High-Accuracy Cardiac Activity Extraction Using RLMD-Based Frequency Envelogram in FMCW Radar Systems

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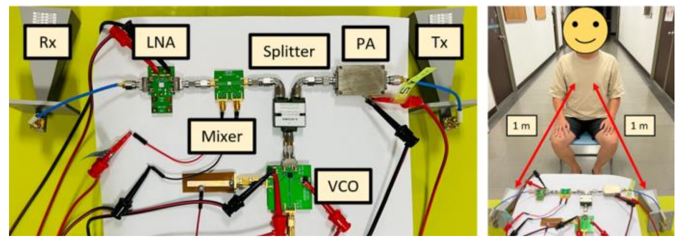
***Abstract*—This paper proposes an accurate extraction of beat-to-beat interval (BBI) using the robust local mean decomposition (RLMD)-based frequency envelogram (FEnv) method in frequency-modulated continuous wave (FMCW) radar systems with lower signal-to-noise ratio (SNR). The FEnv benefits from spectral integration of time-frequency representation (TFR) and can further emphasize the vital signal fragments with strong characteristics. However, the performance of original FEnv suffers from the insufficient time-frequency resolution of the Fourier transform, resulting in poor BBI estimates. RLMD decomposes the reflected signals into the amplitude-modulated (AM) signals and the frequency-modulated (FM) signals, which can be reshaped according to heartbeat frequency band, to improve time-frequency resolution. After proper preprocessing of the received I/Q signals, the cardiac activity can be extracted accurately by the proposed RLMD-based FEnv. The results of the proposed algorithm are in high agreement with the reference signals ECG, and the error rate can reach 1.84 % on average.**

***Keywords*—beat-to-beat interval (BBI), differential enhancement, Doppler radar, Frequency Envelogram (FEnv), FMCW, heart rate variability (HRV) trend, modified DACM, robust local mean decomposition (RLMD).**

I. Introduction

Heart rate variability (HRV) is a reliable indicator for the prevention of myocardial infarction [1]. Continuous wave (CW) Doppler radar is more sensitive and reliable to motion signals and HRV in a non-contact manner [2], [3]. Frequency-modulated continuous wave (FMCW) radar is another promising technology and capable of distance awareness. However, FMCW radars have less SNR than CW radars. Therefore, it is desired to propose a method to extract HRV by using FMCW radar with advanced algorithms to achieve low error rates.

The heartbeat signal is too weak for the FMCW radar systems, making it impossible to distinguish the R-peak signals, corresponding to the periods when the ventricle is depolarized. Therefore, the preprocessing procedure for the demodulation method must have strong anti-noise ability and enhance signals for FMCW demodulation. The DACM algorithm [4] is a good method to demodulate the target motion phase but relies too much on the accuracy of I/Q signal, such as dc offset calibration. Therefore, Xu et al. proposed the modified DACM to further improve the accuracy of phase restoration [5]. This algorithm does not require calibrated items and arctangent demodulation, so it is less susceptible to the influence of I/Q imbalance, and the demodulation linearity and stability greatly improves. Moreover, a differential enhancement algorithm is applied to perform a differential operation on the phase of the target object to suppress low-frequency breathing and enhance the relative high-frequency heartbeat motion component [6].



(a) (b)

Fig. 1. (a) Block diagram of the FMCW radar system in this work; (b) Measurement set up with a sitting person.

High-resolution of cardiac motion waveforms in time domain is required for HRV analysis. Xia et al. integrated the spectral energy at each time point in the time-frequency representation (TFR) of the short-time Fourier transform (STFT) to obtain the frequency envelogram (FEnv) [7]. The energy distribution in TFR depends on the vibration amplitude of the signal; the stronger vibration, the greater energy in TFR. Therefore, the signal with strong characteristics or activities can be distinguished, and the high-resolution heartbeat movement can be obtained by using FEnv. However, the resolution of heartbeat movement is limited by time-frequency resolution of the Fourier transform. Liu et al. proposed robust local mean decomposition (RLMD) based TFR [8]. Because the signals are decomposed in the time domain, RLMD-based TFR does not suffer from time-frequency resolution. TFR achieves better resolution by combining with the amplitude-modulated (AM) and the frequency-modulated (FM) signals, decomposed by RLMD. Therefore, the RLMD-Based FEnv generated from this TFR also has higher resolution.

