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Novel signal processing techniques for Doppler radar cardiopulmonary sensing

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ABSTRACT

In this paper, we develop new signal processing techniques for Doppler radar cardiopulmonary sensing. These techniques enable independent recovery of respiration and heartbeat signals from measurements of chest-wall dynamic motion, which are subsequently used for independent estimation of respiration and heart rate. In particular, three novel elements are introduced: the concept of representing the composite demodulated signal in the complex plane as a vector sum of various components, combining dc coupling with block mean removal, and adaptive cancellation of respiration harmonics. From this, algorithms are derived for arc-length demodulation and cardio/pulmonary separation. A test signal generator is developed to simulate actual signals. Also, an experimental setup is presented and several sets of real data are analyzed using the new signal processing techniques.

1. Introduction

There are many potential applications for a non-invasive technique to monitor respiration and/or heartbeat. Doppler radar, operating at microwave frequencies in the range of 1–10 GHz, has long been suggested as a means to accomplish this [1–5]. More recently, RF technology developed for mobile phones has been applied to implement such devices [6–10], and generalized to sensing of multiple subjects [11–13]. A particularly comprehensive discourse on the subject including physiological background can be found in [14].

Fig. 1 shows a block diagram of the basic Doppler radar technique. A continuous-wave (CW) source feeds an antenna through a circulator, and radiates to a desired object in the field that experiences motion $x(t)$. The object reflects the signal back to the same antenna (or, alternatively a separate receive antenna) which is then captured by the circulator and sent to an I/Q (complex) demodulator. The demodulator takes a portion of the CW source signal, splits it into two components with 90° relative phase shift, and mixes with the received signal to derive in-phase and quadrature (I/Q) outputs, $i(t)$ and $q(t)$, respectively. (In early work, only one demodulated channel was used, and the subject had to move into the "sweet spot" so as not to be near a null when the reference and return signals are in phase or 180° out of phase; recent work uses the I/Q technique to avoid that problem.) The lowpass filters (LPFs) are used to remove interference and retain only signals that are changing relatively slowly compared to the CW frequency. As the scattering object moves, the phase of the return signal varies as $2\pi x(t)/(\lambda/2)$, where $\lambda = c/f_c$ is the wavelength of the CW signal, c is the velocity of light, and f_c is the CW carrier frequency. (The divisor of 2 on λ is due to the two-way propagation path to and from the scatterer.) Therefore, as the scattering object moves radially, the phase will rotate 360° every $\lambda/2$. For example, if $f_c = 2.4$ GHz, then the wavelength is approximately $\frac{1}{8}$m or 12.5 cm for $c = 3 \times 10^8$ m/s and the phase rotates 360° for every 6.25 cm of motion.

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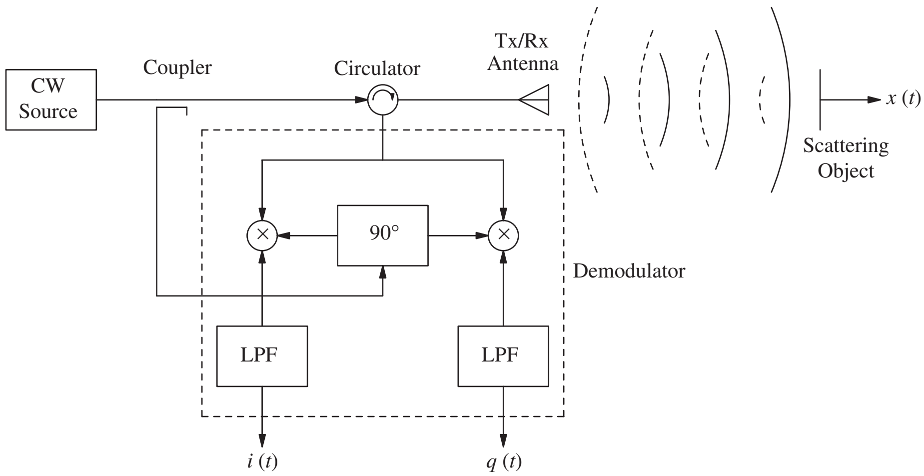

Fig. 1. Block diagram of basic Doppler radar technique.

Most of the studies to date have been done in the form of laboratory experiments under ideal conditions, so there is some concern about the prospects of developing the technology into reliable products. Some of the potential problems include the effects of background (BG) scatter, motion of the subject as well as the BG, and interference between the respiration and heartbeat signals. BG scatter both from the ambient surroundings as well as from parts of the subject's body exclusive of the relevant chest-wall area [15] adds a component to the desired signal that must be dealt with. Gross motion of the subject, as well as other objects in the BG will introduce undesired dynamics into the desired signal, making the problem even more difficult. Finally, as documented in this paper for the first time, there is the problem of respiration harmonics falling close to the heartbeat frequency so as to make reliable heart-rate estimation difficult. It is the intent of this paper to study these problems and introduce novel signal processing techniques to ameliorate these disruptive effects.

Three novel elements are introduced in this paper pertaining to signal processing for the Doppler radar cardiopulmonary (CP) application. The first is the concept of representing the composite demodulated signal in the complex plane as a vector sum of backscattered components from the BG and subject. Second is the notion of combining dc coupling with block mean removal to avoid long transient settling times. Third is a technique for adaptively cancelling respiration harmonics, which can interfere with the detection of weaker heartbeat signals.

We emphasize here that the main thrust of this paper is to *introduce* novel signal processing techniques for this application from viewpoints not previously expressed in the literature. It is *not* meant as a "be all, end all" comprehensive study that includes all of the real-world aspects of this problem, such as performance over a population of subjects and heart-rate variability.

The next section develops a physical model of the signal and propagation scenario to set the stage. Then in Section 3, we discuss the basic signal processing techniques, including prefiltering and analog-to-digital conversion, extraction of the raw CP signal, and spectral analysis. Section 4 introduces a technique for mitigating heartbeat signal interference from the respiratory component. Simulation techniques are developed in Section 5, where we introduce a test signal to represent chest-wall motion and use this to demonstrate the signal processing techniques. Section 6 validates and extends the simulation results using experimental data collected with a real RF Doppler radar system using a live subject.

2. Signal model

Fig. 2(a) shows a schematic geometrical sketch of the propagation scenario. The desired backscattered signal comes from the chest-wall area of the subject. Undesired interfering components will come from other backscattering areas on the subject, as well as from other BG objects in the antenna field of view. Using an antenna with a narrow beam pattern (i.e., high gain) can significantly reduce the interference from BG objects, although there is a trade-off here in making sure the desired subject is entirely in the beam at all times. Also, for many applications, it is probably not feasible to use the antenna pattern to exclude undesired returns from subject areas outside of the chest wall. We will subsequently designate the two types of subject backscatter as CP and *non-cardiopulmonary* (NCP), and everything else as BG, which includes objects, walls, ceiling, etc. that are within the field of view.

The return from each backscatterer within the antenna field of view can be visualized as a vector in the complex plane, where its length is proportional to the reflection coefficient and its orientation represents the RF phase, which as previously discussed varies with radial distance. The various CP, NCP, and BG components discussed above are then added in this vector space as depicted in Fig. 2(b), where the resultant vector represents the composite return from all scatterers. In this diagram, the BG component is presumed stationary, but the position of the CP and NCP subject components can lie anywhere along the dashed circle loci. As the subject moves a small