Sensor signal processing

Noncontact Measurement of Heartbeat of Humans and Chimpanzees Using Millimeter-Wave Radar With Topology Method

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Abstract—This letter proposes a method to determine the filter parameters required for the topology method, which is a radar-based noncontact method for the measurement of heart interbeat intervals. The effectiveness of the proposed method is evaluated by performing radar measurements involving both human participants and chimpanzee subjects. The proposed method is designed to enable the setting of the filter cutoff frequency to eliminate respiratory components while maintaining the higher harmonics of the heartbeat components. Measurements using a millimeter-wave radar system and a reference contact-type electrocardiogram sensor demonstrate that the smallest errors that occur when measuring heart interbeat intervals using the proposed method can be as small as 4.43 and 2.55 ms for humans and chimpanzees, respectively. These results indicate the possibility of using noncontact physiological measurements to monitor both humans and chimpanzees.

Index Terms—Sensor signal processing, chimpanzees, heart interbeat interval, millimeter-wave radar, noncontact measurement, topology method.

I. INTRODUCTION

Radar has been used to detect the body displacements caused by physiological activities such as respiration and heartbeats, thus allowing the physical and mental health conditions of humans and animals to be monitored in a noncontact manner. Noncontact monitoring of animals is especially important when the captive animal has a health condition but cannot communicate with its human caretakers. In addition, use of these technologies can contribute to the well-being of animals because they avoid the stress caused by wearing sensors attached to their bodies. Radar-based measurements have acquired physiological signals from animals, including a rabbit and a rat [1], a horse [2], and a cow [3]. In this letter, we have selected chimpanzees as the target animal because they are known to be the species most closely related to humans with the aim of developing an effective method for noncontact measurements of their heart interbeat intervals (IBIs). Although camera-based measurements of chimpanzee cardiac signals [4] and radar-based measurements of average chimpanzee heart rates [5] have been reported previously, this represents the first report of accurate radar-based measurements of the time-dependent heart IBIs of chimpanzees. A preprint of this letter has been posted [6].

One of the greatest challenges with regard to radar-based heartbeat measurements is the effect of respiration because the body displacement caused by a heartbeat is much smaller than that caused by respiration [7], [8]. Several studies have, therefore, aimed to eliminate the respiratory components from the radar signals [9], [10], [11], [12]. Yamamoto and Otsuki [9] used a bandpass filter with a machine learning algorithm to extract the heartbeat component of radar echo signals. Wang et al. [10] used variational mode decomposition to separate the heartbeat and respiration components of radar echo signals. Petrović et al. [11] used a bandpass filter bank that was applied to the radar echo signal without arctangent demodulation. These methods largely rely on the fundamental frequency component of the heartbeat component, which is often masked by the higher order harmonics of the respiratory component, thus reducing the accuracy of heart IBI estimation.

In this letter, we propose a method to determine the optimum cutoff frequency for a high-pass filter for use with the topology method [13], which is known as a method for radar-based IBI estimation using waveform features. In previous studies, Wu et al. [14] used the topology method with a bandpass filter with cutoff frequencies that were selected empirically. Through numerical examples performed using measured radar data, we clarify that the cutoff frequency should be selected to reject the respiratory component of the signal while maintaining the higher-order harmonics of the heartbeat component. After confirming the effectiveness of the proposed method by performing measurements on humans lying in the prone position as in [15], we apply the same method to two chimpanzees under anesthesia.

II. SYSTEM MODEL AND TOPOLOGY METHOD

In this letter, we use a frequency-modulated continuous-wave radar system with a linear antenna array. First, we generate a complex-valued time-dependent radar image $I_\mathrm{c}(t, \boldsymbol{r})$, as detailed in [16], where $\boldsymbol{r}$ is the position vector, and t is the slow time. Then, we suppress the static clutter components by subtracting the time-independent component $\bar{I}_\mathrm{c}(\boldsymbol{r})$ obtained by averaging $I_\mathrm{c}(t, \boldsymbol{r})$ over the time period T and obtain a real-valued radar image $I(t, \boldsymbol{r}) = |I_\mathrm{c}(t, \boldsymbol{r}) - \bar{I}_\mathrm{c}(\boldsymbol{r})|^2$ that is used to estimate the target position $\boldsymbol{r}_0$ by detecting the highest peak of the radar image $\bar{I}(\boldsymbol{r})$ obtained by averaging $I(t, \boldsymbol{r})$ over the time period T.

