LETTER

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Accurate heartbeat monitoring using ultra-wideband radar

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Abstract: We demonstrate an accurate remote measurement of heartbeats using an ultra-wideband radar system. Although most conventional systems use either continuous waves or impulse-radio systems for remote vital monitoring, continuous waves suffer from non-stationary clutters, while impulse-radio systems cannot detect heartbeats. Our ultra-wideband radar system has a moderate fractional bandwidth intermediate of these systems, resulting in both the suppression of clutters and high sensitivity in measuring accurate heart rates even in a dynamic environment. A simultaneous measurement of the vital signal of a participant employing the ultra-wideband radar and electrocardiography reveals the high accuracy of the radar system in measuring the heart rate varying over time.

Keywords: ultra-wideband, radar, vital monitoring, heart rate

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

The instantaneous heart rate is the heart rate that varies beat to beat over time. Its temporal development is referred to as heart-rate variability and is known to be an indicator of aging, sleep apnea, diabetic neuropathy and sudden cardiac death [1, 2]. Contact measurements such as classical electrocardiography and measurements made using the recently commercialized Apple Watch (Apple Inc., CA) are uncomfortable for the subject during sleep and exercise, and not suitable for newborn babies or patients with severe burns or skin problems. Therefore, non-contact heartbeat monitoring technology would have a wide range of application in,

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for example, homecare of the elderly and the care of patients in hospital without requiring cables or electrodes to be attached to the body. The use of microwaves is promising for such application because of the microwave's unobtrusive nature and ability to penetrate clothing. However, one of the challenges of the technology is the small displacement generated by heartbeats, which is typically only a few hundred micron yet must be accurately detected in the presence of breathing motion.

In existing studies, continuous-wave (CW) microwaves are commonly used to monitor vital signs, and CW-based remote vital measurements have been reported using frequencies of 2.4 GHz [1, 3, 4, 5], 2.45 GHz [6], 5.8 GHz [7, 8], 10.0 GHz [2, 9, 10], 15.0 GHz [11], 24.0 GHz [12, 13, 14], and 94.0 GHz [15, 16, 17, 18]. Among these studies, only a few [1, 2, 8] successfully measured the instantaneous heart rate, which would allow the assessment of heart-rate variability. A received CW signal contains not only the echo from the subject but also echoes from other objects called clutters and crosstalk between antennas. These undesirable components must be removed using DC suppression techniques [1, 8] and the center estimation method [10, 19]. Such techniques, however, work only when the clutter is stationary; if there is more than one person or other moving objects in the scene, their motion cannot be distinguished from that of the target. Thus, as long as a CW-based system is used, vital signals cannot be accurately measured in many realistic scenarios.

To resolve the problem of clutters, it is necessary to apply ultra-wideband radar that has high range resolution, allowing most clutters to be removed by time gating. The application of impulse-radio (IR) ultra-wideband radar to vital monitoring has been reported, for center frequency $f_0 = 6.0$ GHz, bandwidth $B = 3.5$ GHz, and fractional bandwidth $B_\mathrm{f} = 60\%$ by Lai et al. [20], for $f_0 = 7.0$ GHz, $B = 4.9$ GHz, and $B_\mathrm{f} = 70\%$ by Schleicher et al. [21], and for $f_0 = 1.5$ GHz, $B = 3.0$ GHz, and $B_\mathrm{f} = 200\%$ by Bernardi et al. [22]. However, these IR radar systems are only able to measure respiration and not the heart rate because of their low sensitivity to the target displacement.

The above observations suggest that there is a trade-off between displacement sensitivity and robustness against clutters in dynamic scenarios. To achieve high sensitivity, it is necessary to use the phase information of a CW system, but this works only if there are no other moving targets. In contrast, IR radar systems cannot measure a small displacement generated by heartbeats owing to their limited sensitivity. To balance these factors, we use ultra-wideband radar that has a relatively narrow fractional bandwidth. The radar used in this study has a center frequency, bandwidth and fractional bandwidth of $f_0 = 26.4$ GHz, $B = 730$ MHz, and $B_\mathrm{f} = 3\%$. This system possesses the advantages of both CW and IR radar systems; the system has high sensitivity like CW-based systems and the ability to reject clutters like IR-based systems. Employing time gating, this system can obtain clutter-free vital signals that can be used to detect an accurate heart rate even in a dynamic environment. This paper demonstrates accurate measurements of the instantaneous heart rate using the ultra-wideband radar. The estimation of the heart rate is evaluated by comparing it with a reference electrocardiography measurement.

