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RESEARCH ARTICLE

Heartbeat detection using a Doppler radar sensor based on the scaling function of wavelet transform

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Abstract
The heartbeat detection using the scaling function of Wavelet transform is proposed for a Doppler radar sensor. The conventional methods such as the fast-Fourier transform and the autocorrelation show the respiration rate and the heartbeat from the raw data of the radar sensors acquiring for a sufficient sampling time. The methods have the limit to detect the biometric information that varies with real-time because they only show the overall statistical information of the sampled data. In the proposed method, the scaling function in the Daubechies wavelet transform can be used to accurately find out the periodicity of radar signals for detecting heartbeat varying in real-time. The results of the signal processing using the radar signals acquired for 3 min results show that the proposed method lowered a mean error rate of 2.5% and a SD of 2.0% compared with the method using the wavelet function. The proposed method in the measurement for 1 minute using the radar sensor also showed the lowest mean error rate of 3.8% and the low SD of 3.2% using the contact sensor as the reference among various signal processing methods including autocorrelation and peak detection with filtering.

KEYWORDS
Doppler radar sensor, heartbeat detection, radar signal processing, scaling function, wavelet transform

1 | INTRODUCTION

Doppler radar sensors are used to remotely detect vital signals of a human being, such as the heartbeat and respiration rate.[1] The fast-Fourier transform (FFT) and the autocorrelation are conventional analysis methods to obtain the signals from the raw data of the radar sensors.[2] On the other hand, the conventional methods show only the overall statistical information from the data obtained for a sampling time, and cannot accurately show the biometric information that varies with real time. The signal processing method based on a discrete wavelet transform (DWT), which can simultaneously obtain information in the frequency and time domains, has been presented in electrocardiogram (ECG) sensing and image processing to overcome the limits of conventional methods.[3] Previous studies reported that the DWT method using the Daubechies wavelet function could obtain biometric information with high accuracy from the shape of the ECG signals.[3,4] On the other hand, they had a limit in acquiring the shape of the vital signal in real-time because the time-domain waveform cannot be extracted directly from the coefficients of the wavelet function.

In this study, a signal processing method using Daubechies-DWT based on a scaling function of the wavelet transform is proposed to improve the accuracy of heartbeat detection using the radar sensor. The proposed method can be more accurate than the method based on the wavelet function because the shape of the scaling function is similar to the known shape of the heartbeat signal obtained from the radar sensor. The scaling function in the proposed method can be extracted from the time-domain waveform of the vital signal using the reconstruction and decomposition coefficients of the transfer function using in the DWT. The high accuracy of the proposed method was verified experimentally by comparing to the method using the FFT with measured data. A comparison of the measured heartbeat using the contact-type sensor showed that the proposed method could detect the heartbeat with the highest accuracy among the signal processing methods in the radar sensor.

2 | PROPOSED METHOD BASED ON THE SCALING FUNCTION OF WAVELET TRANSFORM

Two mathematical expressions, $y_{\text{low}}[n]$ and $y_{\text{high}}[n]$, can be used in the DWT method.[5]

$$y_{\text{low}}[n] = \sum_{k=-\infty}^{\infty} x[k]\cdot g[2n-k], \quad (1)$$

$$y_{\text{high}}[n] = \sum_{k=-\infty}^{\infty} x[k]\cdot h[2n-k] \quad (2)$$

where, n is the number of the sampling data; k is a sampling data point; $x[k]$ is a discrete input signal. Calculated from the order of the vanishing moment,[5] the transform functions, $g[2n-k]$ and $h[2n-k]$, show the scaling and wavelet functions, which are called the low-pass and high-pass decomposition coefficients, respectively.[5] The $y_{\text{low}}[n]$ and $y_{\text{high}}[n]$, which were obtained by applying the transform functions, are referred to as approximation coefficients (cA) and detail coefficients (cD), respectively. Equations 1 and 2 are used repeatedly at each level, and the reconstructed signal S_R calculated at the N levels is divided into the frequency region of 2^N under the cut-off frequency. $x[k]$ can be expressed by $S_R[k]$ in the DWT as follows:

$$S_R[k] = \sum_{l=a}^{b} y_{\text{l.low}}[n]\cdot G[2n-k] + \sum_{m=a}^{b} y_{\text{m.high}}[n]\cdot H[2n-k] \quad (3)$$

where, $y_{\text{l.low}}[n]$ is the approximation coefficient in the low-pass region corresponding to each l, and $y_{\text{m.high}}[n]$ is the detail coefficient in the high-pass region corresponding to each m. $G[2n-k]$ and $H[2n-k]$ are low-pass and high-pass reconstruction coefficients for scaling and wavelet functions, respectively.[5] The a, b, and c variables in Equation 3, which show sections to apply the function, are determined by the desired frequency region, as shown in Figure 1.

