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Dynamic Arctangent Center-Tracking Method for Respiratory Displacement Monitoring of Subjects in Arbitrary Positions

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***Abstract*— Accurate continuous measurement of respiratory displacement using continuous wave Doppler radar requires rigorous management of dc offset which changes when a subject changes distance from the radar measurement system. Effective measurement, therefore, requires robust dynamic calibration which can recognize and compensate for changes in the nominal position of a subject. In this paper, a respiratory displacement measurement algorithm is proposed which can differentiate between sedentary and non-sedentary conditions and continuously adapt to provide long-term monitoring of a subject's sedentary respiration. Arctangent demodulation is an effective means of quantifying continuous displacement using a quadrature Doppler radar, yet it depends on accurate identification of dc offset and dc information contributions in the radar I-Q arc with the subject in a particular position. The dynamic calibration method proposed here is demonstrated to differentiate between sedentary and non-sedentary conditions for six subjects to produce accurate sedentary respiration measurements even when the subject arbitrarily changes position, once the appropriate thresholds are established for the measurement environment.**

I. INTRODUCTION

Microwave Doppler radar has been successfully demonstrated for unobtrusive and continuous non-contact monitoring of human cardiopulmonary motion, typically under controlled conditions. However, more robust monitoring is hindered by the sensitivity of a radar system to a subject's nominal position due to the periodic phase relationship between transmitted and received radar signal [1]. Quadrature direct conversion doppler radar is a popular candidate for non-contact physiological monitoring as it can address the issue of null and optimal target position sensitivity prevalent in single-channel receivers. With a quadrature system, one channel is always at an optimal signal point when the other is at a null. One way to put this feature to use is to make a relative assessment for each channel and then rely on the channel with the better signal-to-noise ratio (SNR). However, this method is still limited to the accuracy of a single channel [2] which may be subject to distortion in assessing the target displacement. In particular, the accuracy of such a single-channel method is insufficient for measuring large displacements or using high-frequency systems [3]. Other diversity techniques for combining quadrature channels such as equal ratio combining and maximal ratio combining also suffer from degrading SNR with increasing distance between the target and the radar [1]. The arctangent demodulation method addresses the issues of nominal subject position limitations and small angle limitations. Rather than choosing either of the channels, it uses both channels together to directly extract the phase information which is proportional to the subject's actual motion. Additionally, in cases where the subject's motion is larger than half the carrier wavelength, resulting in a 2π phase change, the phase information can still be accurately recovered by unwrapping demodulated signal with appropriate dc compensation.

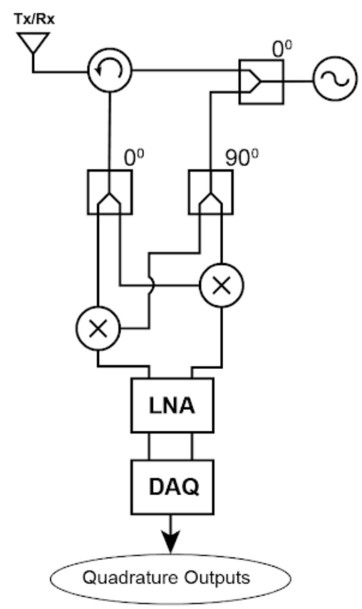

Fig. 1. Block diagram of a quadrature architecture Doppler radar measurement system.

Previous demonstrations of respiratory displacement measurement by arctangent demodulation have required the subject to be sedentary and positioned at a specific location. This is due to the dc offset caused by clutter, TX-RX leakage, and the nominal distance between the subject and the radar. The latter contribution means that any effort to calibrate for dc offset in order to get a true assessment of the center of the phase-change arc will be rendered ineffective if the nominal position of the subject changes during monitoring

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[4]. Therefore, robust monitoring requires analyzing the data for movement and updating the dc offset after movement in order to get an accurate representation of the displacement waveform.

