Modified template matching filtering based on breath-by-breath segmentation for heart rate variability analysis using CW Doppler Radar

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***Abstract*— Template matching filtering (TMF) is an effective method for beat-to-beat interval extraction for HRV analysis. The selection of the template may significantly impact HRV accuracy. In this paper, a template generation method is proposed based on breath-by-breath segmentation of CW Doppler radar data. A template is generated from six consecutive breaths selected based on circle fitting with the minimum deviation from the circle radius. This method was proven to be effective for accurate HRV parameter extraction, resulting in an average absolute error of 5.21 ms for RMSSD and 3.55 ms for SDNN.**

***Keywords*— Doppler radar, modified template matching, HRV, breath-by-breath segmentation.**

I. Introduction

Heart rate variability (HRV) reflects the balance between the parasympathetic and sympathetic nervous system activity offering the assessment of cardiac status and can be employed as a prognostic index of cardiovascular outcomes [1]. HRV is conventionally measured using sensors such as Elecardiogram (ECG) sensors, and Photoplethysmogram (PPG) sensors. However, these methods often lead to issues like limited mobility, discomfort from body-attached sensors, skin irritation, and allergic reactions. Consequently, non-contact HRV monitoring using Doppler radar (DR) is becoming increasingly popular. Furthermore, DR offers simultaneous detection and monitoring of both heart and respiration signals allowing separate assessments of HRV and HRV specifically related to Respiratory Sinus Arrhythmia (RSA) [2].

Since DR measures the heart signal from the chest wall displacement, the peaks are not very prominent and suffer from respiration harmonics [3]. Previous work by Hu et. al. proposed the use of Ensemble Empirical Mode Decomposition (EEMD) for HRV analysis by removing the respiration interference. However, using such a method requires selecting the optimal decomposed intrinsic mode functions (IMFs) and solving the mode mixing problem [4]. A computationally intensive bandpass filter bank approach for HRV analysis used in [5] depends on the estimation of average heart rate (HR) which can result in a large error if the HR is estimated incorrectly. Sakamoto et al. analyzed HRV using six features from UWB radar compared to ECG signals [6], but this novel method requires a 2000 kHz sampling rate which is unsuitable for real-time monitoring.

A more computationally efficient method called template matching filtering (TMF) has been employed in several works for HRV analysis using radar signals [7]- [8]. However, the main challenge for the TMF method is to generate a suitable template waveform. In [7] template extraction based on singular value decomposition (SVD) using the trajectory matrix formed from clipped 2s arctagent demodulated (AD) signal is proposed. However, the error rate for the extracted HRV feature standard deviation of heartbeat interval is very high for both seated and supine postures. In [9], polynomial fitting is applied to the selected breathing segment to extract the heart signal by subtracting the fitted signal from the initially selected segment. This method was proved to be effective for heart rate extraction in the presence of body motion. In [8], [10], a single heartbeat containing the dicrotic notch or defined by multiple characteristic points has been taken as a template for TMF. Although a low root mean square error (RMSE) of 18ms was reported for the extracted beat-to-beat intervals, HRV parameters were not analyzed.

Previously, we used Maximal Overlap Discrete Wavelet (MODWT) to improve the beat-to-beat analysis of heart signals by suppressing the respiration harmonics [11]. Extending the findings in [11], we have demonstrated high accuracy in HRV analysis in [12] by employing TMF on arctangent demodulated signals. However, the template used for this TMF method depends on using a reference PPG signal and ignores the alignment of the template and the input signal by using a fixed window in TMF.

In this paper, we introduced a novel template extraction based on breath-by-breath segmentation of the signal from 2.4 GHz Continuous Wave (CW) quadrature radar. Using the proposed method, a 3s-long template is taken from the Arctangent demodulated output formed by IQ arcs having the lowest radius variation. We have also introduced a modified TMF by incorporating a sliding overlapping window to ensure alignment between the input and template signal. This method offers an effective approach for the analysis of HRV time-domain parameters with an accuracy better than 10 ms. The proposed method is described in section II along with the experimental setup and the results are presented in the following section III.

