A novel adaptive range-bin selection method for remote heart-rate measurement of an indoor moving person using mm-wave FMCW radar

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Abstract: This study provides a solution for mm-wave FMCW radar-based heart-rate detection of an indoor moving person. The range-bin where the person is located will change during the moving state, and the signal energy is weaker than clutter at farther distances. Therefore, we propose an adaptive range-bin selection method that effectively selects the optimal range-bin cell to obtain the correct radar vital sign before heartbeat signal reconstruction. The experimental results show that the proposed method can reconstruct the heartbeat signal with high precision when used in conjunction with the ICEEMDAN method.

Keywords: FMCW radar, health care, heart-rate, ICEEMDAN, radar signal processing

Classification: Sensing

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1 Introduction

In [1], they proposed the X-band array radar with adaptive array processing for heart-rate measurement when there is more than one person in the scene. The authors of [2] proposed the time-window-variation technique with continuous-wave Doppler radar to measure heartbeat. However, their subjects were lying on the bed or sitting on the chair, which will cause many inconveniences to patients in the actual round-the-clock medical monitoring. Therefore, a method that can effectively measure the heart-rate of an indoor moving person is urgently needed.

In [3], They measured a moving person's heart-rate based on a 24 GHz-band radar module by analyzing multiple range-bins data simultaneously. However, the lower range-bin resolution of 0.75 m results in the inability to remove interference from other objects by range-bin selection in practice applications. Therefore, the 77 GHz-band radar (range-bin resolution: 4 cm) is used in our experiments to improve measurement accuracy by selecting optimal range-bin cells. In this case, the proposed method in [3] is no longer be applicable because the computation of processing 125 signals consisting of different range-bins (measurement range: 5 m) simultaneously and then segmenting them to form a radar vital sign is large and inefficient. Moreover, the heart-rate measurement of [3] was interfered with by the harmonics of the respiratory signal and did not reconstruct the heartbeat signal. The authors of [4] conducted experiments using a mm-wave radar with high range-bin resolution. However, their volunteers moved too slowly (0.01 m/s) and close to the radar. This slow body movement does not affect the heart-rate estimation because it can be separated into higher-order intrinsic mode functions (IMFs) or residuals by the improved complete ensemble empirical mode decomposition with adaptive noise (ICEEMDAN) method after being sampled in segments [5]. Besides, there is no significant clutter (rehabilitation centers or hospitals have many metal equipment in the room) around the volunteers in [3, 4]. Therefore, in [4], their volunteers' distance can be easily detected from the range profile matrix (RPM) by peak-seeking post-processing manually, this causes the system to lose adaptive and real-time performance. Instead, our volunteers will simulate the patients' indoor moving speed, and the received signal will be interfered with by other objects. So, this is the first paper to incorporate practical factors for the mm-wave FMCW radar-based heart-rate estimation of an indoor moving person.

We propose an adaptive range-bin selection method to address the above-mentioned issues, which differs from conventional tracking filters (e.g., Kalman filter and α-β filter). This method is used to select the optimal range-bin cell

directly in each frame data and thus obtaining the IF signal's phase information, rather than using measurements (e.g., distance, velocity, and angle) to estimate the target's position by the tracking filter. Besides, the proposed method is arithmetically simple and introduces a secondary error in selecting range-bin by the results of conventional tracking filters. Therefore, we use the proposed method to calculate the radar vital sign by IF signal's phase, containing the person's body shaking and interference within the same range-bin besides the respiratory and heartbeat signals. And then, the radar vital sign is adaptively decomposed by the ICEEMDAN method to reconstruct the heartbeat signal with high precision [5].

