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Further Applications of Doppler Radar for Non-contact Respiratory Assessment

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***Abstract*— This paper further investigates the use of Doppler radar for detecting and identifying certain human respiratory characteristics from observed frequency and phase modulations. Specifically, we show how breathing frequencies can be determined from the demodulated signal leading to identifying abnormalities of breathing patterns using signal derivatives, optimal filtering and standard statistical measures. Specifically, we report results on a robust method for distinguishing cessation of the normal breathing cycle. The proposed approach can have potential application in the management of sudden infant death syndrome(SIDS) and sleep apnea.**

I. INTRODUCTION

Non-contact techniques for detecting and measuring human physiological functions such as heartbeat and respiration rates have recently received significant attention over more conventional methods such as ECG or chest strap monitors [5]. Research has already been reported on using microwave Doppler radar for measuring respiratory function[10], [16], [8], [15], [3], [4] as well as other approaches using ultra wideband (UWB) radar [13], [11]. Such non-contact monitoring has significant potential for a range of applications from rescue operation in disaster management (earthquake and tsunami) to sleep pattern monitoring and sudden infant death syndrome (SIDS).

The Doppler effect occurs when there is a shift in the frequency of the wave, either reflected or radiated, due to relative motion between the transmitter and receiver [14]. In other words, a target that moves in a quasi periodic movement will reflect the transmitted signal with it's frequency or phase modulated by the time varying position of the target[9]. The frequency of the wave will be shifted directly proportional to the object's motion and will be increases when the wave is compressed (smaller wavelength) [14]. That is, in radar, Doppler shifts are generated when there is a relative motion between the radar and the object.

Typically, using Doppler radar, information for both vital signs heartbeat and respiration can be extracted from the phase modulated by the time varying physiological movement of the chest-wall. However, such physiological motions are elastic, deformable and, with clothing, create significant issues of noise, adversely affecting the sensitivity. Partially due to this and the envisaged application, we simply focus on robustly detecting if a given breathing pattern is normal or abnormal for an individual (for both chest and diaphragm breathing[6]). We focused more on diaphragm breathing as the Doppler shift is stronger compared to chest breathing, the latter being more shallow, less displacement and so lower amplitude[12].

Detecting anomalies in breathing patterns is essential for successful intervention strategies in diseases such as SIDS. Here, typical anomalies are defined by the cessation of breathing for a period of time. Equally, sleep apnea is defined when a patient does not breathe for more than 10 seconds and occurs more than 5 times [2] while sleeping. We will see that demodulated I/Q signals from the Doppler radar can be reliably used to distinguish between breathing and non-breathing for such conditions after signal processing is applied.

This paper is organized as follows. Section II briefly describes the fundamental idea in using Doppler radar for the detection of physiological movement of abdomen for breathing. Section III discusses the experimental setup of the Doppler radar system. Section IV presents the method of digital signal processing and statistical analysis. Section V concentrates on the results of the experiment with concluding remarks in Section VI.

II. THEORETICAL REVIEW

Considering a continuous wave (CW) transmitted signal from the radar defined by

$$T(t) = cos(2\pi ft + \phi(t)), \quad (1)$$

where f is the operating frequency, t is elapsed time, and $\phi(t)$ is the phase noise of the signal source. If $T(t)$ is reflected by a target at a nominal distance d_0 with a time varying displacement, $x(t)$ caused by the movement of the abdomen,whch has periodic movement with no net velocity, the recieved signal at the receiver can be approximated by $R(t)$, [5]

$$R(t) \approx cos(2\pi ft - \frac{4\pi d_0}{\lambda} - \frac{4\pi x(t)}{\lambda} + \phi(t - \frac{2d_0}{c})), \quad (2)$$

The phase needs to be demodulated in order to determine the motion signature or to be detected in the receiver.

Typically, the received signal will be mixed with the local oscillator and fed into low pass filtered to yield the baseband

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output, $B(t)$ which is given as

$$B(t) = cos(\theta + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)). \quad (3)$$

As in quadrature receiver systems, local oscillator (LO) is split into two quadrature LO signals which have $\frac{\pi}{2}$ phase difference and the received signal is split into two receiver chains where each is mixed with corresponding LO signals and filtered to yield in phase and quadrature phase signals denoted by $I_B(t)$ and $Q_B(t)$ correspondingly.

In quadrature systems, the two orthogonal baseband outputs are

$$I_B(t) = cos(\theta + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)), \quad (4)$$

$$Q_B(t) = sin(\theta + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)). \quad (5)$$

θ is the constant phase shift dependent on the nominal distance to the target, and $\Delta\phi(t))$ is the residual phase noise.The main advantage of using a quadrature receiver is to overcome the null problem where at least one output (either I/Q) is not null when the other is null as described in [5]

III. Experimental Setup

We used a simple Doppler radar system as shown in Fig. 1 for this experiment. A CW radar operation at 2.7 GHz with 2.14 dBm, two panel antenna (a transmitter and a receiver), I/Q demodulator (Analog device,AD8347), data acquisition (NI-DAQ) were used. Signals received at the receiver were direct converted into I/Q. The demodulated signal was then sent to the DAQ and processed in a MATLAB environment.