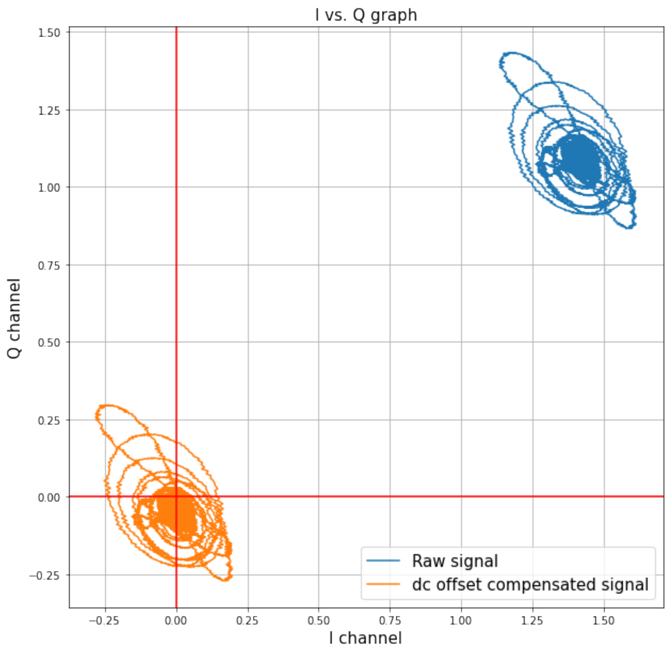

Fig. 2. DC offset compensation of the quadrature radar signal. The center of the arc is determined and matched with the origin of the I vs Q graph to obtain the highest resolution from arctangent demodulation.

Park et. al. proposed a method of dc offset compensation called "center tracking," where the center of the quadrature I vs Q arc is determined in the first 3 seconds of monitoring for a sedentary subject [3]. Thereafter, arctangent demodulation is performed to extract respiratory and cardiac motion, dependent on the condition that the subject remains at the same nominal distance from the radar. The research also separately examined the use of unwrapping on arctangent demodulated data to quantify the physical walking motion of a subject but did not examine the practical scenario where respiratory motion must be monitored for a subject that undergoes arbitrary changes in a position.

In this paper, the use of unwrapping is examined to identify sedentary motion as distinct from non-sedentary motion, and the use of continuous dc offset recalibration is examined to facilitate accurate monitoring of sedentary respiratory displacement for a subject that undergoes arbitrary changes in nominal position with respect to the radar monitoring system. The proposed dynamic center tracking method can facilitate ubiquitous monitoring of sedentary respiration activity for a subject that enters a room and sits or stands at arbitrary locations. This transcends prior limitations that required a subject to remain in an anticipated position, as in the case of a patient in a hospital bed, to a more robust smart-building scenario where a subject can be monitored without such onerous restrictions.

II. THEORETICAL BACKGROUND

A continuous wave Doppler radar emits a single frequency directional wave at a targeted subject. The reflected wave is phase modulated depending on the displacement of the target surface associated with the periodic cardiopulmonary motion of the chest surface. The phase difference between the transmitted and the received wave corresponds to the motion of the chest surface and can be implemented to find the rate of respiration and an accurate real-time respiratory signal. The block diagram of the quadrature Doppler radar system is shown in Fig. 1. The quadrature baseband outputs of a mixer comparing transmitted and received waves can be expressed as,

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

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

where the target's motion variation is given by $x(t)$, A_B represents the baseband amplitude due to receiver and mixer gain, 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 represented by $\Delta\phi(t)$).

In the above equations, the SNR decreases at every even multiple of $\pi/2$, while a peak in the SNR is observed at every odd multiple of $\pi/2$. These positions, where the SNR changes, are known as "null points" and "optimum points," respectively. Thus, having two orthonormal outputs using a quadrature receiver ensures that one channel will be at the optimum position while the other is in the null position.

A. Arctangent Demodulation

Arctangent demodulation can be applied to the I and Q output ratio for extracting accurate phase demodulation irrespective of the target's position. However, there are dc offsets present that act as a linear transform on both signals. Hence, the calculated phase using such a method can be given as,

$$\phi(t) = arctan(\frac{V_Q + B_Q(t)}{V_I + B_I(t)}) \qquad (3)$$

where V_I and V_Q represent the dc offsets present in I and Q signals respectively [5].

The dc offset in the I vs Q graph is represented by the distance between the center of the arc formed by respiratory motion and the origin of the graph. By compensation of the dc offset, the arc is centered around the origin and the resolution and fidelity of the signal with respect to the original motion are improved. It is to be noted that having a change in the nominal distance of the subject with respect to the radar changes the dc offset as well.

When a subject changes nominal position, the phase is changed over large multiples of the radar wavelength. In such cases, the I vs Q graph wraps around a fixed center. It is essential to unwrap the demodulated arctangent to determine the actual change in nominal distance.

