Remote heart-rate estimation based on phase accumulation-linear interpolation method for mm-wave FMCW radar

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Abstract: Vital signs measurement with phase analysis for mm-wave FMCW radar contains various kinds of noise. In this research, a phase accumulation-linear interpolation (PA-LI) method for mm-wave FMCW radar is proposed, which can quickly and efficiently reduce phase noise and improve the SNR of the radar vital sign before EMD/EEMD processing. Experimental results show that the proposed method can accurately extract the heartbeat signal with high SNR and the HR estimation is more accurate.

Keywords: EEMD, FMCW, heart rate, mm-wave, vital signs monitoring

Classification: Sensing

References

[1] C. Ye, K. Toyoda, and T. Ohtsuki, “A stochastic gradient approach for robust heartbeat detection with Doppler radar using time-window-variation technique,” IEEE Trans. Biomed. Eng., vol. 66, no. 6, pp. 1730–1741, June 2019. DOI: 10.1109/TBME.2018.2878881

[2] T. Sakamoto, P.J. Aubry, S. Okumura, H. Taki, T. Sato, and A.G. Yarovoy, “Non-contact measurement of the instantaneous heart rate in a multi-person scenario using X-band array radar and adaptive array processing,” IEEE J. Emerg. Sel. Topics Circuits Syst., vol. 8, no. 2, pp. 280–293, June 2018. DOI: 10.1109/JETCAS.2018.2809582

[3] D. Yang, Z. Zhu, and B. Liang, “Vital sign signal extraction method based on permutation entropy and EEMD algorithm for ultra-wideband radar,” IEEE Access, vol. 7, pp. 178879–178890, Dec. 2019. DOI: 10.1109/ACCESS.2019.2958600

[4] M. Adjrad, S. Dudley, and M. Ghavami, “Experimental vital signs estimation using commercially available IR-UWB radar,” 2014 Int. Radar Conf., Lille, pp. 1–4, Oct. 2014. DOI: 10.1109/RADAR.2014.7060328

[5] G. Wang, C. Gu, T. Inoue, and C. Li, “A hybrid FMCW-interferometry radar for indoor precise positioning and versatile life activity monitoring,” IEEE Trans. Microw. Theory Techn., vol. 62, no. 11, pp. 2812–2822, Nov. 2014. DOI: 10.1109/TMTT.2014.2358572

[6] G. Wang, J.-M. Muñoz-Ferreras, C. Gu, C. Li, and R. Gómez-García, “Application of linear-frequency-modulated continuous-wave (LFMCW) radars for tracking of vital signs,” IEEE Trans. Micro. Theory Techn., vol. 62, no. 6, pp. 1387–1399, June 2014. DOI: 10.1109/TMTT.2014.2320464
1 Introduction

In recent years, radar-based non-contact vital signs monitoring has been greatly improved after long-term research. In [1], they used Doppler radar based on time-window-variation technique to measure heartbeat with high accuracy. In 2018, T. Sakamoto et al. proposed the X-band array radar with adaptive array processing technique for heart-rate (HR) measurement of a person when there is more than one person in the scene [2]. A vital sign extraction method based on permutation entropy and ensemble empirical mode decomposition (EEMD) algorithm for ultra-wideband radar was proposed [3]. Overall, there are several commonly used radar techniques for non-contact vital signs monitoring, which are Doppler radars [1], impulse ultra-wideband (UWB) radars [3, 4]. On the one hand, Doppler radars operate based on single-tone continuous wave (CW) to obtain phase history and they have high precision in displacement measurement. But CW Doppler radars do not have the ranging capability [5]. This means that CW Doppler radars are susceptible to interference from surrounding moving objects and other clutter. And these effects cannot be ignored in practical application. On the other hand, impulse UWB radars are capable to achieve high range resolution by transmitting a very large bandwidth. The limitation of impulse UWB radars is that the accuracy is influenced by very strong signal-energy levels that cannot be transmitted during the short period of the pulse, which reducing the SNR [6]. Comparing with CW Doppler radars and impulse UWB radars, frequency-modulated continuous-wave (FMCW) radar does not only has the high sensitivity of CW Doppler radars but also has the ranging capability of impulse UWB radars. Furthermore, the wavelength of 77 GHz FMCW radar is about 4 mm and a small movement can cause a large phase change of IF signal. Therefore, this research chooses the radar for the experiment to achieve high ranging accuracy.