A heartbeat signal $S_{HR}[k]$ can be obtained using the scaling function, $g[2n-k]$, in the frequency range where the signal is expected to be present as

$$\sum_{k=-\infty}^{\infty} S_R[k]\cdot g[2n-k] = S_{HR}[k]. \quad (4)$$

The number of sampling data to use for processing the information is reduced by half at each level of the DWT method because the frequency region, in which the desired signal is expected to be present, is only calculated in the two frequency regions. A reconstruction process is needed to obtain the time-domain waveform in the conventional method based on the wavelet function because the detail coefficients by the wavelet function represent only the signal correlation within the frequency range of each level. In contrast, the curve-fitting process is sufficient to obtain the time-domain waveform in the proposed method because the approximation coefficients using the scaling function is expressed by approximating the signal shape at each level. Figure 2 shows that the proposed method can detect the vital signal enough, even at a lower level, while the conventional method cannot recognize the signal at a higher level without a reconstruction process. Therefore, the proposed method has an advantage in the radar sensor, which detects the heartbeat and the variation of the rate for a certain time, because the method can obtain the periodicity of the signal accurately in real time using only low-pass frequency region of the DWT at a low level.

3 | HEARTBEAT DETECTING DEMOSTRATION

3.1 | Doppler radar sensor

A 2.45 GHz Doppler radar sensor in Figure 3 was implemented to obtain the raw signals to demonstrate the performance comparisons of heartbeat detection depending on the signal processing methods. The 2.45 GHz signals, which are generated by a voltage-controlled oscillator (VCO) are divided into the transmission and reference signals in the power divider on FR4 PCB with a substrate thickness of

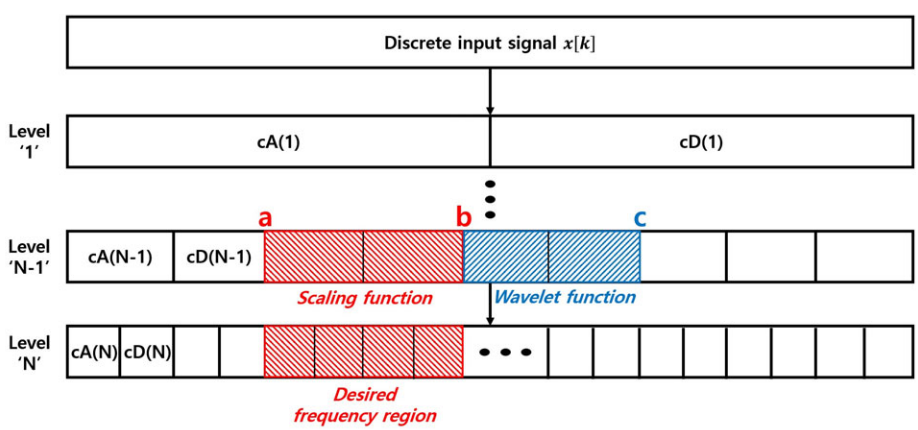

FIGURE 1 Signal processing using the proposed DWT method based on the scaling function [Color figure can be viewed at wileyonlinelibrary.com]