II. MEASUREMENT SETUP AND DATA PROCESSING

A. Experimental Setup

Fig. 1 shows the 2.4 GHz CW quadrature channel DR used to collect data from 3 human subjects under testing protocol no. 14884 approved by the Committee on Human Studies (CHS) at the University of Hawaii. The subjects were asked to sit still at 1 meter away from the patch antenna and breathe normally. The radar system setup included a 90-degree ZX10Q-2-25-S+ splitter, ZFM4212 mixers from Mini-circuits, and a Narda 4923 circulator. The mixers' outputs were passed through a 10 Hz low pass filter and amplified 20 times through a DC Coupled SR560 low noise amplifier (LNA). The in-phase (I) and quadrature (Q) baseband outputs were recorded using 18-bit DAQ at a 100 Hz sampling rate. PPG signal was used as the reference in this study.

B. Template selection

Template selection was carried out individually for each data set. The steps for generating the template are outlined in Fig. 2. Fig. 3 shows the IQ plot from the whole dataset of 3 min long for subject 1. It is visible from the data that the circle center and radius are changing during the measurement, making circle fitting on the whole data set, and thus AD less accurate. This circle fitting can be more accurately obtained by breath-by-breath segmentation. The I and Q outputs are then segmented according to each breath. As shown in Fig. 4 this is done by detecting the local minimums within each breathing cycle. The IQ arc of each segment is circle-fitted using the Levenberg Marquardt (LM) algorithm and the radius of the fitted circle is calculated (Fig. 5). Next, the variation of the circle radius for each point on the arc is calculated for all segments as:

$$E = \sum_{i=1}^{N} \left| \frac{r_c - \sqrt{(x_c - I_{segment}[i])^2 + (y_c - Q_{segment}[i])^2}}{2r_c} \right| \quad (1)$$

where, r_c is the radius of the fitted circle, x_c and y_c are the center coordinates, and N is the number of breath segments. Using this method, six consecutive arcs with the lowest error, E are selected for template extraction. Fig. 5 shows IQ plots of selected arcs with the minimum error for Subject 1.

Next, arctangent demodulation (AD) is done on the selected arcs' segments, and the demodulated output is filtered from 0.85 to 5 Hz. The filtered signal is denoised by decomposing it into 10 levels using maximal overlap discrete wavelet transform (MODWT) [11]. After reconstructing the signal at level 6, the template is selected by considering the segment having the highest average peak-to-peak amplitude and lowest variation in this amplitude. Fig. 6a shows AD output for six consecutive arcs with the lowest error, E calculated using (1). The filtered and denoised signal (blue) and the section of the denoised signal that was selected as a template in orange are shown in Fig. 6b.

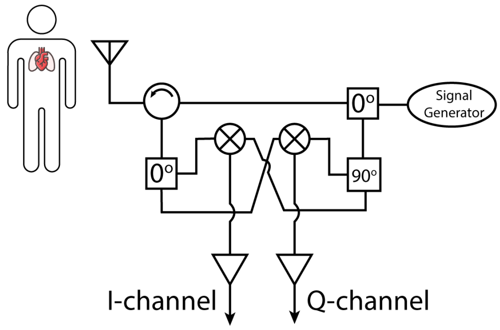

Fig. 1. Block diagram of a 2.4GHz CW DR for vital signs detection.

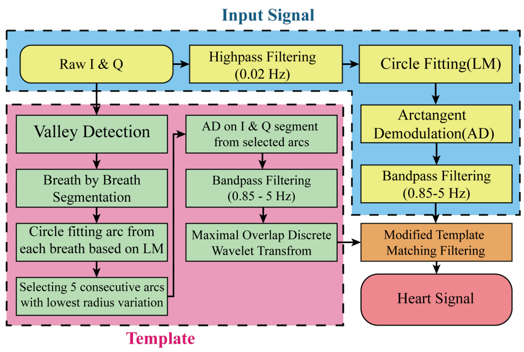

Fig. 2. Flowchart showing the signal processing steps of the proposed method.

