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Suppression of interference in continuous wave Doppler radar based respiratory measurements

Yee Siong Lee*, Pubudu N. Pathirana

Deakin University, 75 Pigdons Road, Waurn Ponds, Australia

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ABSTRACT

Microwave Doppler radar has received considerable attention as a non-contact form of measuring human respiration; in particular for long term monitoring. One of the main challenges in converting this into a viable application is to suppress or separate the artefacts and other interfering signals from the desired respiration signal using a less complex and practically feasible design for regular and potentially real time use. Existing systems either require complex experimental setups or multiple Doppler radar modules to achieve this. In this paper, we propose an approach based on EMD-ICA and approximate entropy ideas to systematically separate received Doppler shifted signal into distinct components and reconstruct the desired respiration pattern pertaining to respective physiological activity. Indeed this allows suppression of the undesirable artefacts and interference from other competing signals. Practical experiments confirmed comparable performance of the proposed method to the measurements obtained through chest straps which are widely used clinically for monitoring respiration.

1. Introduction

The relevance of respiratory patterns to certain medical conditions has not received sufficient attention in the past particularly due to practical limitations in collecting such information. Respiratory information such as long term trends of subjects in their natural environment is currently not available in practically and economically viable forms. Chest straps and spirometers are commonly used in such studies and, as wearable devices, these are not only uncomfortable, but also interfere with the physiological process of respiration; hence the captured information (measurements) is inherently influenced.

Human respiration sensing in a non-contact form [1–4] is made possible with the recent developments in microwave Doppler radar technology. With respiration rates and signal patterns considered as key predictors for certain medical conditions [5,6], the suppression or separation of motion artefacts are essential to increase the accuracy and reliability of measurements captured by the Doppler radar. Involuntary motions such as small head movements to large movements such as jerking of the arm during sleep can cause interferences in observations. Despite certain artefacts generally being considered as noise or interference, these could also be considered to extract vital information in relation to specific conditions. For instance, the jerking of a limb considered as an artefact in breathing signals can be a useful activity to monitor in patients with periodic limb movement disorder [7]. Thus, the separation of these signatures are essential to understand the strength and the frequency of these movements and refine diagnostic procedures in addition to capturing more accurate respiration patterns. As the Doppler radar by nature is sensitive to any form of movement, in general, more spatially distributed sensors are required to separate different sources from the observations as demonstrated by Vergara et al. [8] and Pathirana et al. [9]. In this paper, we present an approach to reconstruct the respiration patterns as well as to separate the artefacts using only one observation channel. We utilise the ideas of approximate entropy to select corresponding sources (respiration source and artefact source) in the pre-processing stage of empirical mode decomposition (EMD) and independent component analysis (ICA).

2. Doppler radar sensor

In Doppler radar, the transmitted signal is modulated by the motion of the abdomen during the inhalation and exhalation activities where the change in phase can be derived from the received signal. Using a continuous wave (CW), the modulated signal at the receiver can be approximated as $R(t) \approx \cos\left(2\pi ft - \frac{4\pi d_0}{\lambda} - \frac{4\pi y(t)}{\lambda} + \phi\left(t - \frac{2d_0}{c}\right)\right)$ where ϕ is the phase

* Corresponding author. Tel.: +61 423331273.
E-mail address: yeel@deakin.edu.au (Y.S. Lee).

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Table 1
Evaluation of Doppler radar measurements with respiration belt for three subjects.

	Dataset 1		Dataset 2	
Subject	MSE	Corr	MSE	Corr
1	0.010	0.95	0.017	0.94
2	0.025	0.97	0.016	0.97
3	0.027	0.96	0.012	0.95

noise of the signal source, $y(t)$ is the time varying displacement of the chest or abdominal wall due to respiration activity at a nominal distance d_0.

The received In phase (I) and Quadrature Phase (Q) signal at the Radar quadrature output are denoted as $I_B(t) = \cos\left(\theta + \frac{4\pi y(t)}{\lambda} + \Delta\phi(t)\right)$ and $Q_B(t) = \sin\left(\theta + \frac{4\pi y(t)}{\lambda} + \Delta\phi(t)\right)$. Using arctangent demodulation, I and Q output data can be combined as follows:

$$x(t) = \tan^{-1}\left(\frac{Q_B(t)}{I_B(t)}\right) = \frac{4\pi y(t)}{\lambda} + \Delta\phi \quad (1)$$

2.1. Experiment protocol

The measurement of humans respiration signals using a non-contact Doppler radar was approved by the Faculty of Science and Technology Ethics Sub-Committee HEAG (Faculty Human Ethics Advisory Groups), Deakin University. No film recordings of subjects were made in this study and all the subjects provided their written informed consent for their participation in the experiments.

The Doppler radar module [10] was used where it transmits a 2.4 GHz continuous wave at 0 dBm (1 mW) and was attached to the patch antennas (a transmitter and a receiver) connected to a data acquisition module (NI-USB6009) to be further processed in a MATLAB environment. The Doppler radar module used in this work adopts the direct-conversion radar architecture where the receiver chain on the RF board includes a low noise amplifier (LNA), a balun, a gain block, and an operational amplifier [11]. An external respiration strap (MLT1132 Piezo Respiratory Belt Transducer) attached to PowerLab (ADInstruments) was used as a reference signal.

