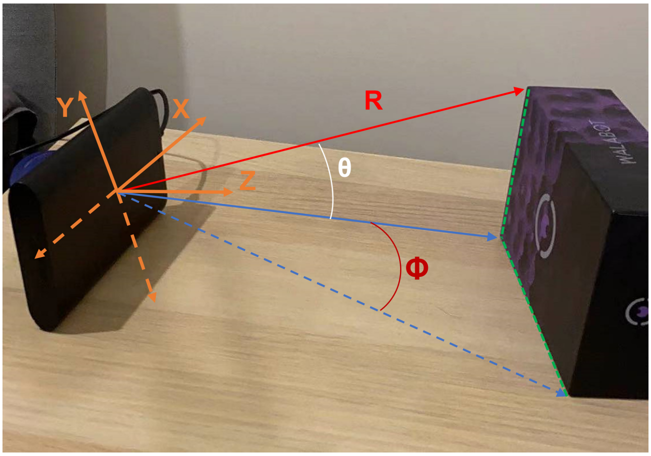

Fig. 1. Walabot parameters (Theta, Phi, and R)

the RF signals, a 3-dimensional heatmap image is constructed. The 2D heatmap is the projection of the 3D image along one axis. By placing the Walabot sensor in a correct orientation, the produced 2D heatmap can be used to extract the vital signals like respiration.

To eliminate the environmental impact on the heatmap, Walabot, in the calibration phase, produces RF signals and records reflected signals as a reference, so that reflections from static objects in the subsequent signals are removed. The obtained 2D heatmap is further simplified to a single point representing the moving object's centre. Since the centre point represents the overall movements of the detected moving objects, by tracking this centre point, vital information like respiration waveform is observed.

2.3 Experimental Protocol

The experimental setup for the data collection is shown in Fig. 2. The experimental data were collected on five healthy subjects, from 25 to 30 years old. The experiment was conducted indoor with controlled room temperature. Walabot was placed 60 cm above the bed with specifications adjusted to mainly the subjects' torso (Theta: 10 to $-10°$, Phi: 15 to $-15°$, and R: 50 cm to 70 cm). Generated 2D heatmap and the extracted respiratory waveform were recorded for future analysis. To compute the accuracy of the calculated result, each subject's respiratory rate was simultaneously counted as the reference signal.

Fig. 2. Experiment setup for data collection

Subjects were required to lie on the bed and simulate the scenarios with different breathing speed. The experiment started with breathing normally for 3 min. Then, the subjects were asked to hold their breath for as long as possible. In the end, subjects need to have deep breathing for 3 min. The recorded signals were processed to extract respiratory waveform. The result was evaluated in Sect. 3 to analyse the breathing visualisation performance and the accuracy of the estimated respiration rate.

2.4 Signal Processing

The respiratory motion is measured by computing the relative displacement of the centre point in two contiguous heatmap frames. For example, the centre point locates at the top of the heatmap during inhalation and the point will move to the bottom of the heatmap during exhalation. Then the respiratory motion can be simulated by comparing the difference between these two locations. To emphasize the current respiratory process, a curve is generated by connecting the relative zero, representing the previous location of the target, and the current location. The amplitude of the displacement represents the respiratory motion magnitude, and the curve shape indicates either the target is in inhalation or exhalation. Figure 3 shows the generated visualisation graph where there are two threshold lines defining the valid displacement range, which means any movement detected outside this area will not be considered as breathing.

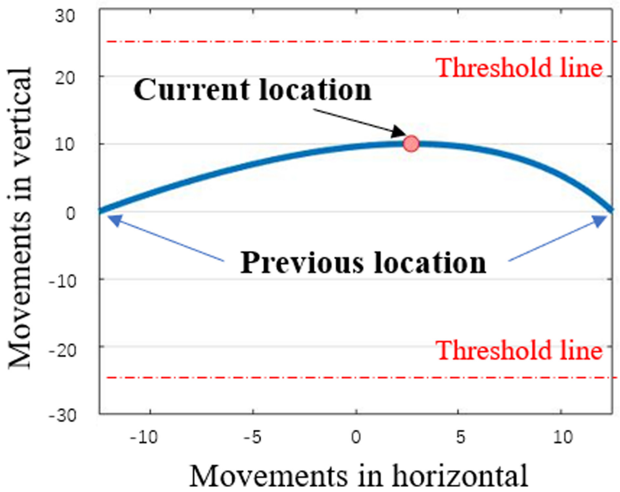

Fig. 3. Line graph of the abstract representation of breathing process

The respiration waveform fluctuates significantly and erratically during the target object's movement, as shown in Fig. 4. Therefore, to maintain the respiration monitoring accuracy, the respiration recording related to the target movements is eliminated. Only the respiration waveform of the target in static status is considered.