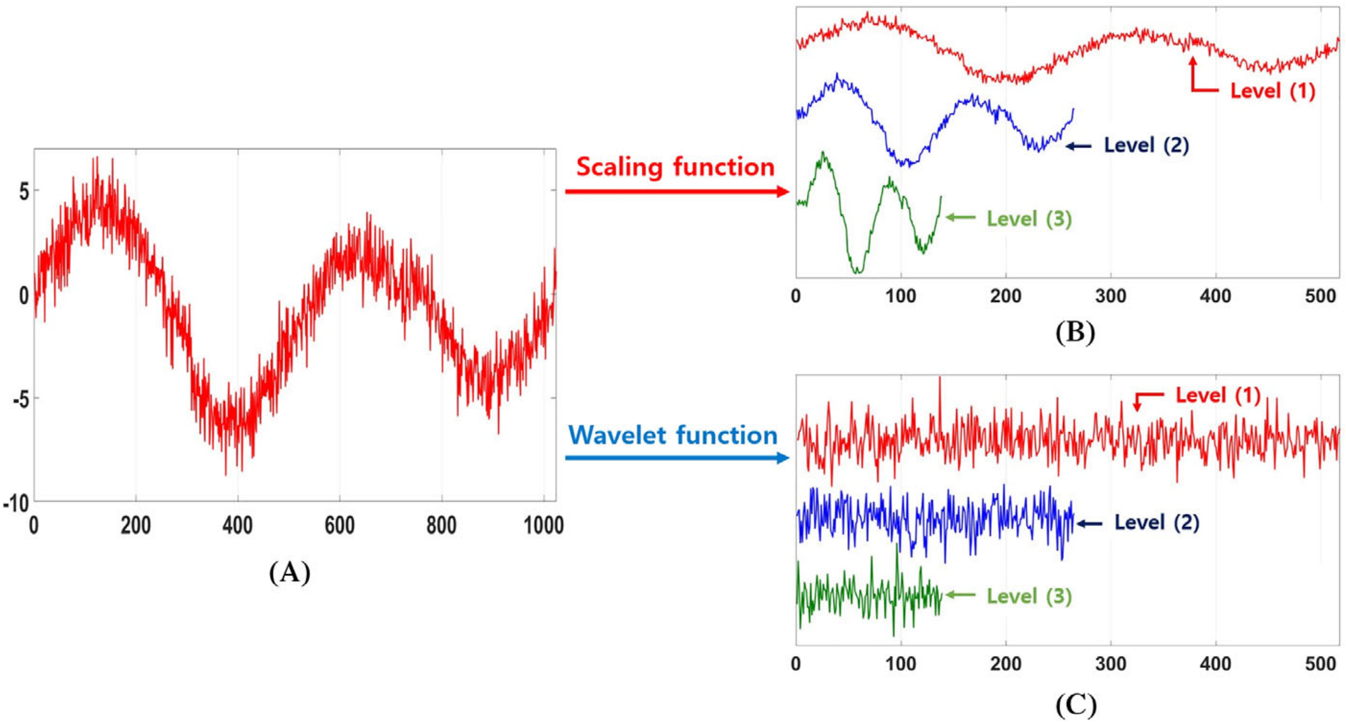

FIGURE 2 Time-domain waveforms at each level of the DWT. (A) Raw data from the radar sensor; (B) Processed data using approximation coefficients form the scaling function; (C) Processed data using detail coefficients from the wavelet function [Color figure can be viewed at wileyonlinelibrary.com]

1 mm. The transmitted signals are divided into two equally-powered signals with a phase difference of 90° by a directional coupler. Circularly polarized signals are generated and transmitted to the human body in a patch antenna with two feeding lines that have 90° way different from each other. The polarization of the transmitted signals is changed by the boundary condition on the round-a-trip channel to the human body, but the signals are received into the same patch