To further evaluate the sensitivity and accuracy of the Doppler radar in capturing human respiration under minimum interference/artefact, few experiments were performed on three subjects. From the results shown in Table 1, an average correlation factor (Corr) of 0.96 and mean square error (MSE) of 0.018 were obtained which indicate that the measurements from Doppler radar are highly correlated to the respiration belt. Additionally, as reported in [12], a sub-millimetre measurement accuracy was also demonstrated in respiration sensing using continuous wave Doppler radar.

Later, respiration signals of two subjects in two different positions (seated and supine – approximately 1 m away from the antennas) under the influence of motion artefact were acquired in this study. In the seated experiment, subject moved the right arm back and forth approximately a minute of duration while in supine experiment, the other subject performed an involuntary limb movement to resembles the jerking of the limb in a period of approximately 6 min.

3. The proposed system architecture

The overall signal processing approach is shown in Fig. 1. Here, we used EMD in combination with fastICA for source separation using a single channel for measurements. Multiple channel signals h or IMFs formed by the EMD process are passed into the fastICA source separation algorithm and approximate entropy (ApEn) is used as the quantitative measure in selecting the relevant IMFs (pre-filtering for IMFs that purely corresponds to noise – stage 1). Subsequently (stage 2), at the source separation stage, the

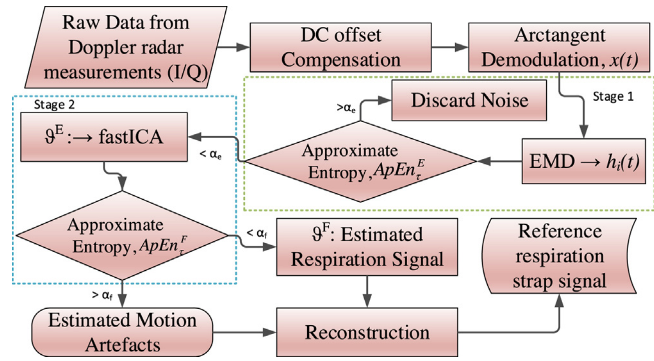

Fig. 1. Signal processing flow.

sources deemed to be motion artefacts are identified using approximate entropy estimation where the corresponding columns $\tilde{S}$ are assigned to zero. From the un-mixing matrix of W^{-1}, the remaining respiration sources were then recovered which are expected to be free from motion artefacts. Lastly, the respiration signal is reconstructed by simply adding all the corresponding IMFs.

3.1. Raw data processing

The received I and Q signals were sent to the data acquisition module where it is then re-calibrated to eliminate DC offsets using the curve fitting technique in [13]. Subsequently, the I and Q signals are recombined using arctangent demodulation given in Eq. (1) and further analysed using EMD-ICA approaches.

3.2. EMD-ICA

Empirical mode decomposition (EMD) [14–16] was first detailed in 1998 specifically for non-linear signal processing as well as for non-stationary data distributions. The algorithm actually decomposes a time series into multiple modes known as intrinsic mode functions (IMF). Given the arctangent signal of radar denoted by $x(t)$, take $c_0(t) = r_j(t)$ and let c_K satisfy the standard deviation condition [15]

$$\sum_{t=0}^{T}\left[\frac{(c_{K-1}(t) - c_K(t))^2}{c_{K-1}^2(t)}\right] < \epsilon, \quad (2)$$

where $c_n(t) = c_{n-1} - m_n(t), m_n(t) = \frac{U_n(t)+L_n(t)}{2}$ with $U_n(t)$ and $L_n(t)$ are the upper and lower envelope of $c_n(t)$. $h_0(t) = 0$, $r_0(t) = x(t)$, Now we take $h_{j+1}(t) = c_K(t)$. $r_{j+1}(t) = r_j(t) - h_{j+1}(t)$.

The shifting process steps are then repeated till the residual $r_{j+1}(t)$ becomes a monotonic/constant function. The original arctangent signal of radar can be reconstructed by summing up all the IMFs given as $x(t) = \sum_{i=1}^{N} h_i(t) + r_N(t)$.

Although the EEMD (Ensemble Empirical Mode Decomposition) [17] approach is more robust and less sensitive to noise, it requires additional information such as the noise level and the ensemble size. Further, Mijovi'c et al. also proposed using wavelet-ICA which heavily relies on the prior knowledge of the signal of interest. This process involves selecting a mother wavelet (types and orders) and also a number of decomposition levels. Without this prior knowledge and the relevant signal processing information, the entire process would be complicated as it involves a wide range of parameter selections.

Therefore, in this paper, EMD-ICA with approximate entropy was proposed due to its simplicity and also as a conceptual means of automatically suppressing the interference from Doppler radar based respiratory measurements. Nevertheless, future work will includes more advanced signal processing schemes such as