The weak vibration detection based on the phase analysis of the IF signal, the DC term and phase noise will interfere with the phase quality [7]. The DC term can be removed by nonlinear-least-squares (NLLS). In addition, although the chest movement (radar vital sign) is extracted by phase information, it still contains the body shaking of the object and interference from other objects within the same range-bin, besides the respiratory and heartbeat signals. Since the respiratory-rate and HR are very close, the HR is interfered with by the harmonic of the breathing signal and it cannot be solved by band-pass filter [8]. So, we consider performing time-frequency domain analysis on radar vital sign, such as empirical mode decomposition (EMD) and ensemble empirical mode decomposition (EEMD) methods. The latter one can
solve the “mode mixing” of EMD. In [3, 4], they used impulse UWB radar to estimate HR based on EMD or EEMD. However, the range measurement of UWB radar is not based on phase measurement and the ranging accuracy is lower than that of mm-wave FMCW radar. Furthermore, they did not perform an objective error analysis between the results and ECG data. More importantly, we will perform pre-processing to improve the SNR of the movement signal obtained by radar before decomposing it. As for the research of vital signs monitoring based on mm-wave FMCW radar, such as [7], due to HR is 0.8–2.0 Hz under normal conditions, they set up only a single chirp in one frame and the frame period is usually chosen to be 50–100 ms. This means that the time utilization is very poor.

In this letter, we propose to transmit multiple chirps in each frame period and a phase accumulation-linear interpolation (PA-LI) processing for FMCW radar signal before time-frequency domain analysis, which can eliminate phase noise and improve the SNR of radar vital sign. And then the radar vital sign is adaptively decomposed by EMD/EEMD to reconstruct the heartbeat signal with high SNR.

2 Proposed method

The proposed signal processing chain is shown in Fig. 1(a). In this study, the phase of IF signal can be illustrated by $\varphi(t) = 4\pi f_{\text{min}} [(R_0 + x(t))/c]$, where $c$ means the speed of light, $f_{\text{min}}$ is the chirp start frequency, $R_0$ is regarded as the distance

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**Fig. 1.** The proposed method
between the object and the radar, $x(t)$ is the radar vital sign.

In fact, measured phase change due to the chest movement is very slow and HR is 0.8–2.0 Hz under normal conditions. Therefore, there is only single chirp in one frame and the frame period is usually chosen to be 50–100 ms (sampling-rate corresponds to 10–20 Hz) [7]. In the case, the time utilization is very poor because the idle time between frames is too long. Besides, the phase analysis processes under highly non-linearity. So, we propose to transmit multiple chirps in each frame period and then accumulate all received signals in a single frame period to eliminate phase noise, which called the phase accumulation (PA). The phase diagram of the received signal is shown in Fig. 1(b). $\tilde{p}, \tilde{n}, \tilde{s}$ are the original signal, phase noise and the received signal, respectively. As shown in Fig. 1(c), we assume that the numbers of chirp per frame is $L$, and the phase after accumulation can be expressed as the following formula:

$$\varphi = \arctan \left\{ \langle (\tilde{p}_i + \tilde{n}_i) \rangle \right\},$$

where $\langle \ldots \rangle$ is ensemble average of the data. The result of phase accumulation is that $\tilde{p}$ will be amplified several times, and $\tilde{n}$ will cancel each other out and it is very small compared to the accumulated $\tilde{p}$, because of $\tilde{p}$ is almost constant in a frame period and $\tilde{n}$ is small and random. In other words, the phase quality is improved according to $L$. After phase accumulation, the phase values are unwrapped and $x(t)$ is obtained. Since the HR is not necessarily constant and the shaking of the body during the test is inevitable, $x(t)$ is a non-linear and non-stationary signal. To extract heartbeat signals with high SNR from $x(t)$, we perform linear interpolation (LI) on the acquired $x(t)$, before performing EMD/EEMD processing, because the movement of the chest is very slow. The LI process is shown in Fig. 1(d), the ordinate value of a certain interpolation point between two adjacent original data is written as:

$$y' = Y_n + \Delta t \frac{Y_{n+1} - Y_n}{t_{n+1} - t_n},$$

where $\Delta t$ represents the time difference between the interpolation point and the previous original data. After LI processing, the radar vital sign is defined as $X(t)$. It is worth noting that this does not contradict the aforementioned phase accumulation for two reasons. First, as shown in Fig. 1(c), the raw data in each frame period will be stored in the buffer, and then sent to the PC after all the chirps are transmitted in the frame period. This means that the data sampling-rate is not constant when processing data of multiple frames directly. Second, in the actual experiment, due to the time consumption in the data transmission, the frame period should not be less than 50 ms (the corresponding sampling-rate cannot be higher than 20 Hz), otherwise it is easy to cause data loss.