The new method proposed in this paper, using preprocess including the modified DACM, differential enhancement and RLMD-based FEnv. DACM provides strong anti-noise ability to demodulate chest motions. The band-pass filter followed by the differential enhancement algorithm to amplify heartbeat motion signals and eliminate respiratory motion signals and its harmonics. RLMD-based FEnv has better resolution which eases the extraction of the high-precision cardiac motion. Finally, the HRV analysis can be performed with simple peak detection. The algorithm proposed in this paper can extract HRV under the FMCW radar system to achieve extremely high accuracy and retain the position information of the target.

II. PROPOSED METHODS

A. Pre-Processing

Fig. 1(a) shows the architecture of the homodyne radar system, and Fig. 1(b) is a schematic diagram of the measurement. The target echo received by the receiver (Rx) is down-converted by the mixer to obtain the quadrature beat frequency of the I/Q signals. The fast time-slow time matrix can be obtained by arranging the signals according to each fast time. Then FFT is performed for each column which is composed with fast time, and the range-slow time matrix represented by different beat frequencies can be obtained. The I/Q phase information of the range corresponds to the target location along the slow time. After the fundamental frequency I/Q signal is calibrated by amplitude imbalance and DC offset, the modified DACM algorithm is applied. This algorithm differentiates the signals and performs cross-multiplication and combination with the original signal [5]. Finally, the differential term of the target motion can be obtained by a simple operation:

$$x'(t) = \frac{\lambda}{4\pi}\,[I(t)Q'(t) - I'(t)Q(t)] \quad (1)$$

where $x(t)$ is the target motion signal. To restore the target motion and reduce the high-frequency noise interference introduced by the differential form, (1) is integrated numerically:

$$x(n) = \frac{\lambda}{4\pi}\sum_{k=2}^{n} I[k-1]Q[k] - I[k]Q[k-1] \quad (2)$$

Compared with the existing DACM [4], the restored target motion in (2) does not include the $I^2 + Q^2$ item in the denominator due to arctangent demodulation. This means that strict calibration steps can be omitted for I/Q signals. After accurately restoring the chest movement signal, the differential enhancement algorithm is applied to boost and extract the tiny heartbeat movement [6]. This method is to generate a differentiator using a band-limited antisymmetric finite impulse response (FIR) filter of the third kind, as follows:

$$x_0' = \frac{5(x_1 - x_{-1}) + 4(x_2 - x_{-2}) + x_3 - x_{-3}}{32\Delta t} \quad (3)$$

where x_0' is the first order differential at a particular sample, x_i (i = -3,-2,-1, 1, 2, 3) denotes the value of the time series i samples away. The Δt is the time interval between consecutive samples. The differentiator is combined with a band-pass filter to amplify high-frequency signals represented by cardiac motion and suppress low-frequency signals represented by respiration and its harmonics. It also has the advantage of a short window and can track cardiac motion sensitively to ensure that the signal is not distorted.

B. RLMD-Based FEnv

In [9], local mean decomposition (LMD) method is specially designed to solve multicomponent AM-FM signals. The original signal minus the average of the extreme values produces a zero-mean signal. The average of difference between the extrema values are called envelope signal. The zero-mean signal divides by envelope signal constantly until the zero-mean signal becomes a pure FM signal. The product of all decomposed envelope signals can be regarded as a pure AM signal. The FM signal is multiplied by the AM signal to obtain so-called the first product function (PF_1). Subtract PF_1 from the original signal and iterate continuously to find all PFs until the remaining signal does not oscillate.

However, LMD decomposition has two main disadvantages. First, it is difficult to verify whether the pole is selected for the real pole, leading to the end effect. The other disadvantage is that serious mode mixing problems occur if a false pole is selected. To improve the stability of the LMD algorithm, the robust-LMD (RLMD) algorithm was proposed [8]. RLMD improves the performance of LMD by simultaneously solving problems such as boundary conditions, envelope estimation, and sifting stopping criterion.