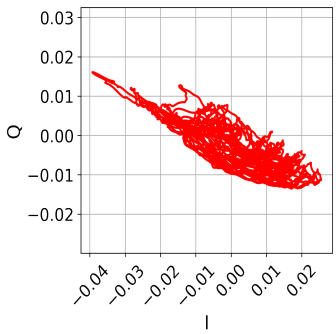

Fig. 3. IQ arc fitted to circle based on LM algorithm using the whole dataset.

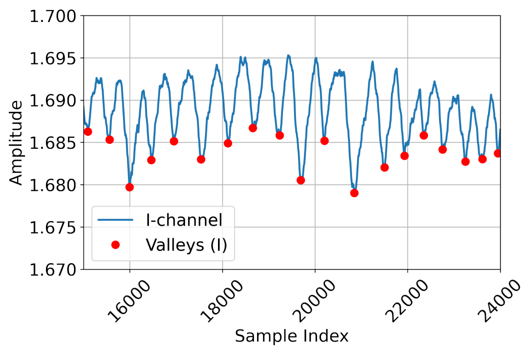

Fig. 4. Valleys detected for breath-by-breath segmentation.

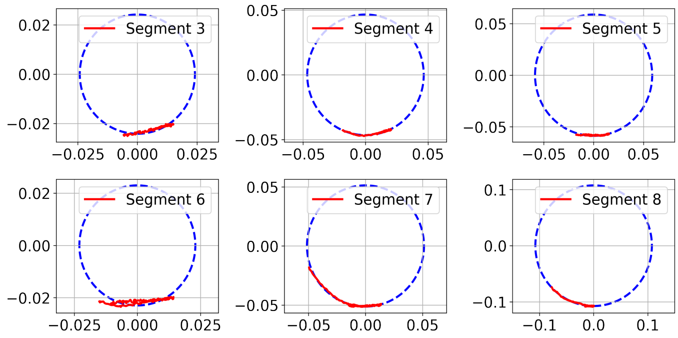

Fig. 5. Finding the best-fitted IQ arcs based on breath-by-breath segmentation.

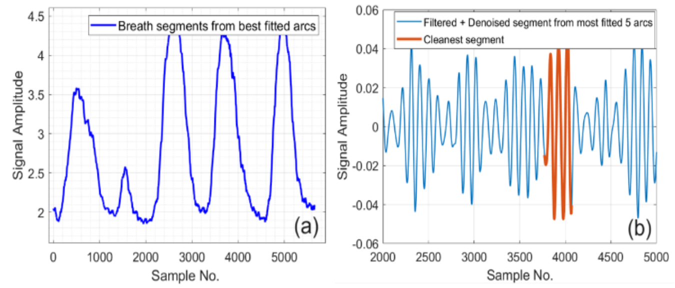

Fig. 6. (a) Arctangent demodulated signal of breath segments having lowest radius variation or best arc fitting and (b) selected template from filtered and denoised signal by MODWT.

C. Modified template matching filtering

Conventional template-matching filtering considers a fixed window to perform cross-correlation of the input signal with the template signal. However, this might result in an error if the template is not aligned with the input signal. Furthermore, the peaks are less significant with a fixed window for TMF. To address this issue, a sliding window with an overlap for TMF is formulated in this study. Based on the sliding window correlation analysis [13], the equation for TMF is modified as shown in (2).

$$x_h[n] = \sum_{k=0}^{K-1} \sum_{m=0}^{W-1} w[m].x[n+k.O+m].h^*[-m] \quad (2)$$

where, W represents the length of the window, the length of the overlap is given by O and K represents the number of sliding windows which is equal to $[\frac{L-W}{O}]+1$.

Table 1. SDNN and RMSSD Difference in ms for all datasets.

