A Study on Pre-Filter Design for Improving Accuracy in Heart Rate Estimation from Backside Using Discrete Wavelet Transform with mm-Wave Radar

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Abstract: We have been considering applying discrete wavelet transform (DWT) to heart-rate estimation using 77 GHz band FMCW radar. The detection accuracy and SNR were improved by using an elliptic High-pass filter (HPF) and a High-pass Chebyshev type II filter. The High-pass Chebyshev Type II filter has less ripple in the passband area, on the other the elliptic HPF has a steeper frequency response compared to the Chebyshev filter. Those filters were used in a pre-processing of DWT for the data acquired from the front and back to reduce respiratory signals and harmonics for comparison. In this letter, the detection accuracy and SNR estimated from the front and back were improved by using two types of filters in DWT pre-processing to decrease respiratory signals.

Keywords: Chebyshev, discrete wavelet transform, FMCW radar, heart-rate estimation, respiration, vital sign monitoring

Classification: Sensing

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1 Introduction

Doppler radar [1, 2], impulse Ultra-wide Band (UWB) radar [3], and Frequency Modulated Continuous Wave (FMCW) radar have been used for non-contact vital sign monitoring [4]. 77GHz FMCW radar was used in this study because of its high resolution and accuracy [5]. When using FMCW radar to detect a subject, the interference to the subject’s signal can be partially eliminated by selecting an appropriate Range-bin. However, an appropriate algorithm is needed for the extracted signal to remove noise such as interference from other objects in the same range-bin and body shaking. Previously, we performed heartbeat signal extraction utilizing Empirical Mode Decomposition (EMD) for time-domain signal processing and Improved Complete Ensemble Empirical Mode Decomposition with Adaptive noise (ICEEMDAN). ICEEMDAN solves mode mixing, a problem of EMD, by adding white noise [6]. The processing of these methods takes a long time. Considering the application of heart-rate estimation with radar, the processing time should be short. Meanwhile, DWT is superior to EMD-based time-domain signal processing in terms of processing time. Therefore, we have been
also considering utilizing discrete wavelet transform (DWT) to estimate heart-rate [7, 8]. DWT is a signal processing method in the frequency domain. It is possible to decompose the signal and extract small signals buried in the original signal by employing a high pass filter (HPF) and a low pass filter repeatedly for signals. However, the DWT results contain noises such as the respiratory signal and its harmonics, because the frequencies of respiratory signal and heart-rate are close. When the heart-rate and respiratory frequency are close, HPF reduces the heartbeat frequency together with the respiratory signal depending on attenuation characteristics near the cutoff frequency. However, in general filter design, the steeper the attenuation characteristic near the cutoff frequency, the larger the ripple within the currency tolerance. This paper report that a Chebyshev type II filter improves both signal-to-noise ratio (SNR) and root-mean-square error (RMSE) comparing without the filter, regardless of subjects, for the backward measurement where body surface movement is less than forward. On the other, the SNR and RMSE improvement depend on the subjects by use of an elliptic filter [10], in which the attenuation characteristic near the cutoff frequency is steeper, but the ripple within the currency tolerance is larger than the Chebyshev type II filter.

2 Signal Processing

2.1 FMCW Radar Principle

Chirp signal is transmitted whose frequency increases linearly from $f_{\text{min}}$ to $f_{\text{max}}$ in time $T_c$. The transmitted chirp hits an object and is received after a time $T_d$. If the distance from the radar to the target is $R_0$ and the speed of light is $c$, the relation between $T_d$ and $R_0$ is expressed as $T_d = \frac{2R_0}{c}$. The IF signal is obtained by mixing the transmitted with the received signals. The IF signal is expressed as

\[
\text{IF signal} = f_{\text{transmitted}} - f_{\text{received}}
\]

(a) Proposed signal processing chain

![Proposed signal processing chain](image1)

(b) HPF frequency spectrum

![HPF frequency spectrum](image2)

(c) Passband ripple of HPF

![Passband ripple of HPF](image3)

(d) BPF frequency spectrum

![BPF frequency spectrum](image4)