2 Proposed Method

In this research, the phase of IF signal of the FMCW radar can be expressed as $\varphi(t) = 4\pi f_{\min}[(R_0 + x(t))/c]$, where $f_{\min}$ is the chirp start frequency, c means the speed of light, R_0 is regarded as the distance between the object and the radar, $x(t)$ is the radar vital sign, respectively. The proposed signal processing chain is shown in Fig. 1(a). After the IF signal is sampled by ADC (sampling points is N), we carry out the range-FFT calculation on the received matrix along the fast-time dimension to obtain the RPM, which contains instantaneous distance information. The RPM is shown in Fig. 1(b), and the red arrow line represents the person's trajectory. Since the range-bin where the person is located will change during the moving state and the signal energy is weaker than clutter at farther distances, we
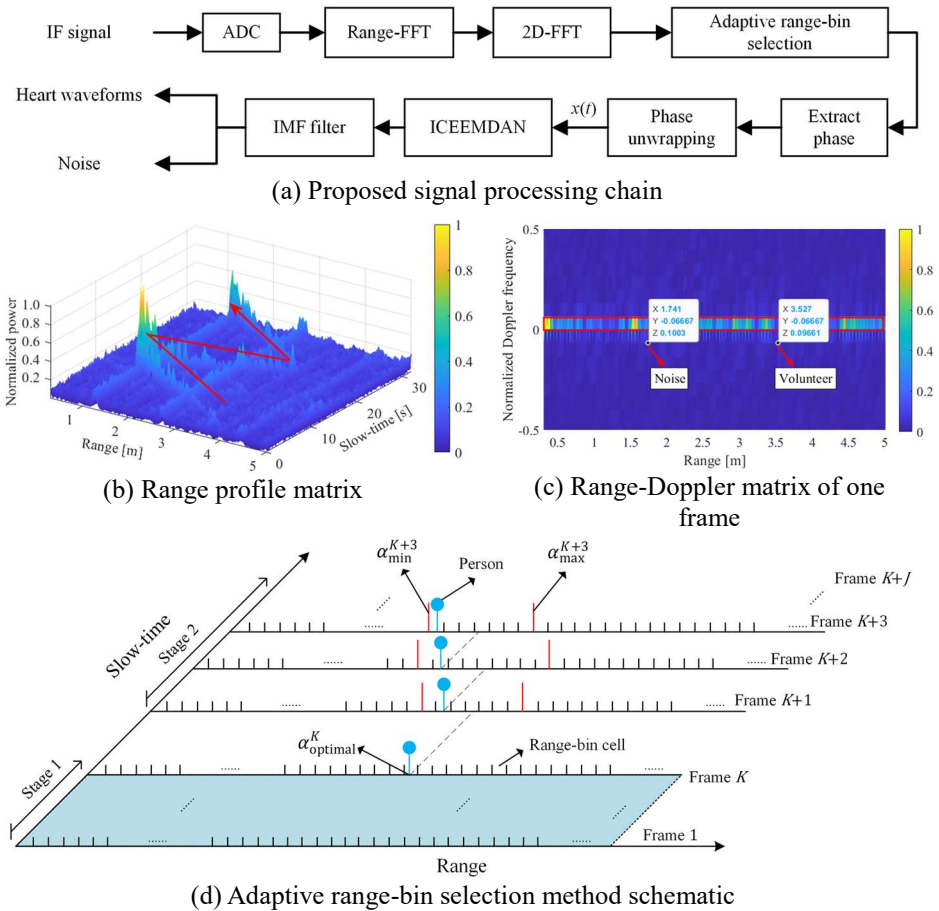

(a) Proposed signal processing chain

(b) Range profile matrix

(c) Range-Doppler matrix of one frame

(d) Adaptive range-bin selection method schematic

Fig. 1. The proposed method

cannot effectively locate by searching peaks in the RPM. Therefore, we emit L chirp signals in each frame, and the frame period is 0.1 s (corresponding to a sampling rate of 10 Hz that is approximately five times the usual heart-rate). Then, we process the RPM separately for each frame with the second FFT along the slow-time dimension to obtain the Doppler information of each range-bin, which improves the range-bin selecting accuracy to a certain extent. Another advantage is that the phase accumulation (PA) of L chirp signals per frame before calculating the $x(t)$ can improve its SNR. Moreover, L will be set to 32 in this experiment by the conclusion based on [6]. The range-Doppler matrix (RDM) of a certain frame is shown in Fig. 1(c). Due to the Doppler shift of all cells in the red box is zero, we need to find the peak value on the upper and lower sides to determine the volunteer's instantaneous position. However, the random background noise can interfere with the range-Doppler spectrum leading to errors in the peak-seeking. Fig. 1(c) shows that the noise's energy may be higher than that of the person in the RDM, which caused an error of about 1.8 m.