1) Boundary conditions

To select local poles accurately, the setting of boundary conditions is very important, so the mirror extension algorithm is introduced [10]. To set the symmetry point by checking whether the local poles are true, the segment signal is mirrored and expanded at the symmetrical point. Then moving average is performed and cut the extended outputs back to the same length as the original signal.

2) Envelope estimation

After performing a moving average, the amount of information in the output envelope is lost if the inappropriate subset size is selected. To ensure that the signal after the moving average retains credible information, the probability of the step size of all segments will be calculated in advance. The probability of the step size can be counted using the histcounts function embedded in MATLAB. Then choose a step size of three standard deviations away from the central step size so that almost all segment steps are covered.

3) Sifting stopping criterion

Ideally, the criterion for stopping the iteration at the i-th PF_i is that the envelope signal a_{ij}(n) of the j-th iteration is one. Subtract one from the envelope signal to get the zero-baseline envelope signal $z(n)$. From the perspective of global measurement, the root mean square (RMS) is introduced to measure the total energy of $z(n)$. In addition, the excess kurtosis (EK) function can be used to measure local anomalies, The cost function F is defined by introducing global and local measurements as follows:

$$F_{ij} = RMS\left(z_{ij}(n)\right) + EK(z_{ij}(n)) \quad (4)$$

After defining the cost function, the proposed sifting criteria are determined. According to the values of three consecutive cost functions F_{ij}, F_{ij+1}, and F_{ij+2}. If $F_{ij+1} > F_{ij}$ and $F_{ij+2} > F_{ij+1}$, then the sifting process stops and returns the result of F_{ij-1}. Otherwise, the iterative process continues until the number of iterations reaches a predefined value.

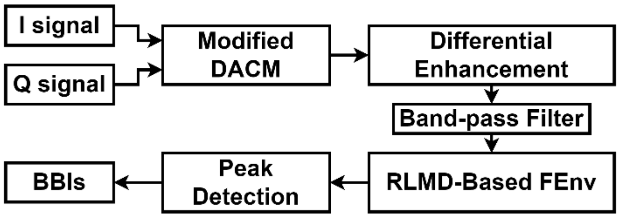


Fig. 2. Flow chart of the proposed method.

After mitigating the problems of end effects and mode mixing, RLMD-based TFR can be generated by combining AM and FM signals. The frequency axis can be transformed from the FM signal into the angular frequency $\phi_i(n)$ through inverse cosine transformation and then obtained by (5):

$$f_i(n) = \frac{d\phi_i(n)}{2\pi T_s} \quad (5)$$

where T_s is the continuous sample time interval, $f_i(n)$ is the instantaneous frequency. The envelope signal $a_i(n)$ can represent the AM signal. That is the energy of the instantaneous frequency at each time point. To filter out $a_i(n)$ with similar heartbeat frequency (0.8Hz – 1.8Hz), apply autocorrelation to all $a_i(n)$ to improve periodicity and then perform spectrum analysis. The RLMD-Based FEnv can be obtained by combining the $a_i(n)$ with the highest peak of heartbeat frequency. Different from the original STFT-based FEnv [7], the proposed method is obtained completely through the time domain, which greatly improves the time-frequency resolution of STFT. Moreover, a screening mechanism is introduced in the process of FEnv, which greatly increases the resolution of heart motion.

Table 1. Key components used in a radar system.

Component	Manufactory Model No.	Specifications
VCO	HMC533LP4E	BW = 23.8-24.8 GHz
PA	AHP2225-38-2523	BW = 18-26.5 GHz, Gain = 25.3 dB
LNA	ALN2200-36-3425	NF=2.5 dB (18-26.5 GHz), Gain = 31 dB
Power Splitter	GF-T-180265	BW = 18-26.5 GHz, Insertion Loss = 0.8 dB
Mixer	HMC524ALC3B	Quadrature, BW=22-32 GHz, CL=15 dB
DAQ	NI: USB-6363	16 bits, 2 MSPS

III. Measurement and Result

The flow chart of the proposed algorithm is shown in Fig. 2. The experiment setting is that a subject sitting at distance of 1 meter from the radar antenna, the center frequency is 24 GHz, the bandwidth BW is 160 MHz, the pulse repetition interval is 2 ms and the chirp rate α = 80 GHz/s. The total measurement time is 60 seconds, and three subjects are measured. During the measurement, the subjects were asked to breathe normally, and the detailed components are listed in Table 1.