The simulation result for PA-LI performance is shown in Fig. 2(a). We set the numbers of chirp per frame to $L = \{1, 2, 4, 8, 16, 32\}$, and the sampling-rate of $X(t)$ is set to $\{20, 40, 80\}$ Hz. The definition of SNR is shown as:

$$SNR = 10\log \left\{ \frac{s^2(l)}{\sum s^2(f) - s^2(l)} \right\},$$

where $s^2(l)$ and $\sum s^2(f)$ are the peak value of the signal spectrum and the total energy of the signal spectrum, respectively. From the result, $X(t)$ have a high SNR when $L$
is 32 and the sampling-rate is 80 Hz. Therefore, we selected the above-mentioned best parameters for our experiment. Next, $X(t)$ is decomposed by the EMD/EEMD into several intrinsic mode functions (IMFs) and a residual component $r_n(t)$. Finally, IMFs whose peak frequency at 0.8–2.0 Hz are selected by the IMF filter as the heart IMF to reconstruct the heart signal.

The results of the frequency spectrum of EMD/EEMD heart IMF with or without PA-LI are shown in Fig. 2(b). The results show that PA-LI can effectively increase the SNR of EMD/EEMD heart IMF. There are two reasons, first, since PA-LI eliminates phase noise and increases the data length within a certain period of time to improve the SNR of the original signal. Secondly, although EEMD can solve the “mode mixing” by a noise-assisted analysis, the residual noise may be generated. However, if the original data with high SNR only needs a small noise amplitude (0.01), the heart IMF can be obtained. The comparison of the reconstructed heartbeat signals and ECG data is shown in Fig. 2(c). In this observation window, the error of the reconstructed signal by EEMD with PA-LI is less than 1 bpm, and the RR-interval also has high consistency with ECG data than other cases.

### 3 Our experiments and results

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 $\mu$s, the frame period is 100 ms and slope of chirp is 70 MHz/$\mu$s, respec-
Table I. Results of heart rate estimation (RMSE: [bpm] SNR: [dB])

| Volunteers | EMD | EMD with PA-LI | EEMD | EEMD with PA-LI |
|------------|-----|----------------|------|-----------------|
|            | RMSE | SNR    | RMSE | SNR    | RMSE | SNR    |
| A          | 8.676 | -21.085 | 6.222 | -15.808 | 5.976 | -12.644 |
| B          | 11.196 | -17.938 | 6.270 | -8.43 | 5.478 | -12.558 |
| C          | 6.972 | -23.497 | 5.424 | -16.687 | 6.006 | -11.241 |
| D          | 6.102 | -17.376 | 5.334 | -15.683 | 6.408 | -9.534 |
| Mean       | 8.238 | -19.974 | 5.814 | -14.151 | 5.967 | -11.494 |

To obtain a reference HR, the volunteers wore the ECG device during the measurement time (60 s). A streaming data of 60 s is analyzed with a 20 s window and a 1 s sliding step. The radar was set 1.2 m in front of the volunteers, and the results of the HR estimation by EMD/EEMD with or without PA-LI are shown in Table I. The SNR of Table I is calculated by averaging the SNR of a streaming data. Compared with other cases, EEMD with PA-LI significantly improved RMSE and SNR, and then the average value of the RMSE was less than 3.303 bpm. This is because improving the SNR will make it easier and more accurate to find the peak value of the heart IMF spectrum. In [1], their average absolute error of HR estimation is (2.61, 3.70, 2.12, 3.32, 4.42, mean: 3.23 [bpm]). Our measurement distance is farther than the 80 cm they measured, and the performance is more stable. In [2], their HR error range is about -7–5 bpm in one participant case. So, the results of the proposed method are within the acceptable range. In addition, on an ordinary PC (i7-9700 CPU 3 GHz), the EMD/EEMD and the PA-LI processing time for one observation window data are 0.033 s/2.9 s and 0.2 s, respectively. This means that the proposed method has high real-time performance.

4 Conclusion

In conclusion, we propose a PA-LI method for mm-wave FMCW radar to improve radar vital sign SNR before extract the heartbeat signal. The results show that, especially when PA-LI is combined with EEMD, it can quickly and efficiently improve the SNR of the original signal, making it more accurate to find the peak value of the heart IMF spectrum. Then, the reconstructed heartbeat signal has a high SNR and the HR estimation is more accurate.