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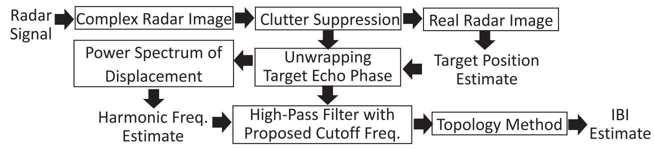


Fig. 1. Flowchart of the radar signal processing method.

The displacement is estimated to be $d'(t) = (\lambda/4\pi)$ unwrap $\angle I_c(t, \boldsymbol{r}_0)$, where $\angle$ denotes the phase of a complex number and unwrap represents a phase unwrapping operator. Finally, the displacement waveform $d(t) = d'(t) - g * d'(t)$ is obtained using a Gaussian filter $g(t) = (1/\sqrt{2\pi}\tau)e^{-t^2/2\tau^2}$, where $*$ denotes a convolution operator, and we set $\tau = 1.0$ s in this study. We set the measurement time $T = 120$ s for human measurements, and $T = 60$ s for the chimpanzee measurements. The use of a measurement time that was shorter for the chimpanzees than that for the human subjects was the veterinarian's decision.

The topology method [13] is known to be an accurate method for radar-based heartbeat measurements. The topology method extracts six types of feature points (peak, trough, and four types of inflection points) from the body displacement waveform $d(t)$ and then introduces a new index called topology similarity, which acts as a measure of the repeatability of the feature sequences. Using the topology correlation, unreliable estimates can then be excluded to achieve accurate heart IBI estimation. The parameters for the topology method were determined empirically to achieve high accuracy and a low data loss rate simultaneously.

One of the main challenges in taking radar-based heartbeat measurements is the interference between the respiration and heartbeat components. In particular, the heartbeat's fundamental frequency component (1.0–1.7 Hz for humans [17] and 1.5–2.2 Hz for chimpanzees [18]) is known to be affected by respiratory harmonics and intermodulation, thus making it difficult to separate or discriminate the measured components [19]. To overcome this issue, we use both the fundamental frequency of the heartbeat and its higher harmonics, as used in [11], [19], [20], [21], and [22]. It was reported previously that the higher harmonics of the heartbeat component are much stronger than the higher (e.g., 8–10th orders) harmonics of the respiration signal [11], [22]. For the reasons described above, the higher harmonics of the heartbeat component can be identified with relatively little effort when compared with the fundamental frequency component, which is masked by the respiratory components. In addition, it was reported that the use of the second harmonic frequency of the heartbeat serves as an effective measure for suppression of the respiratory interference in the radar data [19].

In the proposed method, which is based on an estimate of the power spectral density $D(f) = |\mathcal{F}[d(t)]|^2$ of the estimated displacement $d(t)$, the second harmonic frequency $f_{H2} = 2f_{H1}$ of the heartbeat is identified using the typical heart rate range for each species. We then detect the frequency f_c that corresponds to the trough of $D(f)$ and satisfies $(d/df)D(f)|_{f=f_c} = 0$, $(d^2/df^2)D(f)|_{f=f_c} > 0$, and $f_c < f_{H2}$, where $D(f)$ is smoothed appropriately. If multiple candidates for f_c are available, we select the f_c that minimizes $|f_{H2} - f_c|$. We then apply a high-pass filter with a cutoff frequency f_c to the displacement waveform $d(t)$; the resulting waveform is used as the input for the topology method. Fig. 1 summarizes the radar signal processing adopted in this study. In the next section, we evaluate the performance of the proposed method using the results of measurements involving both human and chimpanzee subjects.

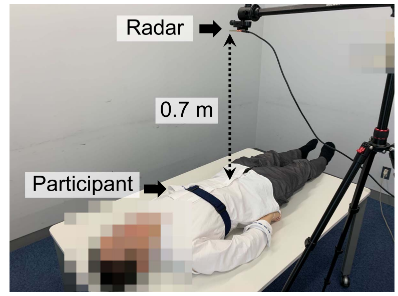


Fig. 2. Photograph of the measurement setup with a human participant.

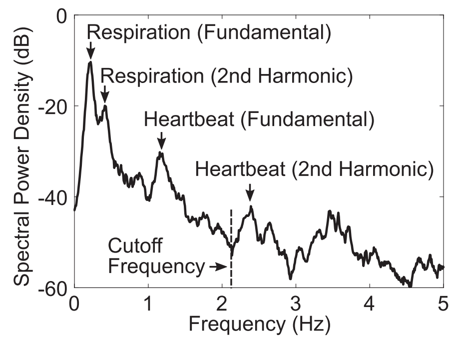


Fig. 3. Estimated power spectral density $D(f)$ characteristic of the displacement $d(t)$ for participant A.