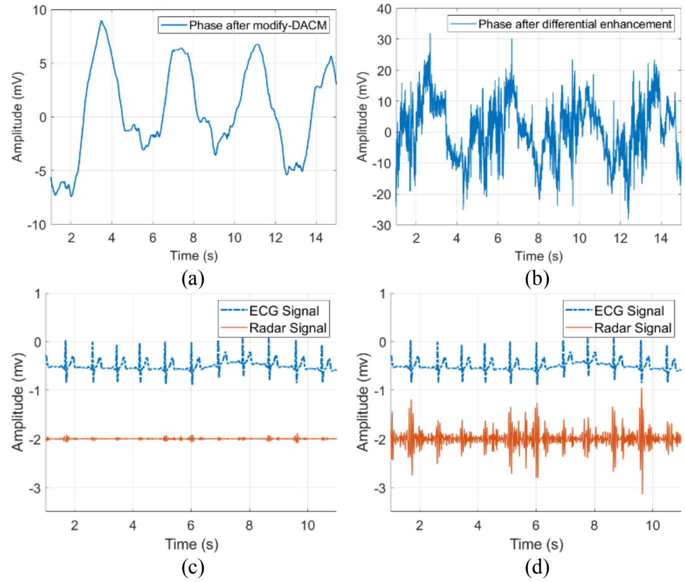


Fig. 3. (a) Target motion phase after modified DACM; (b) The phase after differential enhancement; (c) Filtered signals without applying differential enhancement; (d) Filtered signals after applying differential enhancement.

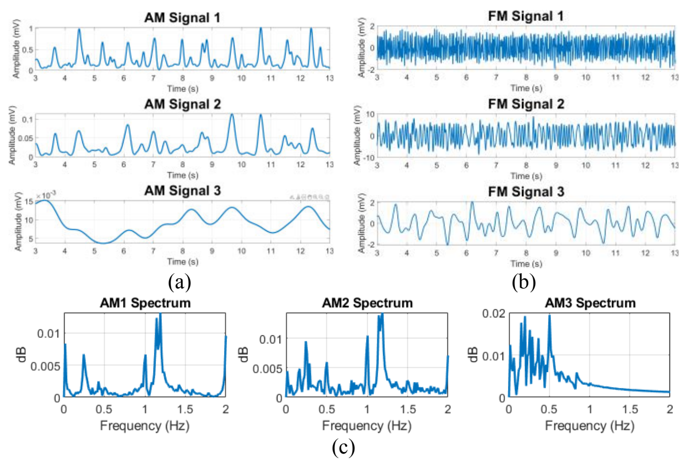


Fig. 4. (a) AM signals from RLMD; (b) FM signals from RLMD; (c) The spectrum of each AM signal.

After phase demodulation, the phase signal of chest motion can be seen as shown in Fig. 3(a). Since the heartbeat amplitude relative to the respiration amplitude is too weak to be detected after phase demodulation, the differential enhancement is applied to the demodulated phase, as shown in Fig. 3(b). The small amplitude of the high frequency is amplified, but the signal is still affected by the low frequency breathing effect. Therefore, a bandpass filter is applied to suppress low-frequency signals, as shown in Fig. 3(d). Compared with the ECG reference signal, the filtered signal has a close tendency to R peak. The signal without differential enhancement in Fig. 3 (c), the SNR in Fig. 3 (d) has been greatly improved.