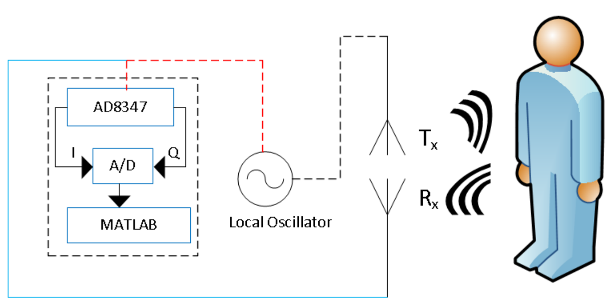

Fig. 1. Doppler Radar System

A male subject was located at a distance of 0.5 m from the panel antenna focused more on the diaphragm rather than the chest in order to obtained a better Doppler shift. Other than that, we have also run the experiment by tilting the body up to 30 degree to the right and left to analyze the sensitivity of the received signal to mimic patient movements while sleeping and to determine the number and position of Doppler configurations to use. The subject was asked to stand with minimal body motion and to breathe normally and abnormally in order to replicate a sleep apnea scenario for synthetic data collection. For abnormal breathing subject was asked to halt breathing after exhaling in a given normal breathing period. Experiment was performed in a comfortable environment with normal (cotton) shirt covering the chest and diaphragm area.

IV. Signal Processing & Statistical Methodology

Summary of the the complete flow is shown in Fig. 2

A. Signal Processing

At the receiver, the signal was send to the AD8347 for direct conversion into differential I/Q signals and then send to the NI-DAQ being sampled at 1000 Hz. The differential signal was converted into single ended I/Q baseband signals and processed via MATLAB. The raw I/Q signals were processed to reject DC offset and smoothed using a SG (Savitzky-Golay polynomial least squares) filter. This filter is designed to preserve steep changes in the signal while still smoothing [7]. A Fast Fourier Transform(FFT) was then performed to estimate the breathing rate with the normal breathing rate range being 0.2-0.5 Hz corresponding to 12-30 breaths/min respectively. We have also used the Fourier filtering toolbox [1] to perform filtering on the time series signal in order to obtain a more informed filtered output signal (breathing pattern) than simply computing breathing frequency.

B. Statistics

Here we have explored the use of statistical means to differentiate the time varying signals into breathing and non-breathing states. Normal breathing creates a significant phase shift compared to the non-breathing state. As we are able to detect the number of breathing transitions via the shape of the demodulated I/Q signal, we used the displacement between the local maxima and local minima of each transition as the state-dependent observation feature. Typically, breathing consists of two components: inhale and exhale and so, for simplicity, we assumed that normal breathing will have corresponding phase shifts compared to the non-breathing state.

Additional to that, we were able to find the derivative of that particular transition where a significant positive gradient is used to denote inhaling and vice versa for exhaling. Furthermore, we also computed the standard deviation with a moving window to see the variation on breathing and non-breathing events.

V. Experimental Results

A. Results analysis derived from curve and measurement

Result of the experiment for Q quadrature outputs for the frontal position from the antenna are shown in Fig. 3 for the normal breathing pattern and Fig. 4 for the abnormal breathing pattern. From Fig. 3, we can see clearly that for a period of 10 seconds there are approximately 3 breathing cycles or approximately 18 breathes/min in (c). From the FFT, in (d), at the range of 0.2-0.4 Hz, we can clearly see the peak occurred at 0.3052 Hz corresponding to 18.3 breathes/min which is quite accurate when compared to the curve in (c). This is the case for normal breathing.

As for abnormal breathing, the subject was asked to halt breathing, after exhaling, in a regular breathing event and this transition can be seen from Fig. 4. From the figure we