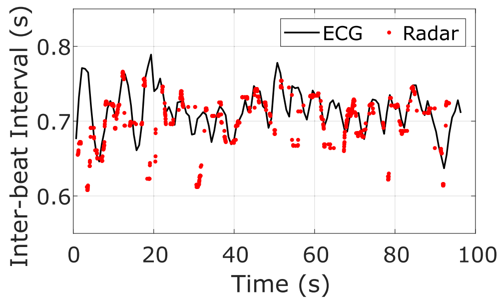
III. EVALUATION OF ESTIMATION ACCURACY OF PROPOSED METHOD

A. Accuracy Evaluation With Human Participants

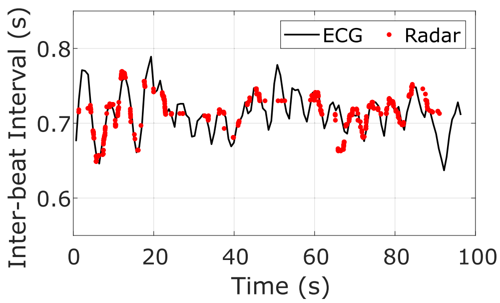
To evaluate the effectiveness of the proposed method, preliminary experiments were conducted with two human participants. The participants were placed in a supine position and breathed naturally for 2 min with the electrodes of an electrocardiogram (ECG) sensor attached to their chest (see Fig. 2). Note that the ECG sensor was only used here to evaluate the accuracy of the radar-based measurements.

We used a commercially available frequency-modulated continuous-wave radar system (T14RE_01080108_2D, S-Takaya Electronics Industry, Okayama, Japan) with a center frequency of 79 GHz, a center wavelength $\lambda = 3.8$ mm, a bandwidth of 3.5 Hz, and a slow-time sampling frequency of 100 Hz. The radar has a multiple-input and multiple-output antenna array that consists of three transmitting and four receiving elements with intervals of 7.6 mm (2λ) between the transmitting elements and 1.9 mm ($\lambda/2$) between the receiving elements; this setup can be approximated using a 12-element virtual linear array. We placed the radar at a distance of 0.7 m from each participant and ensured that the participant's body was oriented in the direction of the array baseline.

Fig. 3 shows the power spectral density $D(f)$ of the displacement $d(t)$ for participant A, along with a dashed line that indicates the proposed cutoff frequency f_c for a high-pass filter. The figure also shows the fundamental and higher harmonics for each component. In the figure, the fundamental and second harmonic frequencies of the respiration and heartbeat components are shown clearly. However, in many cases, the fundamental frequency component of the heartbeat is often masked by the higher harmonics of the respiratory component. Fig. 4 shows the IBI that was estimated using the topology method with a bandpass filter that had the same cutoff frequencies that were used



(a)



(b)

Fig. 4. IBI characteristics estimated using radar and the topology method with (a) the conventional filter [14] and (b) the proposed filter, where the black lines are reference IBIs obtained from the ECG. (a) IBI estimated using conventional filter (participant A). (b) IBI estimated using proposed filter (participant A).

TABLE 1. RMS Error in IBI Estimation for Human Participants.

Participant	RMS error (ms)		
	Fundamental freq.	[14]	**Proposed**
A (1st trial)	55.10	39.62	**11.03**
A (2nd trial)	42.09	6.08	**4.43**
B (1st trial)	122.3	75.22	**50.91**
B (2nd trial)	82.14	48.83	**26.03**

in [14] and the corresponding results obtained with a high-pass filter with the proposed cutoff frequency. The figure shows that the proposed method can achieve accurate estimation, particularly for $t \leq 20$ s and $60\ \text{s} \leq t \leq 80$ s.

We use the root-mean-square (rms) error as a performance index for both the conventional and proposed methods. For the IBI $\tau(t)$ estimated using radar and the corresponding IBI $\tau'(t)$ obtained from the reference ECG, the rms error is defined as $\sqrt{(1/T)\int_0^T |\tau(t)-\tau'(t)|^2 \mathrm{d}t}$. As conventional methods for comparison, we used the topology method with two types of bandpass filters: 1) with cutoff frequencies covering only the fundamental heartbeat frequency and 2) with the same cutoff frequencies as in [14]. Table 1 shows the rms errors for the two conventional methods and for the proposed method for two participants A and B. The proposed method demonstrates higher accuracy than the conventional methods. These results illustrate the effectiveness of the proposed method for accurate heartbeat measurements using radar.