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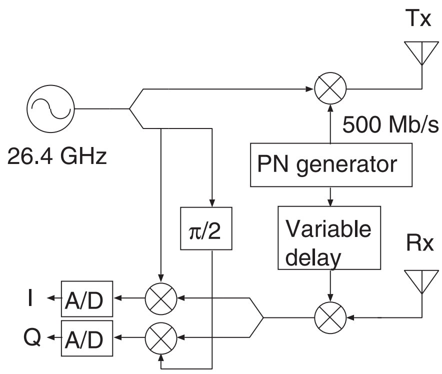

Fig. 1. Block diagram of the code-modulated ultra-wideband radar system.

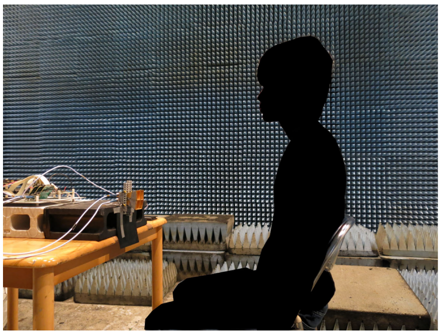

Fig. 2. Measurement setup with a participant sitting in a chair with a backrest. The photograph is edited to protect privacy.

2 Ultra-wideband radar system and measurement setup

The signal transmitted from the radar is a code-modulated signal with a carrier frequency $f_0 = 26.4\,\mathrm{GHz}$ modulated by an m-sequence of 500 b/s, resulting in 10-dB bandwidth of $B = 730\,\mathrm{MHz}$. The receiver uses the same sequence to demodulate the received signal. The demodulated signal is down-converted and sampled to obtain in-phase and quadrature signals with a sampling interval Δt_f of 2.0 ns, which corresponds to a range bin size of 30.0 cm. The range measurement interval Δt is 1.3 ms, which corresponds to the slow-time resolution. The block diagram of the radar system is shown in Fig. 1. We used two horn antennas with gains of 15.0 dBi.

We recorded data for a 23-year-old healthy male participant following a protocol approved by the Ethics Committee of Kyoto University Graduate School and Faculty of Medicine. The test participant remained seated approximately 60.0 cm from the antennas in a chair with his back touching the backrest (Fig. 2). The participant was instructed to remain still while breathing normally during the measurement. The measurement duration was 50.0 s. Both antennas were directed towards the participant's chest. The received complex-valued signal is denoted $s_0(t, r)$ for a slow-time t and a range $r = c\tau/2$ corresponding to the fast-time τ. Unlike the case for CW-based systems, the signal $s_0(t, r)$ does not contain clutters, unless there is a clutter in the same range gate as the target.

We also record an electrocardiogram (ECG) using an RF-ECG EK device (Micro Medical Device, Inc., Tokyo, Japan). The device sampled the voltage

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between a pair of electrodes attached to the body of the participant. The ECG data $s_e(t)$ recorded using this device are used as a reference in the evaluation of the estimation accuracy of the heart rate using the proposed radar system. The time interval between adjacent R-waves in the ECG data is detected and compared with the inter-beat interval (IBI) estimated from radar signals.

3 Measurement data and heartbeat detection

Fig. 3 presents $|s_0(0,r)|^2/\max|s_0(0,r)|^2$, an example of a range profile of the radar data for the slow time $t = 0$, which clearly shows a strong echo from the target in the second and third range bins. The range r_0 with the largest echo intensity is selected as $r_0 = \arg\max_r \int |s_0(t,r)|^2 \mathrm{d}t$. Fig. 4 shows the ECG signal $s_e(t)$ (in red) and radar signal phase $s_p(t) = \angle s_0(t, r_0)$ (in black) measured simultaneously. The temporal variation in $s_p(t)$ is mainly due to the respiratory motion whose peak-to-peak amplitude is approximately 2 rad, which corresponds to displacement of the target of 1.8 mm, considering the center wavelength of 11.4 mm.

We apply a Gaussian low-pass filter with a cutoff frequency of 7.7 Hz to extract the respiration component, which is subtracted from the original signal $s_p(t)$ to generate a high-frequency component $s_h(t)$ that is likely to contain the heartbeat signal. Fig. 5 shows the ECG signal $s_e(t)$ (in red) and the output of the high-pass filter applied to the radar signal phase (in black). We apply a topology-based algorithm [23] to estimate IBIs from $s_h(t)$. The IBIs are compared with the R-R

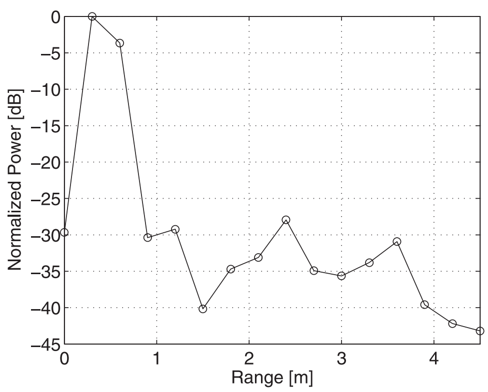

Fig. 3. Range profile of a signal reflected from the participant.

