

Parametric Classification of Recoverable Radar-Assessed Respiratory Rate Data

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Abstract—A static algorithm-based method is described here to differentiate between recoverable sedentary respiratory rate data extraneous motion segments measured using Doppler radar. Extraneous motion such as locomotion and fidgeting can cause drastic changes in dc offset and SNR of the received signal. Such extraneous data may not be excluded and can lead to an erroneous assessment of the respiration rate. In some cases, however, moderate distinct extraneous motion does not completely occlude the measurement of respiratory torso motion, allowing for respiration rate recovery. This work focuses on the accurate classification of data which is suitable for respiration rate analysis in the presence of locomotion and small extraneous movements. The proposed algorithm has been demonstrated to be accurate for classifying data with recoverable respiratory rates for 2 subjects and 3 types of fidgets with 99.4% accuracy on average.

Index Terms—Sedentary, Non-sedentary, locomotion, fidgets

I. INTRODUCTION

Doppler radar biosensing through measurement of chest wall displacement is a reliable method of recovering respiratory and cardiac data in sedentary subjects. Respiratory rate is usually measured using inductance plethysmography, which involves using transducer bands around the thorax and abdomen of the subject to measure the total volume change of the lungs. However, this method is uncomfortable and cumbersome for patients that need to participate in long-duration monitoring, such as a sleep study. Alternatively, respiratory rates are also often measured by medical professionals by counting the number of breaths through visual inspection over a given amount of time, which is cumbersome and not very accurate.

Non-contact and non-invasive respiration measurement made using Doppler radar provides improved comfort and privacy to the subject. Such real-time measurements can be further analyzed to detect sleep apnea, assess sleep posture, and authenticate a subject's identity.

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Doppler radar measurements are sensitive to a subject's extraneous movement and locomotion. While measurement of rate during locomotion is both difficult to achieve and impractical for use (as it depends greatly on the activity and level of exertion), long-term comparative assessment of respiration rate during sedentary periods can be useful for a wide range of health assessments. In general, we can consider subjects to be sedentary if they are not engaged in activity that significantly affects their respiration rate. Realistically, a sedentary subject may fidget or otherwise produce extraneous motion which may impair the assessment of respiration rate from Doppler radar displacement measurements. Ideally, a reliable Doppler radar respiration measurement system should be able to distinguish between data that is suitable for the extraction of sedentary respiration rate and data that is unsuitable. Previous work by Ebrahim et. al. employs a 4 GHz continuous wave Doppler radar to extract respiration rate from data taken in various sitting and walking positions using a series of FIR filters in addition to notch filters [1]. However, this study does not classify the motion interferences. Another study proposes an algorithm for classifying between locomotion and fidgeting based on 10.525 GHz radar data taken from a lizard [2]. This work focuses on identifying segments of the data that can provide reliable respiratory rate information, even in cases involving modest extraneous motion.

For this paper, two sets of human respiratory data were recorded with a quadrature Doppler radar. The recordings included three types of fidgeting of seated subjects, along with locomotion events at predetermined times. A thresholding algorithm is proposed to differentiate between respiratory rate recoverable data and non-recoverable data based on locomotion and extraneous body motions. Section II describes the radar data demodulation process and details the proposed algorithm. Section III elaborates the radar system setup and illustrates the data acquisition process. Section IV outlines the results and Section V summarizes the conclusion of the work.

II. THEORY

Continuous wave Doppler radar transmits a signal at a targeted subject and receives the phase-modulated reflected wave containing the displacement information of the target surface. For a radar wave reflected off from the human chest, the phase difference between the transmitted and received wave can be utilized to extract physiological information such as respiration rate. The received signal is split into two parts and mixed with the local oscillator signals which give the in-phase (I) and quadrature (Q) baseband output signals.

$$B_I(t) = A_B \cos(\theta + \frac{\pi}{4} + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)) \quad (1)$$

$$B_Q(t) = A_B \sin(\theta + \frac{\pi}{4} + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)) \quad (2)$$

Here, $x(t)$ represents the target's motion variation, the baseband amplitude due to receiver and mixer gain is given by AB , θ is the constant phase shift related to the phase change at the surface of a target and the phase delay between the mixer and antenna and the residual phase shift is given by $\Delta\phi(t)$.