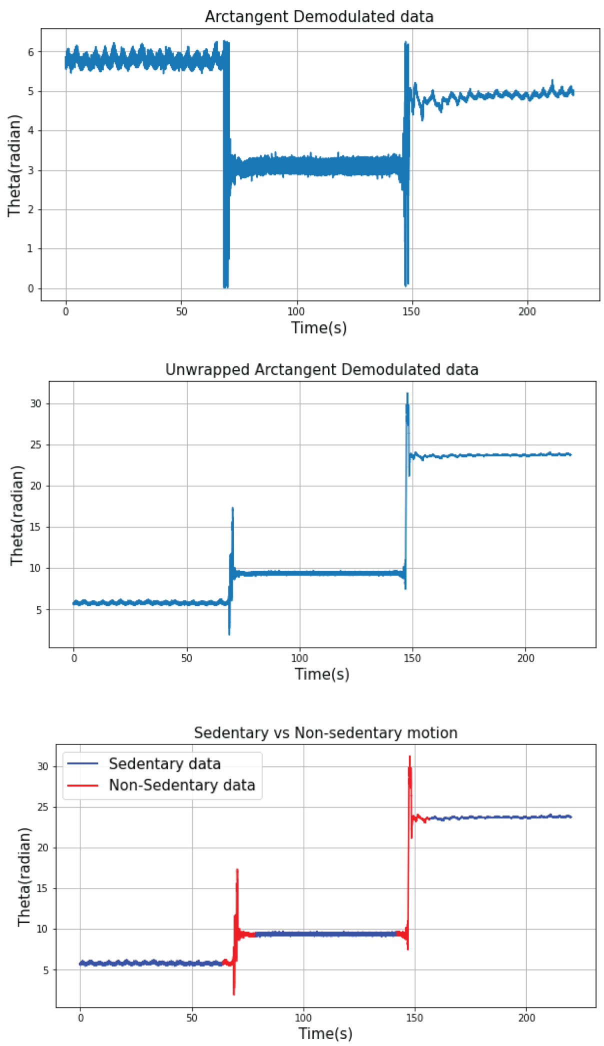

Fig. 3. Comparison of arctangent demodulated data, with and without unwrapping. Unwrapping demonstrates a higher-resolution graph of the change in the nominal distance of the subject. The figure also shows the isolation of non-sedentary data from sedentary data using the proposed algorithm

III. PROPOSED ALGORITHM

The proposed algorithm differentiates between sedentary and non-sedentary data. For sedentary data, the cardiopulmonary signal of the subject can be obtained without being occluded by any overlapping extraneous motion. When the subject is non-sedentary, the body of the subject travels through distances much larger than the wavelength of the radar, and wrapping of the I and Q channels obstructs the desired cardiopulmonary signal. Upon unwrapping the arctangent demodulated signal, the value shows the prominent change in magnitude at the times of extraneous movement.

The proposed algorithm performs dc offset calibration over the available data and derives the arctangent demodulated signal. Fig. 2 demonstrates dc offset calibration of one subject's data. The demodulated signal is then unwrapped to determine the rapid change in value caused by the change of location of the subject. The data is then segmented into 5-second sliding windows with 3-second overlaps. The average and standard deviation values of the signal are determined from the signal segment.

If the window segment has a standard deviation value greater than 1.5 or if the difference between the maximum and minimum value is greater than 5 standard deviations from the average, the segment is marked as an occurrence of location change by the subject. Thereafter, a 10-second portion of the data is isolated as non-sedentary and the algorithm prepares for dc offset calibration of the sedentary data following the non-sedentary event. Fig. 3 shows an example of arctangent demodulated data which is isolated into sedentary and non-sedentary motion using the proposed algorithm.