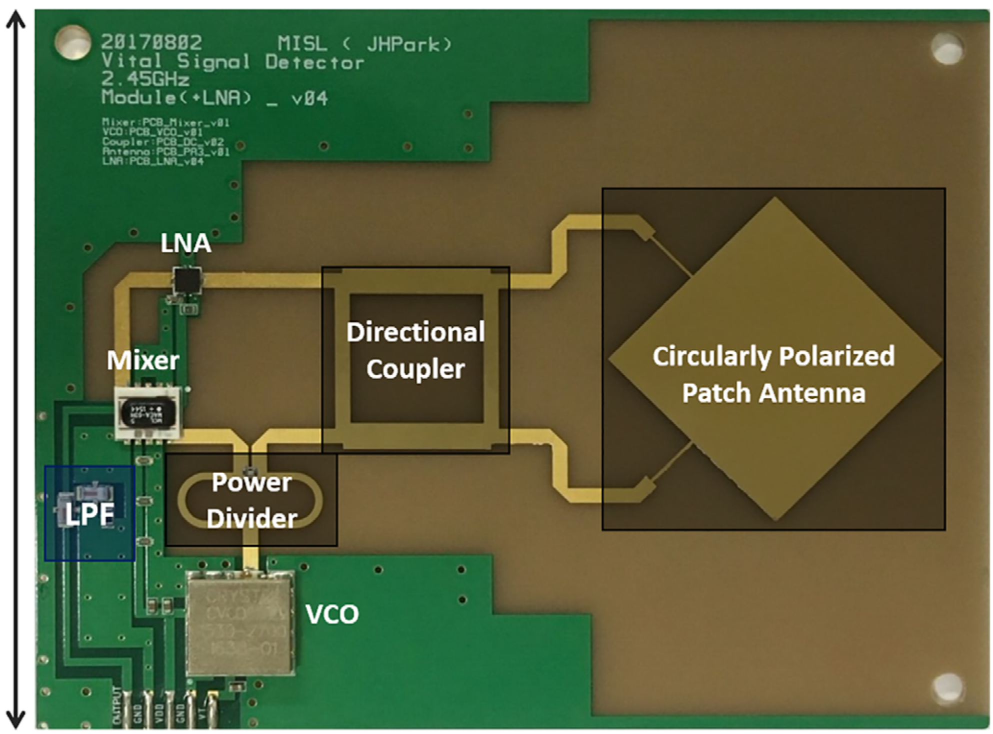

FIGURE 3 The 2.45 GHz Doppler radar sensor module to obtain raw data for heartbeat detection [Color figure can be viewed at wileyonlinelibrary.com]

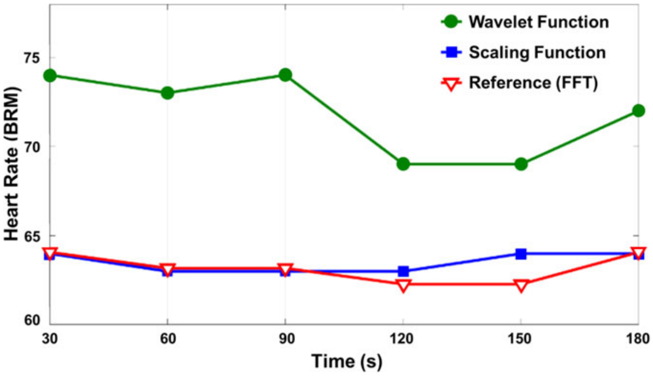

FIGURE 4 Comparison of the accuracy depending on the time in the signal processing methods based on the scaling and wavelet functions for the heartbeat detection [Color figure can be viewed at wileyonlinelibrary.com]

antenna because of the circular polarization characteristics due to the antenna and coupler.[6] The received signal amplified by the low noise amplifier (LNA) is down-converted to the baseband signals in the frequency mixer with the reference signal from the power divider and conditioned to the input level of the data acquisition board using the analog conditioning block including baseband amplifiers and filters. The raw data are collected and processed in a PC environment with the conventional and proposed methods using the MATLAB and NI LabVIEW. The VCO, LNA, and mixer in the radar sensor are used as the discrete components manufactured by Mini-Circuits, Inc. The size of the 2.45 GHz Doppler radar module shown in Figure 3 is 115 mm × 90 mm realized on FR4 PCB with 1 mm thickness.

3.2 | Comparison of the heartbeat detection between scaling and wavelet functions

Using the raw data for 3 min measured by the radar sensor, the heartbeat calculated at 1-min intervals by the DWT methods based on the scaling and wavelet functions were compared with the reference heartbeat obtained using the FFT method. Raw data in the calculation were obtained from four males and four females at a sampling frequency of 1 K samples per second using the Doppler radar sensor. The 1-min interval in the calculation means that the oldest sample is substituted in the dataset with the latest sample when the number of samples exceeds 60 K. The coefficients of the DWT were obtained at three levels using a cut-off frequency of 7.5 Hz; the *a*, *b*, and *c* values were two, three, and five, respectively, by considering the frequency range of the heartbeat. The accuracy of the heartbeat calculated from each method is shown by the mean error rate (MER) and the standard deviation (SD) excluding the maximum and the minimum values in the data of each method. Figure 4 shows that the proposed method based on the scaling function for time-varying heartbeat detection has higher accuracy than the conventional method based on the wavelet function. The proposed method was found to have a MER of 4.9% and SD of 4.0%, while the conventional method had a MER of 7.4% and SD of 6.0%. The maximum error rate of the proposed method was also 14.3% lower than that of the conventional method because of the offset in the calculation results of the conventional method.