Fig. 1. The proposed method
\[ s_r(t) = A_t A \exp \left( j(2\pi f_{\text{min}} T_d + 2\pi K T_d t - \pi K T_d^2) \right) \]

\[ \approx A_t A \exp \left( j(2\pi f_{\text{min}} T_d + 2\pi K T_d t) \right), \quad T_d < t < T_c, \]

where \( A_t \) and \( A_r \) are amplitudes of transmitted and received chirp signals, and \( \pi K T_d^2 \) can be ignored because it is small. The movement of the chest surface due to the vibration of the heartbeat is small, then the phase information of the IF signal, \( \varphi(t) = 4\pi f_{\text{min}} (R_0 + x(t))/c \), is used to calculate the displacement, where \( x(t) \) is the displacement of the target.

### 3 Proposed Method

The proposed signal processing chain is shown in Fig.1(a). In order to reduce the respiratory signal and its harmonics included in the DWT results, we apply HPF in DWT pre-processing to the radar vital sign \( x(t) \). The frequency of body surface movement and respiratory signals depend on the measurement direction. Therefore, we designed some types of filters.

#### 3.1 Filter Design

**3.1.1 Elliptic High Pass Filter**

Normally, the respiration frequency is from 0.1 to 0.6 Hz and the heart-rate is from 0.8 to 2.0 Hz [11]. Therefore, it was necessary to design an HPF with a passband frequency starting at 0.8 Hz. Moreover, there are two types of filters, IIR and FIR. Compared to IIR filters, FIR filters are simpler to design, but the number of taps must be increased to obtain good attenuation characteristics. However, to obtain good attenuation characteristics, it is necessary to increase the number of taps. Increasing the number of taps increases the computational complexity and delay time of the system. Since the response time is important for applications, an IIR type filter was selected in this study. Fig. 1(b) shows the frequency spectrum of the main IIR HPFs. Elliptic filters have a steeper frequency response in the transition band than Butterworth and Chebyshev filters. The Butterworth and

![Fig. 2. Example of frequency spectrums](image-url)
Chebyshev filters may not reduce the respiratory signal enough. In addition, the Elliptic filter has a ripple in the stopband, but -80 dB is already considered to be sufficient attenuation. Therefore, we designed an IIR Elliptic HPF with a passband frequency starting at 0.8 Hz to estimate the heart-rate.

### 3.1.2 High-pass Chebyshev Type II Filter

The passband ripple of HPF is shown in Fig. 1(c). As described later in experiments and results, the accuracy of the heart-rate measurement from the backside worsened when the elliptical filter was used to reduce the respiratory component. The reason for this is that using a filter with a passband ripple on the data acquired from the back, which is less affected by the respiratory component, has a large impact on the accuracy and SNR. In short, a passband ripple negatively affects the data, which has fewer noises. Therefore, a high-pass Chebyshev type II filter with a flat passband area was used to reduce noise such as the respiratory component. Compared to the elliptic filter, the slope in the transition area is milder. However, it is not a big problem for the data acquired from the backside, which contains a little respiratory component. It is assumed that the accuracy and SNR may be improved because the data is not affected by the ripple.

### 3.1.3 Band Pass Filter

A band-pass filter (BPF) is shown in fig. 1(d), which attenuates signals in frequencies other than heart rate in waveforms reconstructed by the DWT, in which the low and high cutoff frequency was 0.8 and 2.0 Hz respectively, due to the typical heartbeat frequency band.

### 4 Experiments and Results

In the experiment, the radar was placed in two directions, front and back, about 1 m away from five subjects, and the vital signs were acquired for 60 seconds. The carrier frequency, bandwidth, chirp slope, chirp time, and frame time of the FMCW radar used were 77 GHz, 3.99 GHz, 70 MHz/μs, 57 μs, and 100 ms, respectively. In addition, heart-rate data was acquired by ECG at the same time as vital sign acquisition by radar. These data were used as reference data. The heartbeat signal is extracted by applying the signal processing described above to