Fig. 5 shows the rms error values versus the cutoff frequency f_c of the high-pass filter for participants A and B, where the red dashed lines indicate the higher harmonics of the heartbeat. The rms error is shown to decrease when f_c is located slightly below each of the higher harmonics of the heartbeat, with a few exceptions, and this results in improved performance. These results validate our proposed method.

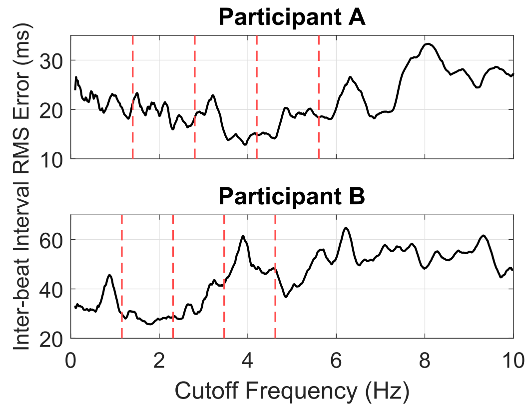


Fig. 5. RMS error (black line) in IBI estimation for the cutoff frequency f_c of the high-pass filter. The red dashed lines indicate the heartbeat's fundamental frequency and its harmonics.

Fig. 6. Photograph of an experiment involving radar measurements of a chimpanzee subject.

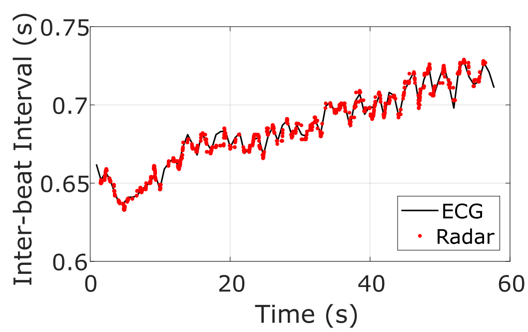


Fig. 7. IBIs estimated using radar and the topology method with the proposed filter (red dots) and the reference IBI results obtained from the ECG (black line) for chimpanzee C.

B. Accuracy Evaluation With Chimpanzee Subjects

Next, we performed radar measurements of two chimpanzee subjects (C and D) during the annual health checkups of these chimpanzees; the subjects were anesthetized before the radar measurements. Subjects C and D were adult male and female chimpanzees, respectively.

We used a radar system (T14_01120112_2D, S-Takaya Electronics Industry, Okayama, Japan) that was almost identical to that used for the human participants in the previous section as a result of radar module availability considerations; the slow-time sampling frequency was 145.56 Hz in this case. The radar system was placed approximately 0.7 m away from the chimpanzee, immediately above its front chest wall, and the ECG electrodes were attached to one arm and one leg as shown in Fig. 6.

As in the preliminary human experiments, the proposed method was applied to the radar measurement data acquired from the chimpanzees to obtain their IBIs. Fig. 7 shows the IBI estimation results for chimpanzee C, which shows good agreement between the radar and ECG results. Note that the IBI is increasing gradually in the figure, which may indicate that the subject animal was calming down during the measurement. The rms errors of the IBI estimations were 2.55 ms and 20.5 ms for chimpanzee subjects C and D, respectively, from which we note that the accuracy for subject D was lower than that for subject C; we noticed large limb movements that occurred every 3–5 s, possibly because of the weak effect of the anesthesia in this case. It will be important to develop a method to suppress the undesired components caused by such body movements, and this will form part of our future research.

IV. CONCLUSION

In this letter, we have proposed a method to set the cutoff frequency of a high-pass filter used for the topology method and then evaluated its effectiveness in noncontact measurements of the heart IBIs of both human participants and chimpanzee subjects. The accuracy of IBI estimation was evaluated quantitatively and the results demonstrated the importance of appropriate selection of the cutoff frequency for suppression of the respiratory components while also maintaining the required heartbeat components. Unlike conventional studies that use empirically set filter parameters, this approach introduced a systematic method for filter parameter settings based on the power spectral density of the displacement waveform. We also noted that the accuracy can deteriorate in the presence of body movements; this problem will be addressed in future studies using additional data taken from larger numbers of both human participants and chimpanzee subjects.

ETHICS DECLARATIONS

The experimental protocol involving animals was approved by the Animal Experimentation Committee of the Wildlife Research Center, Kyoto University (WRC-2022-KS002A). The experimental protocol involving human participants was approved by the Ethics Committee of the Graduate School of Engineering, Kyoto University under Permit 202214. Informed consent was obtained from all human participants in the study.

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