To address the above-mentioned issue, we propose an adaptive range-bin selection method, and its schematic is shown in Fig. 1(d). The proposed method consists of two main parts: the location confirmation and the adaptive range-bin selection. In the first stage, we accumulate K frames' chirp signals to obtain the initial-RDM $\boldsymbol{D}_i$ with $K * L$ rows and N columns, and then the initial range-bin of the volunteer can be effectively separated from the various noises in the $\boldsymbol{D}_i$. In the second stage, the peak index search range of the range-Doppler spectrum for the frame will be specified according to the previous optimal range-bin starting from the processing of the $K + 1$th frame, and the outputs are defined as $\alpha_{\text{optimal}}^{K+j}$. We assume that one range-bin cell corresponds to R_{bin} meters. Then the starting cell $\alpha_{\text{min}}^{K+j}$ and the ending cell $\alpha_{\text{max}}^{K+j}$ of the peak-seeking for the $K + j$th frame ($j = 1, 2, 3 \dots J$) can be expressed as

$$\alpha_{\text{min}}^{K+j} = \alpha_{\text{optimal}}^{K+(j-1)} - \left\lceil \frac{v_{\text{p}}^{K+(j-1)} T_{\text{f}}}{R_{\text{bin}}} \right\rceil - \beta_{\text{p}}^{K+j} , \qquad (1)$$

$$\alpha_{\text{max}}^{K+j} = \alpha_{\text{optimal}}^{K+(j-1)} + \left\lceil \frac{v_{\text{p}}^{K+(j-1)} T_{\text{f}}}{R_{\text{bin}}} \right\rceil + \beta_{\text{p}}^{K+j} , \qquad (2)$$

$$\beta_{\text{p}}^{K+J} = \left\lceil \eta \left(\frac{\alpha_{\text{max}}^{K+j} - \alpha_{\text{min}}^{K+j} + 1}{2} \right) \right\rceil , \qquad (3)$$

where $\lceil \dots \rceil$ rounds the element to the nearest integer greater than it, $\alpha_{\text{optimal}}^{K+(j-1)}$ is the optimal range-bin cell of the $K + (j-1)$th frame, T_{f} is the frame period, β_{p}^{K+j} is the protection cells length, and η is the ratio of β_{p}^{K+j} to the peak-seeking range, respectively. $v_{\text{p}}^{K+(j-1)}$ is the volunteer's instantaneous velocity derived from the Doppler frequency $f_{\text{d}}^{K+(j-1)}$ corresponding to $\alpha_{\text{optimal}}^{K+(j-1)}$ of the RDM $\boldsymbol{D}_{K+(j-1)}$ according to the formula: $v_{\text{p}}^{K+(j-1)} = \lambda f_{\text{d}}^{K+(j-1)}/2$ (λ is the wavelength). The sudden change of the person's instantaneous velocity v_{p} may lead to instability of this method. Therefore, the protection cells β_{p}^{K+j} are added to enhance this feedback

measurement system's robust performance. In this experiment, the average speed is 0.25 m/s (as the initial value), and the maximum allowed increment of speed per second $\Delta v_p = 0.25 + (1 + \eta)^9$. When η is 0.2 and 0.3, Δv_p is 1.29 m/s, and 2.65 m/s, respectively. Considering that the speed can reach about 1.5 m/s when the person walks fast, so set η to 0.3. The negative correlation between sample length and real-time performance, so K is set to 5. The parameters K and η can be adjusted depending on different environments. In summary, for the $K + j$th frame, the peak-seeking range is $\left[\alpha_{min}^{K+j}, \alpha_{max}^{K+j}\right]$. After the proposed method processing, the extracted phase is accumulated and unwrapped, and then the radar vital sign $x(t)$ can be obtained. Next, $x(t)$ is decomposed by the ICEEMDAN into several IMFs and a residual component. Finally, IMFs of peak frequency at 0.8 ~ 2.0 Hz are selected by the IMF filter as the heart-IMF for the heartbeat signal reconstruction.
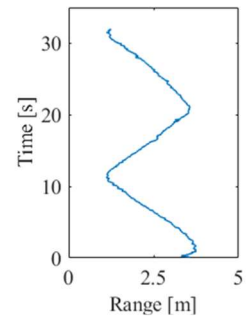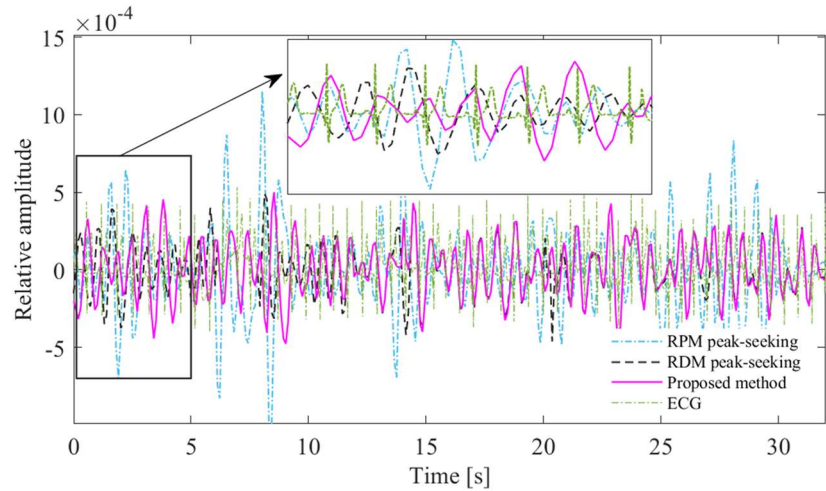