Although the trend of the R peaks can be seen, it is not possible to determine the accurate position of the R peak and analyze HRV from the signals. Therefore, the RLMD is used here to decompose the signal. AM and FM signals from the decomposition process as shown in Fig. 4(a) and Fig. 4(b),

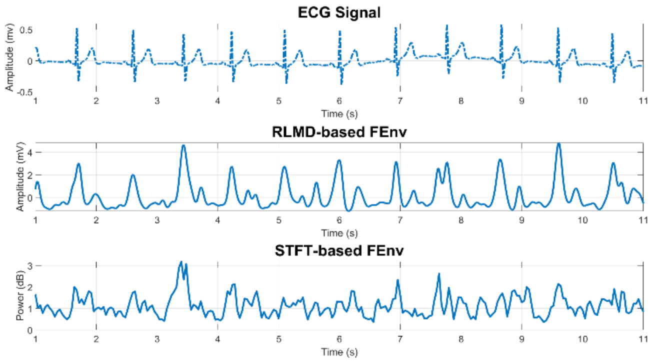


Fig. 5. ECG signal, RLMD-based FEnv and STFT-based FEnv.

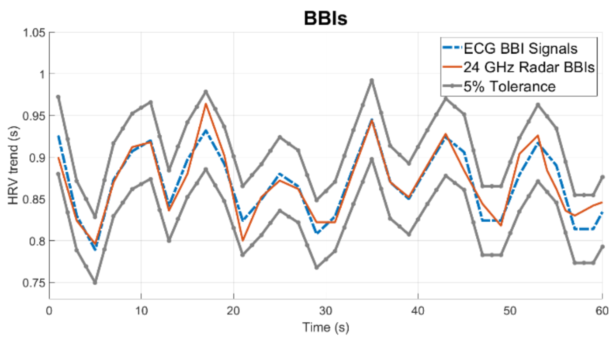


Fig. 6. Error rate of BBIs for the entire measurement time.

respectively. From the spectrum of each AM signal after autocorrelation shown in Fig.4(c), since the desired heartbeat signals are observed only in AM1 and AM2, by combining both signals we can obtain a high resolution heart motion.

The measured results are shown in Fig. 5 and the heartbeat reference uses the Biopac Student Lab System from BIOPAC Systems Inc. The peaks almost have a good correspondence to the R-peak of the ECG signal, but it can be noticed that a single peak is not well resolved in the interval of 7 to 8 seconds, this problem can be solved by a simple filtering mechanism. Since the time interval of each heart pulse interval does not change drastically, the selection of peak can be determined by which peak is closer to the average of the previous two pulse intervals. The results of STFT-Based FEnv are also shown in Fig. 5, under the FMCW system, the peak cannot be accurately found related to the R-peak of the ECG. The error rate of beat-to-beat intervals between the ECG signal and the RLMD-based FEnv is shown in Fig. 6. All error rates in each measurement period are less than 5%, and the performance is calculated by using the mean relative error (MRE) :

$$MRE = \frac{1}{N_{BBI}} \sum_{i=1}^{N_{BBI}} \frac{|BBI_{radar}(i) - BBI_{ECG}(i)|}{BBI_{ECG}(i)} \quad (6)$$

The result of MRE is 1.84% on average. Table 2 shows the comparison of the proposed method with other papers. The method used in this paper has excellent performance in HRV extraction under the FMCW radar system.

Table 2. Comparison of the non-contact HRV measurement with different detection systems and methods.

Ref.	System	Method	Error
[11]	24 GHz CW Radar@0.8m	IZA-SLMS with TWV	< 5 %
[12]	24 GHz CW Radar@0.8m	Spectral Viterbi with RNN-based deep clustering	< 7 %
[7]	24 GHz CW Radar@0.5m	STFT-based FEnv with HSMM	< 2 %
This work	24 GHz FMCW Radar@1m	Differential Enhancement with RLMD-based FEnv	< 2 %

IV. Conclusion

This paper proposes a novel method to accurately extract HRV in the FMCW radar system. The proposed FEnv generated by the RLMD method is not affected by the time-frequency resolution, and the addition of a filtering mechanism can greatly improve the resolution of the original FEnv. The generated heart motion can identify the location of the R-peak clearly. The HRV BBI error of this method is 1.84 %, which has the same accuracy as other methods in the CW radar system and can be achieved in the case of low SNR.

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