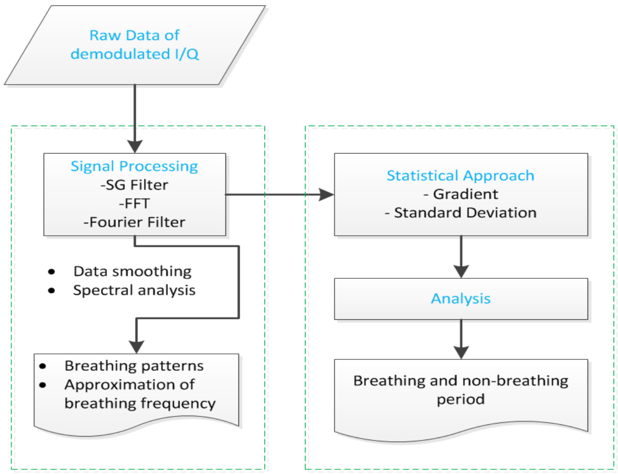

Fig. 2. Signal Processing & Classification Flow

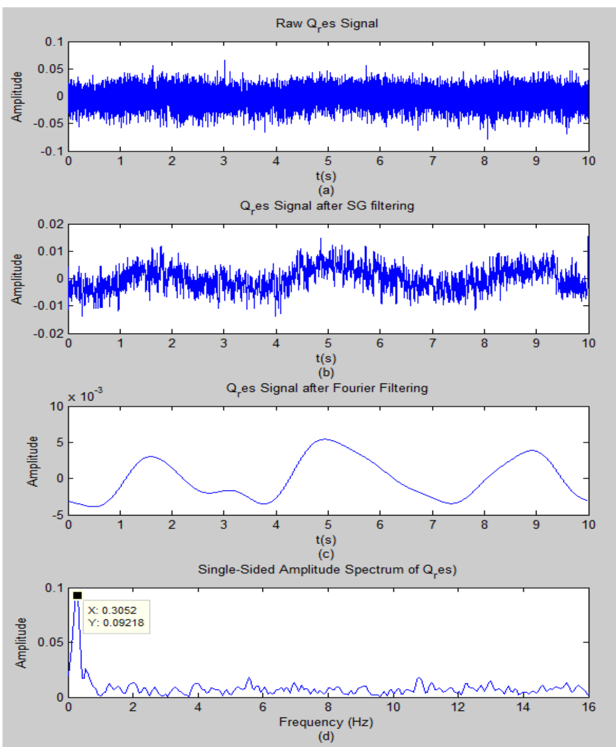

Fig. 3. Q singnal for normal breathing scenario.(a)Raw signal of Q.(b) Q signal after SG filtering. (c) Q signal after Fourier Filtering.(d)Spectrum of Q signal after FFT

can clearly see that the subject was breathing regularly for 10 seconds and stopped breathing from t=10 second to t=30 second and to breathe again normally after that. The data was collected in a period of 40 seconds. From the FFT, in (d), it shows that breathing rate is at 0.1526 Hz corresponding to 9 breathes/min but from the graph,(c) it is expected to be approximation of 6 breathes/min. For the abnormal breathing, it is inaccurate to determine the breathing rate just from the FFT itself due to the more complex breathing pattern as it evolves over time. Furthermore, by analysing the gradient pattern, we could identify the inhale (positive gradient) and exhale (negative gradient) as well as non-breathing event Using standard deviation statistical analysis, we can further identify period of non-breathing event as shown in Fig. 4 (f) where the non-breathing event will have much lower standard deviation compared to normal breathing event.

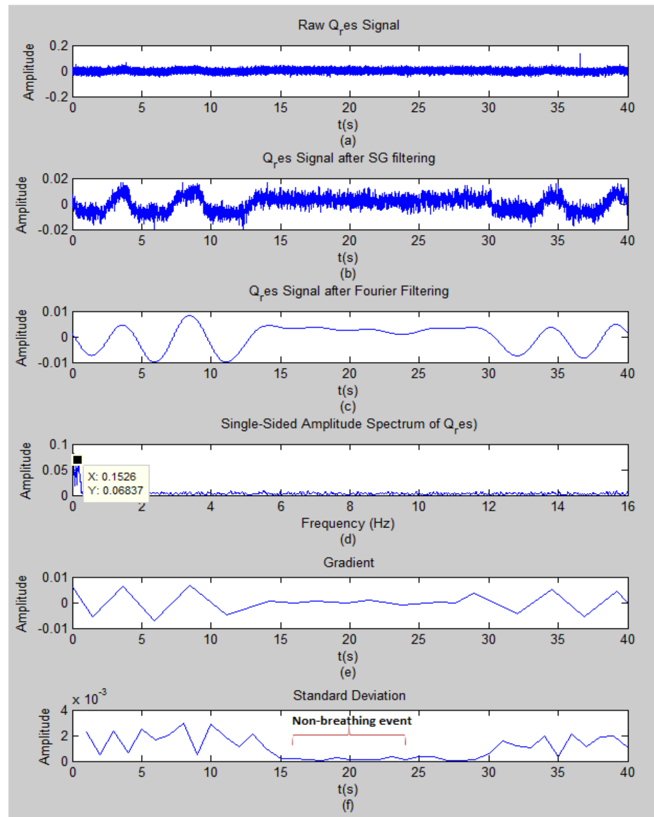

Fig. 4. Q signal for abnormal breathing scenario.(a)Raw signal of Q.(b) Q signal after SG filtering. (c) Q signal after Fourier Filtering.(d)Spectrum of Q signal after FFT. (e) Gradient of the plot. (f) Standard Deviation (1 second moving window)

B. Measurement Sensitivity

We have run another set of experiments where the subject tilted the body up to approximation of 30 degree to the right and left but still in the vicinity of the coverage of the single Doppler system. Both of the results are shown in Figs. 5 and 6. Result shows that as long as the phase modulation due to the movement of the diaphragm is received, we are able to determine the breathing and non breathing event using the simple statistical measures. From both figures, a non-breathing event always had a much lower standard deviation compared to a breathing event. Albeit the transition or breathing signal and non- breathing signal is not that obvious in Fig. 6 though additional sensors would overcome this attenuation.