Dataset	Best fitted arcs		SVD	
	RMSSD Difference (ms)	SDNN Difference (ms)	RMSSD Difference (ms)	SDNN Difference (ms)
Subject 1	3.17	1.92	67.82	10.75
Subject 2	9.49	0.26	40.22	1.79
Subject 3	2.96	8.46	23.09	2.59

III. Results

In this section, the HRV analysis results obtained through a modified TMF with a sliding overlapping window using template selection based on breath-by-breath segmentation are presented. We have investigated the time-domain HRV features: standard deviation of NN intervals (SDNN) and root mean square of successive differences (RMSSD).

As shown in Fig. 2, for the input of the TMF, the raw I and Q signals are passed through a high pass filter at 0.02Hz and then demodulated using AD following circle fitting based on LM algorithm. Next, the AD output is filtered using the same filter specifications as used for the most fitted IQ arcs' segments. Finally, the filtered signal undergoes modified template matching filtering with the 3-second templates extracted as described in section II.

Table 1 presents the results obtained using datasets from three subjects breathing normally. The lowest SDNN difference of 0.26 ms is obtained for Subject 2. The lowest RMSSD difference of 2.96 ms is obtained for Subject 3. The accuracy of HRV analysis from template matching filtering using the template from best-fitted arcs from breath-by-breath segmentation is compared with the template obtained from singular value decomposition [7]. In this case, a trajectory matrix is formed from the 2-second segment clipped from the AD output. Then using SVD the third singular vector is extracted as the template which is used in the TMF.

Although the accuracy of the obtained SDNN is similar to the accuracy obtained using our proposed method, a template from best-fitted arcs showed significantly better accuracy in terms of RMSSD compared to SVD. The average of RMSSD and SDNN difference decreases from 43.71 ms to 5.21 ms and from 5.05 ms to 3.55 ms respectively when the template from best-fitted arcs is used instead of SVD.

Table 2 presents a comparison of HRV accuracy using our proposed method with other studies. As can be seen, using SVD for template generation with the proposed TMF with a sliding window instead of a conventional fixed window can improve the RMSSD accuracy by more than an order of magnitude. Moreover, this work with an S-band CW DR showed a higher HRV accuracy with lower signal processing complexity and hardware requirements compared to the work utilizing a mmWave FMCW radar [14]. Compared to our previous study using conventional TMF with a template from reference PPG signal [12], this work shows an improvement in accuracy of over 2X by employing the modified TMF with sliding overlapping windows utilizing a template from best-fitted arcs based on breath-by-breath analysis.

IV. Conclusion

In this paper, we have proposed a novel method of breath-by-breath segmentation to find the best-fitted IQ arcs. The segments from the best-fitted arcs are used to generate the 3-second long template which is used in the template matching filtering for HRV analysis. The conventional template matching filtering method is modified with sliding windows and overlaps to align the template and input signal before cross-correlation. The performance of our proposed template selection technique based on breath-by-breath segmentation is compared with the template selection technique based on singular

Table 2. Comparing the accuracy of HRV features across various studies.

Ref	Radar System	Sampling Rate (Hz)	Data Collection Setup	SDNN (ms)	RMSSD (ms)	Method
[7]	24 GHz CW DR	100	Supine	57	161	TMF with template from singular value decomposition
			Seated	81.3	255	
[14]	mmWave FMCW radar	-	Seated	6.44	6.42	Optimization of composite phase decomposition
[12]	2.4 GHz CW DR	100	Seated	9.71	12.41	TMF with fixed window and PPG template
This work	2.4 GHz CW DR	100	Seated	5.05	43.71	Modified TMF with sliding window and template based on SVD from [7]
				3.55	5.21	Modified TMF with sliding window and template based on breath-by-breath segmentation

value decomposition using experimental datasets, indicating significant improvement in HRV parameter accuracy.

The average absolute error is 5.21 ms for RMSSD and 3.55 ms for SDNN. To the best of the authors' knowledge, this is the highest reported HRV accuracy obtained with 2.4 GHz Doppler radar, and comparable to the highest accuracy obtained with 24 GHz Doppler radar. Future work will include further optimization of the template length and analysis of frequency domain HRV features.

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