An algorithm was created to detect movements from the analysis of the heatmap. The algorithm compares the difference between the current detected

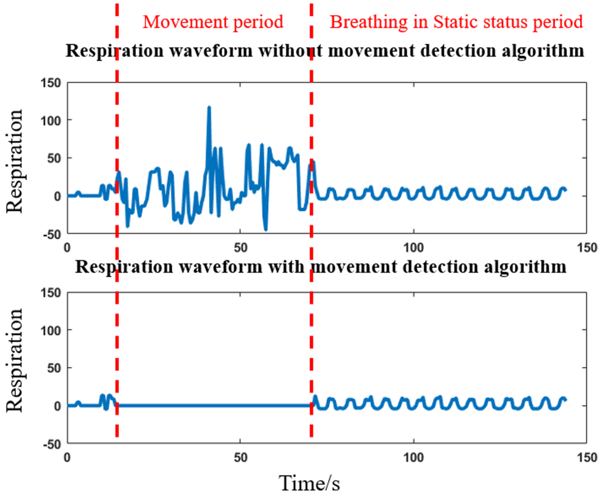

Fig. 4. Respiration waveform after movement signal is removed

heatmap and the previous one. If the difference is larger than the pre-set threshold, the target will be defined as moving and the corresponding respiration waveform will be discarded, shown in Fig. 4, and excluded from the respiration estimation.

The heatmap may sometimes show more than one major power area, which means Walabot detects more than one part of the target, as shown in Fig. 5. This issue may be caused by similar relative distances between various body parts and Walabot. In some situations, the centre point jumps between the detected power areas (e.g., locates at the left object during exhalation and locates at the right object during inhalation). To avoid the negative influence of this phenomenon in real-time monitoring, another algorithm was developed. The new algorithm distinguishes different targets and then marks all object's centre points. For example, there are three main power regions and all movements of these three objects need to be monitored as shown in the left part of Fig. 5. By applying

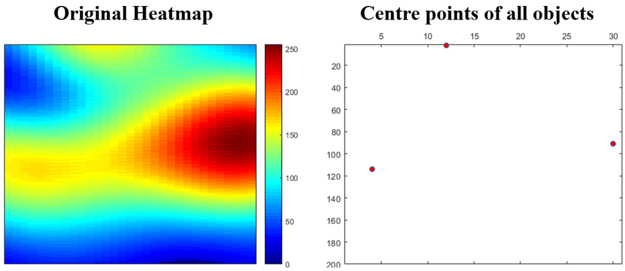

Fig. 5. An example of centre points extraction (Left: 2D heatmap; Right: extracted centre points)

the algorithm, the local maximum points, which is also the centre point of the power region, can be indicated as shown in the right part of Fig. 5. Then, the respiration waveform is generated by comparing the movements of all detected targets' centre points between consecutive frames. Figure 6 shows the flowchart of the signal processing procedures for the real-time respiration monitoring.

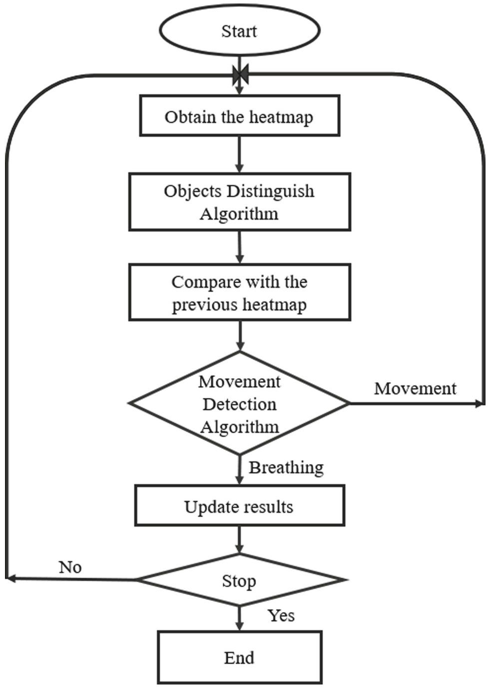

Fig. 6. The flowchart of the signal processing for respiration monitoring with radar sensor

3 Results and Discussion

An example of a monitored respiration waveform is shown in Fig. 7. The monitored subject was breathing normally for 3 min at first and then holding the breath for several seconds, followed by deep breathing for another 3 min. The respiration frequency in one minute is calculated as Eq. 1.

$$f = \frac{BreathingCounts}{T_{end} - T_{start}} * 60 \tag{1}$$

T_{start} is the start time in seconds of the calculated respiration period and T_{end} is the end time in seconds of the calculated respiration period. The result f is the respiration frequency of the calculated respiration period, and the unit is

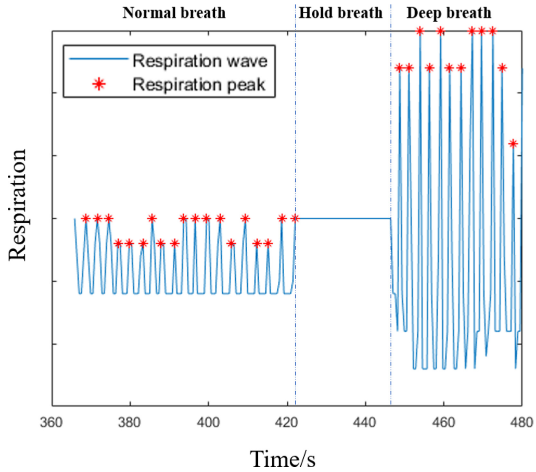

Fig. 7. An example of respiration waveform for normal, hold, and deep scenarios obtained from Walabot

times per minute. In this paper, all respiration frequency values are calculated by using this equation.