3.3 | Accuracy comparison among the signal processing methods in time-domain

The heartbeat was obtained by applying each signal processing method in time-domain to the raw data sampled from five males and five females by using the radar sensor. The methods used in the detection were the peak detection after filtering in the passband from 0.8 to 3 Hz, auto-correlation, and the proposed method based on the scaling function. The data, which were also obtained for 60 sec at a rate of 1 K samples per second, were used to represent the heartbeat per minute. The accuracy of the signal processing is presented by comparing the heartbeat measured from the contact type ECG sensor with the heartbeat measurement results obtained from the radar sensor using each signal processing method.

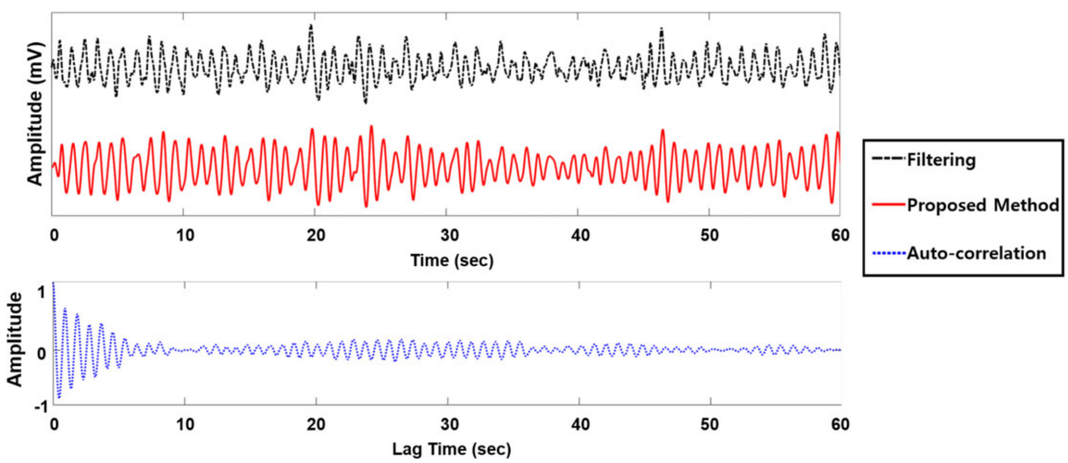

FIGURE 5 Signal obtained using the radar sensor for 1 min in the time domain by applying each signal processing method [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Subjects' heartbeat obtained from each signal processing method for 1 min

Subjects	Contact sensor <Reference>	Radar sensor		
		Peak detection	Auto-correlation	Proposed method
Male A	75	82	75	70
Male B	80	88	67	79
Male C	72	84	66	69
Male D	64	74	60	65
Male E	65	76	72	65
Female A	66	70	67	64
Female B	70	84	75	72
Female C	66	78	60	69
Female D	62	76	75	67
Female E	70	78	60	65
MER (%)	–	14.3	9.4	3.9
SD%	–	3.1	7.6	3.2

To reduce the specificity effect of the subject, the MER and SD in each processing method are used in the comparison. The MER of the heartbeat obtained from the peak detection increased due to the noise in the passband, but the SD analyzed from the same method was reduced by the data normalization, as shown in Figure 5. Although the heartbeat by the auto-correlation improves the MER by decreasing the effect of the noise signal, there is a limit in that the SD in the auto-correlation increases because the heartbeat varying for 60 sec can be approximated to a single frequency. Table 1 lists the differences in the heartbeat obtained from each method and shows that among three time-domain methods, the proposed method is the most suitable for the radar sensor because of the lowest MER of 3.9% and SD of 3.2%, which is a similar value to the peak detection.

4 | CONCLUSION

The DWT method using the Daubechies scaling function is proposed to improve the accuracy in the time-domain signal processing of the Doppler radar sensor for heartbeat detection. The MER and SD of the proposed method were 4.9% and 4.0%, respectively, which were 2.5% and 2.0% better than the conventional method using the wavelet function, respectively. The lowest MER of 3.9% was obtained as compared with the other signal processing methods of the radar sensor. The proposed method can be used to analyze and describe the vital signals, such as heartbeat variation in the time domain, owing to its high accuracy.

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