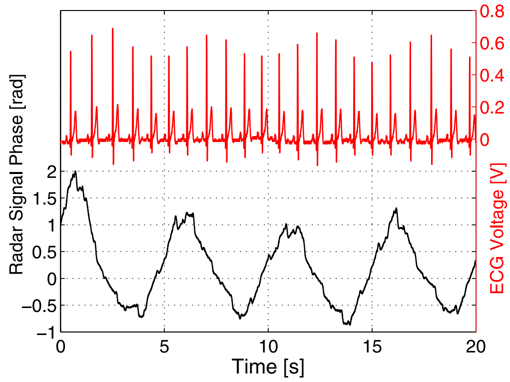

Fig. 4. Radar signal phase $s_p(t)$ (black) and ECG signal $s_e(t)$ (red) measured simultaneously.

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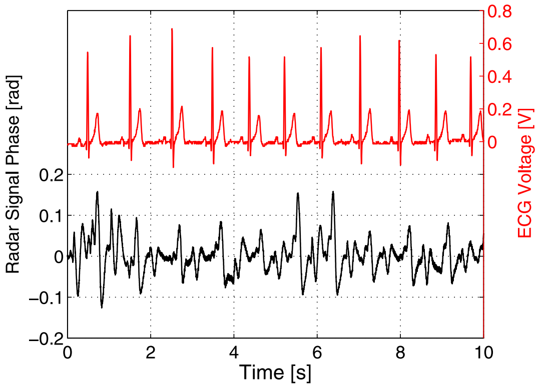

Fig. 5. Radar signal phase after applying a high-pass filter $s_h(t)$ (black) and ECG signal $s_e(t)$ (red).

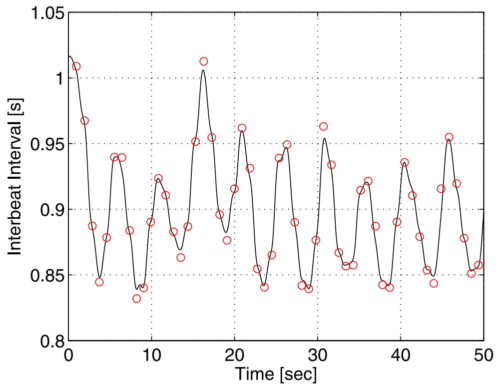

Fig. 6. IBI estimated from the radar signal $s_h(t)$ (black line) and R-R intervals calculated from the ECG signal $s_e(t)$ (red circles).

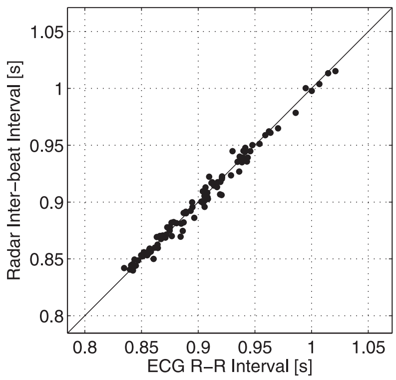

Fig. 7. Scatter diagram of the IBI estimated from the radar signal and R-R intervals calculated from the ECG signal.

intervals calculated from the ECG signal $s_e(t)$ in Fig. 6. In this measurement, the maximum and minimum R-R intervals are 0.83 and 1.02 s, respectively, and the average heart rate is 64.1 bpm, corresponding to an average IBI of 0.94 s. The root-mean-square error of the estimated IBIs is 5.1 ms, corresponding to error of 5.4% relative to the average heart rate. Fig. 7 shows a scatter diagram of the IBIs estimated from the radar signal and the R-R intervals calculated from the ECG signal. The correlation coefficient is 0.993. These results demonstrate the high accuracy achieved in estimating IBIs using the ultra-wideband radar.

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4 Conclusion

We measured a subject's heart rate employing ultra-wideband radar and evaluated the accuracy of the measurement by electrocardiography. Unlike conventional CW-based and IR-based systems, our radar system is sufficiently sensitive to measure the heart rate, while most clutters can be suppressed by its high range resolution. The root-mean-squared error in the heart-rate estimation was 5.1 ms, corresponding to relative error of 5.4%. The coefficient of correlation between the IBIs estimated from the ultra-wideband radar and the R-R interval of ECG data was 0.993. These results reveals the possibility of reliable remote monitoring of the instantaneous heart rate in many realistic scenarios. The focus of future work is to compare the proposed ultra-wideband radar with CW-based systems. It is also important to evaluate the accuracy in estimating IBIs as the distance between the antenna and the subject changes.

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