During the experiment, the line graph shows the breathing process intuitively. In Fig. 8, we only use two simple symbols (line and dot) to demonstrate the current breathing process. Inhalation is shown when the vertical displacement is positive, and vice versa for exhalation. The amplitude of displacement indicates whether the subject is breathing deeply or gently. Similarly, a straight line means that there is no breathing detected.

The normalised root-mean-square error (NRMSE) method is used to measure the device's accuracy, as described by Eq. 2. In the equation, n is the number of observations; RR_{ref} and RR_i are the respiration rates obtained from the manual counter and the estimated calculation, respectively. The NRMSE method can emphasise the magnitude of the variance if the reference is accurate and large errors will be accentuated in such case [4].

Table 1. NRMSE between the estimated RR and reference RR of 5 subjects for normal and deep breathing

Subject No.	Normal breathing (%)	Deep breathing (%)
1	1.26	2.32
2	3.48	3.82
3	2.26	4.36
4	3.53	5.74
5	2.77	4.17

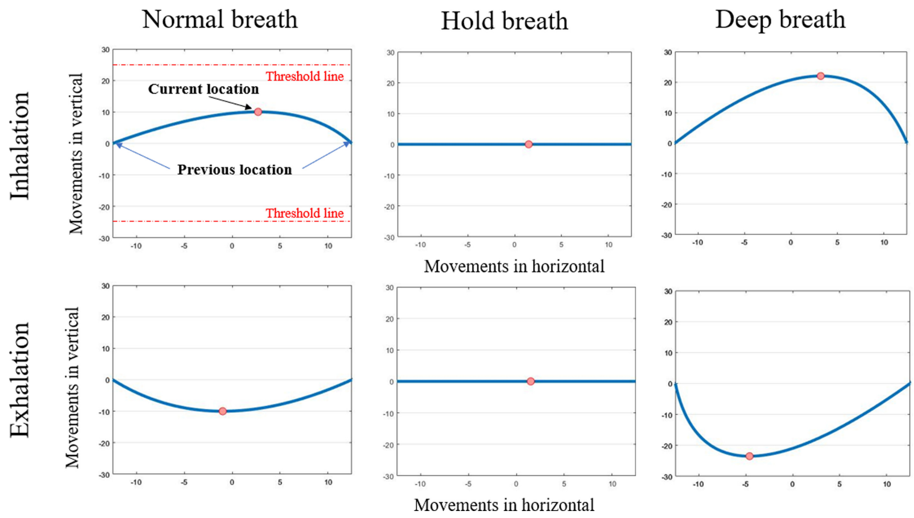

Fig. 8. Examples of the line graph for different breathing scenarios (column) and different breathing processes (row)

$$NRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(RR_i - RR_{ref})^2}}{\frac{1}{n}\sum_{i=1}^{n} RR_{ref}} \tag{2}$$

Five subjects were observed for both normal breathing and deep breathing, and the result is shown in Table 1. The NRMSE shows an accurate estimation of RR obtained from the experiment. The maximum NRMSE is 5.74% in deep breathing for subject 4 and the minimum NRMSE is 1.26% in normal breathing for subject 1. In terms of RR per minute, the average difference between the estimation and manual count is less than 1 bit per minute.

4 Conclusion

This paper proposes an image-based visualisation solution for breathing monitoring with a real-time abstract representation of breathing processes and the estimated respiratory rate from the extracted respiratory waveform. The evaluated sensor is a UWB radar called Walabot which produces a real-time 2D heatmap from the reflected RF waves of all detected moving objects in range. The heatmap is simplified into a line graph emphasising the change of signals. This abstract graph highlights the physiological movement corresponding to the state of inhalation or exhalation.

The developed object distinguishing algorithm ensures the accurate and reliable result of respiration monitoring. Furthermore, the movements of each distinguished object can be collected and recorded. Then the movement frequency is obtained by convoluting the first signal with the rest of the signals and taking the maximum value [6]. By drawing the spectrum of the analysed signal, the number of people and each person's respiration rate can be obtained.

Sleep apnoea is defined as a repeated phenomenon of apnoea and hypopnea during sleep, together with the risk of myocardial infarction, stroke etc. [13]. An appropriate sleep study is an essential tool to help physicians develop a diagnosis plan for the patient [9]. In this case, our solution can provide an accurate and real-time contactless respiration monitoring for sleeping patients in the home and easily operating by themselves. This feature is useful for countries with a large distance between patients and hospitals or sleep centres.

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