VI. CONCLUSIONS

A simple Doppler radar system is used to detect breathing pattern as well as non-breathing events in relatively noisy

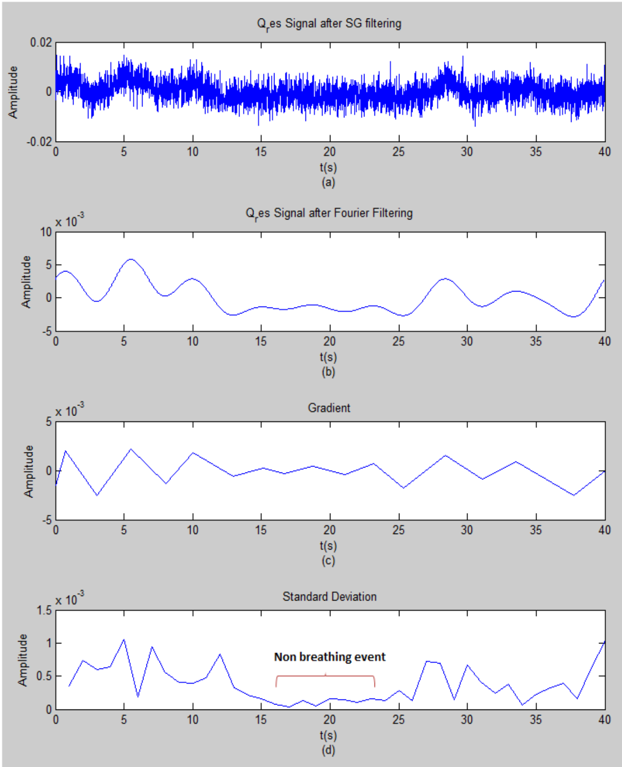

Fig. 5. Q signal for abnormal breathing scenario for tilted body to the right. (a) Q signal after SG filtering. (b) Q signal after Fourier Filtering.(c) Gradient of the plot. (e) Standard Deviation (1 second moving window)

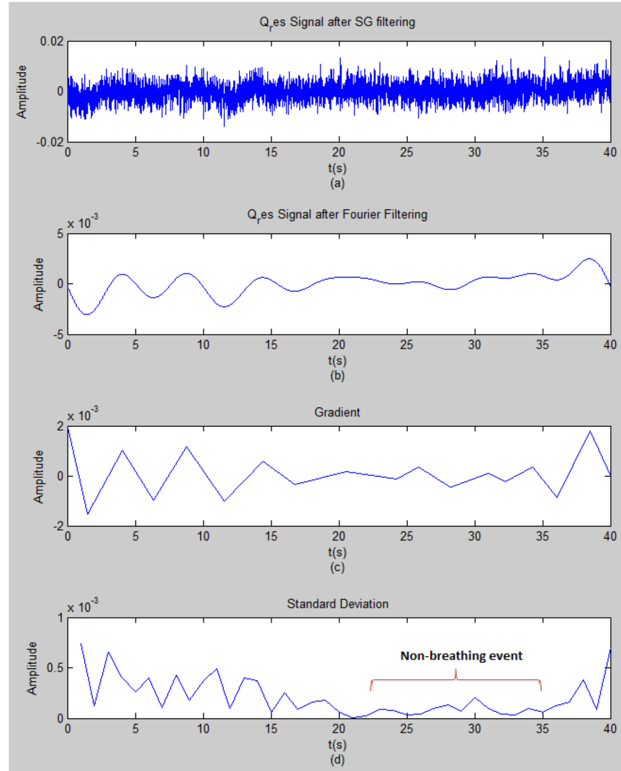

Fig. 6. Q signal for abnormal breathing scenario for tilted body to the left. (a) Q signal after SG filtering. (b) Q signal after Fourier Filtering.(c) Gradient of the plot. (e) Standard Deviation (1 second moving window)

radar signals. The demodulated I/Q is used to overcome the null point problem where it is then filtered, FFT and spectral finding using MATLAB. We have only used simple statistical measures but with very positive results. In all, our results demonstrate the potential of Doppler radar for monitoring and detection critical events for SIDS and sleep apnea.

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