To combine the two baseband outputs, an arctangent demodulation technique can be applied which is given as-

$$\phi'(t) = \arctan\left(\frac{V_Q + B_Q(t)}{V_I + B_I(t)}\right) \quad (3)$$

where V_I and V_Q represent the dc offsets present in I and Q signals respectively. Using circle fitting, we can estimate the dc offset values of V_I and V_Q , and therefore equation 3 becomes,

$$\begin{aligned} \phi'(t) &= \arctan\left(\frac{B_Q(t)}{B_I(t)}\right) \\ &= \arctan\left(\frac{\sin(\theta + p(t))}{\cos(\theta + p(t))}\right) = \theta + p(t) \end{aligned} \quad (4)$$

where θ is the constant phase shift dependent on the nominal distance of the subject from the radar and $p(t)$ is the phase change containing cardiorespiratory activity and movement information [3].

It is important to note that the values of V_I and V_Q are susceptible to extraneous movement, eg. fidgeting, of the subject. When the subject does return to the sedentary state, the values of V_I and V_Q may be altered. Therefore, implementing arctangent demodulation without properly eliminating the dc offset may result in incorrect respiratory information.

A. Proposed Algorithm

The proposed algorithm uses a rolling window technique to determine a fidgeting or extraneous motion event. Recorded data is segmented into 5-seconds windows with a 3-seconds overlap. The data is then dc offset compensated and arctangent demodulation is determined. The mean and standard deviation (SD) of the data segment is calculated. The algorithm checks if any data sample of the given window exceeds an upper threshold of $(\text{mean} + 50*\text{SD})$ or drops below a lower threshold of $(\text{mean} - 50*\text{SD})$. The window segment is then marked as

non-sedentary and not included in the respiratory rate recovery. Also, the next sedentary segment is DC offset compensated again to account for the change in values of DC offset in the I and Q channels.

Afterward, the same operation is run on the window again with the thresholds of $(\text{mean} + 5*\text{SD})$ and $(\text{mean} - 5*\text{SD})$. This second step provides us with information on the fidgets that are classified as sedentary and do not have a significant effect on the respiratory rate information.

If a window segment is marked as non-sedentary, the next 5 seconds is assigned as a period in which the subject settles down. If the window segment is marked as sedentary, the algorithm is run on the next window.

III. EXPERIMENTAL METHODS

A homodyne 2.4 GHz CW quadrature radar system was used in this experiment with commercial off-the-shelf components consisting of two 0° ZFSC-2-2500 splitters, one 90° ZXI0G-2-25-S+ splitter and two ZFM-4212+ mixers. All data were recorded at a sampling rate of 1 KHz using a data acquisition unit with 18-bit resolution.

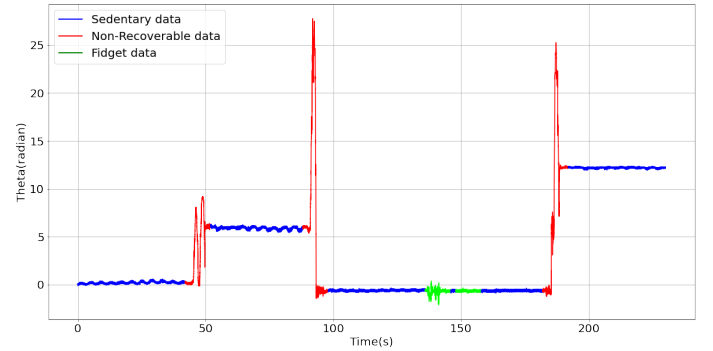


Fig. 1. Plot of measured 230-second data segment. The red section around the 50 second mark is extraneous motion near the radar, while the green section is the same motion farther away from the radar. The remaining red sections at 90 seconds and 180 seconds are locomotion that were correctly classified by the algorithm

Data were collected from 2 subjects breathing at a fixed rate of 15 breaths per minute (b/m) following protocol number 14884 approved by the Committee on Human Studies. A metronome was employed to assist the subjects in breathing at a rate of 15 breaths per minute. The breathing rate is taken as ground truth. Each measurement was 230 seconds long and three datasets were collected from each subject for three different types of fidgeting. The subject was asked to sit still 1.5 meters away from the radar in each measurement. Then the subject created minor fidgeting movements after 45 seconds and returned to a still condition for another 45 seconds. After the first 90 seconds, the subject was asked to sit 2 meters away from the radar and repeat the same process for the next 90 seconds. The subject then returned to a position 1.5 meters away from the radar and for the next 50 seconds maintained a sitting position. During the last 50 seconds, no fidgeting motion was performed.