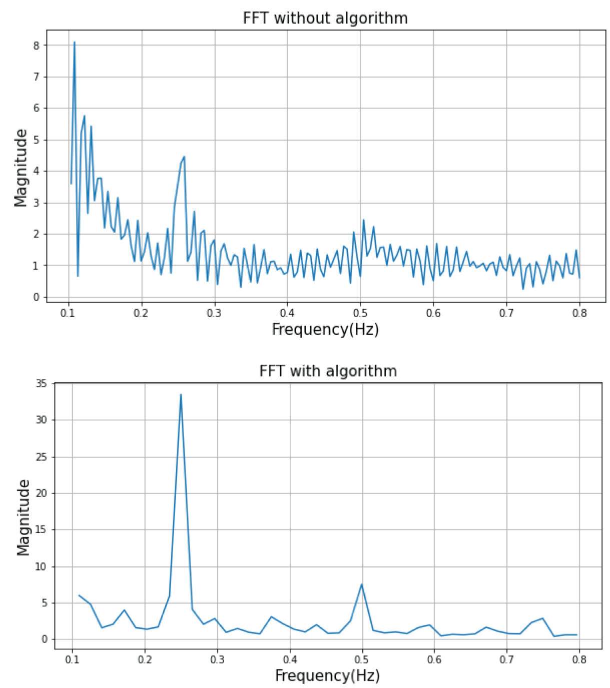

Fig. 4. Difference in rate accuracy using only dc offset compensation and using the proposed algorithm. Due to the changing dc offset caused by non-sedentary motion, arctangent demodulation with a one-time offset calibration does not preserve the respiratory rate information. The proposed algorithm isolates sedentary motion and calibrates dc offset separately for each sedentary time period.

IV. EXPERIMENTAL SETUP

The quadrature architecture radar setup used to take the data consisted of a signal generator (HP E4433B) that transmitted a signal of 2.4 GHz. It was then connected to a 0-degree power splitter (ZFSC-2-2500-S+) and drove the transceiver antenna (Alpha APA-M25) through a circulator. Next, the signal was fed through a 90-degree power splitter(ZX10Q-2-25-S+). Both the in-phase and quadrature signals were mixed with the LO signal to create the I-channel and the Q-channel signals.

TABLE I

COMPARISON OF EXTRACTED SEDENTARY DATA WITH IDEAL CASE

Subject ID	Sedentary data duration (sec)	Deviation from Ideal(190 sec) case
1	190	0%
2	190	0%
3	190	0%
4	190	0%
5	133*	30%
6	134*	29.47%

*Excessive non sedentary time.

TABLE II

DATA SEGMENTS WITH ACCURATE RESPIRATORY RATE INFORMATION

Subject ID	Time Segment 1	Time Segment 2	Time Segment 3
1	Yes	Yes	Yes
2	Yes	Yes	No
3	Yes	No	Yes
4	Yes	Yes	Yes
5	Yes	Yes	No*
6	Yes	Yes	No*

*Non-sedentary portion of time segment too short for effective FFT measurement of breathing rate.

To validate the proposed method, experimental data were collected from 6 subjects individually according to Committee on Human Studies (CHS) approved protocol number 14884. All the subjects were asked to sit still and breathe at a metronomic rate of 15 breaths per minute (b/m). Each data set was recorded for 220 seconds at a sampling rate of 1kHz with an 18-bit DAQ. For the first 70 seconds, the subjects were asked to sit 1m away from the radar. The subjects then move 2m away from the radar and sit still for the next 75 seconds. For the last 75 seconds, the subjects move to and sit back at their starting position until the end of the recording.

V. RESULT

The data was taken over 220 seconds over two movement events spanning 5 seconds each. Since the algorithm is designed to isolate 15 seconds of data when a movement occurs, the ideal case would be to acquire 190 seconds of sedentary data. The duration of extracted sedentary data was compared with the ideal value to determine the efficacy of the algorithm in Table-I.

To further validate the algorithm, the FFT peaks corresponding to the measured breathing were extracted from each section of sedentary data. The rates in each of the three sedentary periods are validated if the fundamental frequency within the respiratory signal range (0.2 - 0.3 Hz) matches the 0.25 Hz breathing rate of subjects as shown in Table-II.

Extraneous body motion and higher duration taken to change positions were classified as non-sedentary by the algorithm. Long-duration data recordings made some subjects restless and contributed to deviation in the ideal sedentary period in Table-I and inaccurate respiration rate measurements in Table-II.

Fig. 4 demonstrates the difference between the FFT plots before and after using the proposed algorithm. Isolating and removing the non-sedentary sections of the data improve the respiration rate measurement from the readings.

VI. CONCLUSIONS

A dynamic center-tracking algorithm has been proposed for monitoring respiratory displacement for a subject at arbitrary nominal distances from a physiological radar system. The algorithm distinguishes sedentary from non-sedentary human respiratory motion for a subject and compensates for changing dc offset conditions as the subject moves to different positions. The algorithm was validated for six subjects seated at two different positions with respect to the radar system, indicating that appropriate thresholds can be set to provide robust monitoring.

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