(a) The experimental scene
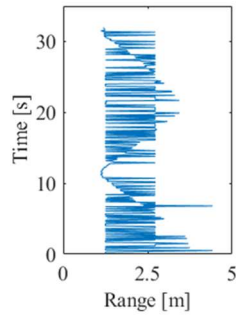
(b) RPM peak-seeking method
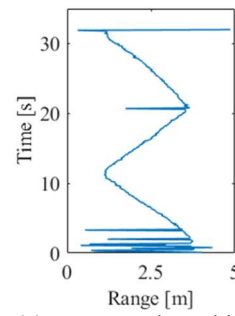
(c) RDM peak-seeking method

(d) Proposed method ($K = 5, \eta = 0.3$)

(e) The results of heartbeat signal reconstruction

Fig. 2. The results of the proposed method

3 Experiments and Results

Table I. Results of heart-rate estimation (Absolute error: [beat per minute: BPM])

Volunteer	ECG	RPM peak-seeking		RDM peak-seeking		Proposed method	
	BPM	BPM	Absolute error	BPM	Absolute error	BPM	Absolute error
A	101.28	90.14	11.14	105.21	3.93	103.13	1.85
B	88.14	78.75	9.39	82.13	6.01	84.38	3.76
C	76.86	92.81	15.95	90.05	13.19	82.50	5.64
D	88.04	76.88	11.16	94.69	6.65	91.88	3.84
E	95.64	84.75	10.89	88.13	7.51	92.44	3.20

The mm-wave FMCW radar based on the IWR1443 device used in our experiment, where sweeping bandwidth is 3.99 GHz (operating frequency is 77 ~ 81 GHz), sweep time is 57 μs, and the slope of chirp is 70 MHz/μs. The experimental scene is shown in Fig. 2(a), a volunteer wearing an ECG device walked from approximately 3.5 m to 1 m in front of the radar and then made two round trips. The experiment's duration was 32 s, and the average speed was about 0.25 m/s considering patients and the elderly. There were five volunteers, and each volunteer took one measurement. The results of range-bin selection by RPM peak-seeking, RDM peak-seeking, and the proposed methods are shown in Fig. 2(b), (c), and (d), respectively. The comparison of the reconstructed heartbeat signal after the ICEEMDAN processing of the $x(t)$ obtained by the above three methods is shown in Fig. 2(e). Due to the interference of other objects and random background noise, random jitter occurs in the range-bin selected by the contrast methods. Instead, the proposed method can accurately obtain the smooth range-bin change information, and the uncertainty of the initial range-bin is solved by stage 1 of this method. From the results in Fig. 2(e), the correlation between the RR-interval of the heartbeat signal reconstructed by the proposed method and the ECG signal is higher than the contrast methods. The results of the heart-rate measurements are shown in Table I. The mean absolute error of the measurements of the proposed method is 3.658 BPM. In [3], their heart-rate error range is about 3.6 ± 3 BPM in an ideal environment. Besides, the volunteers' speed and moving distance in this experiment were higher than that of paper [4]. Therefore, the proposed method has more potential, and the results are within the acceptable range.

4 Conclusion

In conclusion, we propose a novel adaptive range-bin selection method for FMCW radar-based indoor moving person heart-rate estimation, which effectively selects the optimal range-bin cell to obtain the correct $x(t)$. The experimental results show that the proposed method can reconstruct the heartbeat signal with high accuracy when used in conjunction with ICEEMDAN. In the future, we will consider the adaption of K and η depending on different environments and construct an integrated adaptive multi-person heart-rate estimation system by combining the two states (stationary, moving).