TABLE I
PERCENTAGE OF ACCURACY TO REFERENCE BREATHING RATE(15 B/M)

Side to Side				
	Section 1	Section 2	Section 3	N\A
Subject 1	99%	99%	99%	N\A
Subject 2	100%	100%	99%	N\A
Front to back				
	Section 1	Section 2	Section 3	Section 4
Subject 1	100%	100%	99%	99%
Subject 2	99%	100%	100%	99%
Readjusting				
	Section 1	Section 2	Section 3	Section 4
Subject 1	100%	100%	99%	99%
Subject 2	99%	100%	99%	99%

Three different fidgeting motions were selected for the subjects - moving side to side, front to back, and slight readjustment in the seat. Each subject was recorded for three different fidgeting motions.

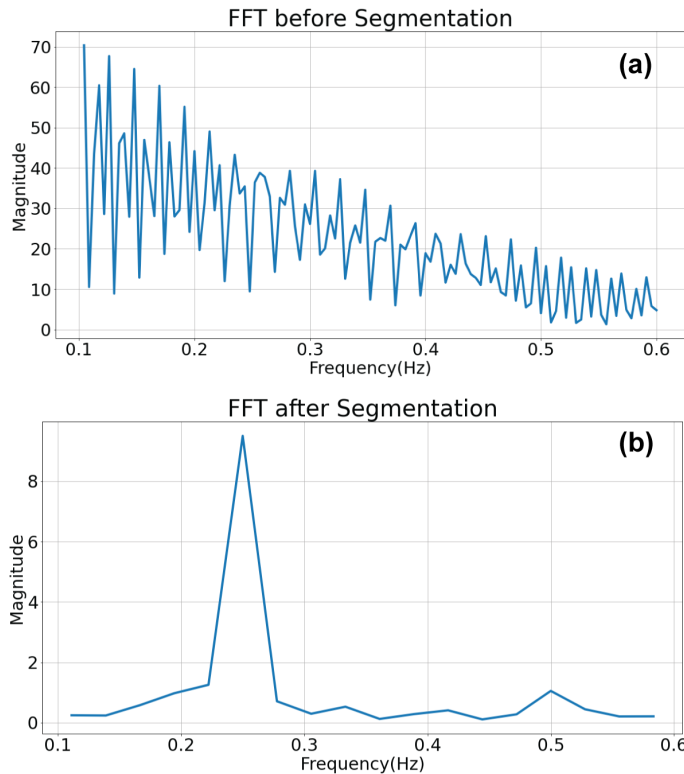


Fig. 2. FFT of sedentary data plotted (a) before and (b) after segmentation. The extraneous motion occludes the respiratory rate in the first figure. Once the extraneous motion data is classified and excluded, and the recoverable segment is dc-offset compensated, the respiratory rate can be accurately determined

IV. RESULTS

The proposed thresholding algorithm can identify locomotion or extraneous body motion events that require a recalibration and compensation of the dc offset. The data is divided into sedentary respiratory data sections. The Fig. 1

demonstrates the results of the algorithm in differentiating between sedentary, non-recoverable and fidgeting data. The sedentary sections are arctangent demodulated and respiratory frequency is determined through Fast Fourier Transform(FFT). The resultant respiratory frequency is compared to the ground truth of 15 bpm and error is determined. The Fig 2 shows the FFT results before and after the segmentation is done using the proposed algorithm.

The Table I shows the accuracy of respiratory rate after each non-sedentary section of the data was processed. The Side-to-Side portion shows three sections as the extraneous body motion is not detected by the radar system at 3 meters away. From the table, it is observed that implementing the algorithm results in accurate recovery of the sedentary respiratory rate.

V. CONCLUSION

This research demonstrates an effective method for accurately monitoring respiration rates with Doppler radar. An algorithm was implemented that can classify Doppler radar displacement measurements as suitable for accurate rate extraction under completely sedentary conditions, and in the case of minor fidgeting which does not obscure accurate rate assessment. It also identifies conditions involving locomotion or overwhelming fidgeting, reliably removing such data from the sedentary respiration rate data in order to avoid erroneous rate measurement results. This work serves as a proof of concept of sedentary motion classification. Future work will involve a larger set of human subjects for the verification of the algorithm's efficacy. This technique can potentially be extended to more comprehensive motion classification and establishes a basis for avoiding inaccurate rate reporting issues in medical applications.

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