#### Table I. SNR and RMSE

|          | SNR [dB] | RMSE [Hz] |
|----------|----------|-----------|
|          | w/o filter | Elliptic | Chebyshev II | w/o filter | Elliptic | Chebyshev II |
| **Front** |           |         |              |            |         |              |
| Subject A | -30.749   | -29.606 | -29.541       | 0.05036    | 0.04398 | 0.03525       |
| Subject B | -30.864   | -30.532 | -30.785       | 0.07035    | 0.06910 | 0.03997       |
| Subject C | -32.181   | -29.909 | -31.187       | 0.06582    | 0.05323 | 0.03168       |
| Subject D | -30.111   | -29.515 | -29.290       | 0.04334    | 0.03595 | 0.03776       |
| Subject E | -31.869   | -30.523 | -30.595       | 0.06508    | 0.02961 | 0.02758       |
| Mean      | -31.155   | -30.017 | -30.280       | 0.05899    | 0.04637 | 0.03445       |
| **Back**  |           |         |              |            |         |              |
| Subject A | -30.722   | -31.160 | -30.212       | 0.04512    | 0.06512 | 0.04171       |
| Subject B | -28.788   | -29.208 | -26.580       | 0.19715    | 0.18884 | 0.03310       |
| Subject C | -32.082   | -33.373 | -29.964       | 0.06497    | 0.06040 | 0.05017       |
| Subject D | -35.601   | -36.083 | -30.270       | 0.06710    | 0.07390 | 0.04207       |
| Subject E | -31.888   | -29.014 | -27.170       | 0.05760    | 0.05047 | 0.03734       |
| Mean      | -31.816   | -31.768 | -28.839       | 0.08639    | 0.08775 | 0.04088       |
the data obtained by radar. The radar vital sign was processed by moving the observation window of 200 frames by 10 frames. Root-Mean-Square Error (RMSE) was used to evaluate the accuracy by comparing the heart-rate estimated by DWT with the reference heart-rate measured by ECG.

Fig. 2(a) shows the experimental scene. Fig. 2(b) and (c) show the effect of the proposed method on the heartbeat displacement data acquired at the front and back. The figures show the comparison between the proposed method with and without HPF, elliptic, and Chebyshev HPF. In the estimation from the front, the reference frequency obtained by ECG was 1.2 Hz, and the frequency estimated by DWT was around 1.19 for all filters. The obtained frequencies were the same, but the SNR was improved by employing the Chebyshev type II filter. The SNR was further improved by employing the elliptic filter. The result of DWT without filter includes larger noises than the heartbeat signal around 1.0, 1.4, 1.5, 1.6, and 2.0 Hz. Even though the Chebyshev type II HPF reduced those noises, the heartbeat signal is still smaller than them. While the elliptic HPF reduced those noises, and the heartbeat signal became the largest. Since the noise around 0.85 Hz is reduced. This is probably due to the steep transition band of the elliptic filter. In the estimation from the back, the subject's heart-rate frequency was around 1.1 Hz in the ECG data, 1.14 in the DWT only and with the Chebyshev type II filter, and 1.19 with the elliptic filter. By reducing the respiratory component with the Chebyshev type II filter, the SNR of the heartbeat signal was improved.

Table I (a) and (b) show the SNR and RMSE of the heart-rate estimation using the data acquired from the front and back, respectively. The SNRs of each subject are the average value calculated from the each SNR of all observation windows. Table I (a) shows that the frontal measurements were better with the Chebyshev type II filter than without the filters. However, the SNR improvement for subjects B, C, and E was higher when the elliptic filter was used. The reason for this is that the slope of the transition area of the Chebyshev type II filter is slower than that of the elliptic filter. Therefore, the Chebyshev type II filter may not be able to reduce noise such as the respiratory component included in the data acquired from the front. As shown in Table I (b), SNR and RMSE were improved by employing the Chebyshev type II filter in the backward measurement compared to the case without HPF and with the elliptic filter for all subjects. Therefore, it was confirmed that the ripple in the passband affected the data acquired from the back, because the respiratory component was hardly included in the data.

5 Conclusion

In this research, heartbeat signals were acquired using a 77GHz FMCW radar, respiratory signals and their harmonics were reduced by high-pass filters, and heartbeat signals were extracted by discrete wavelet transform and finally with a band-pass filter. For the backward measurement, the SNR and RMSE improvement depend on the subjects with the elliptic filter. On the other, the Chebyshev type II filter improved both the SNR and RMSE, regardless of the subjects, that had less ripple characteristics within the currency tolerance.