Instantaneous Heartbeat Detection using a Cross-Correlation based Template Matching for Continuous Wave Radar Systems

Christoph Will, Kilin Shi, Fabian Lurz, Robert Weigel, and Alexander Koelpin
Institute for Electronics Engineering, University of Erlangen-Nuremberg
Cauerstr. 9, 91058 Erlangen, Germany
Phone: +49(0)9131 85-27190, Email: christoph.will@fau.de

***Abstract*—Instantaneous heartbeat detection is necessary for an optimal patient monitoring in healthcare centers. Whereas electrocardiogram (ECG) and ballistocardiogram (BCG), for instance, are established methods for real time monitoring nowadays, contact-free systems are appreciated. Herewith, a 24 GHz continuous wave (CW) radar system with an intelligent signal processing is presented. Common heartbeat detection algorithms use the fast Fourier transform (FFT), and therefore require an adequate observation time window and rather detect an averaged heart rate. The proposed algorithm in contrast accomplishes the detection of single heart beats directly in the time domain with an insignificant delay. The core of that algorithm is a template matching using the cross-correlation method. In this paper, after describing the radar system with the novel signal processing, the presented system is compared to a commercial ECG product.**

***Keywords*—Radar interferometry, Biomedical signal processing, Template matching.**

I. Introduction

In healthcare centers technical systems for vital sign monitoring are compulsory. Due to reliability reasons approved methods like ECG or BCG are widely-used, but contactless systems operating from remote are appreciated and getting more and more established. CW radar systems have been used for wireless sensor applications since the 1970s [1]. These systems were improved over the years, and nowadays novel healthcare products use that technique to detect vital signs, like respiration and heart rate. Meanwhile, several variations of CW-radars have been developed, e.g. Doppler radar [2], frequency modulated CW radar (FMCW) [3] or Six-Port radar [4]. The Six-Port principle has its origin also in the 1970s and was primarily used for power measurement purpose [5]. In recent years, the Six-Port network has been converted into an alternative microwave receiver setup and it is also the basis of the used radar system for this paper [6].

All of the mentioned CW radar systems commonly use the FFT as signal processing routine for vital sign detection. The drawback of this method is the necessity of a particular recording time (10 s...30 s) until the respiration or heart rate can reliably be specified. A first step towards real time detection is constituted by the auto-correlation function (ACF) method, which has already been tested with radar systems [7]. The usage of the short-time ACF facilitates the detection of single heart beats, but this method has been shown for ECG systems only [8]. Since the ACF works best with sinusoidal waveforms, the characteristic curve of a heart beat is still an issue for these methods, due to the existence of a second peak in the heart beat curve, called dicrotic notch. That additional peak is detectable on the skin by photoplethesmography (PPG) systems [9] and should therefore also be measured by CW radars. A further enhancement of heart beat detection is envisioned by exploiting this feature by cross-correlating a template of the specific waveform with the received microwave signal. This is called template matching and has been realized for BCG [10] and ECG [11] [12] systems, but has not proven its usability for radar systems. In [13] the Levenberg-Marquardt algorithm has been used as a similar approach, but a parameter optimization method implicates a much higher signal processing complexity than a cross-correlation based template matching as newly introduced in the presented paper.

II. Measurement System

As described in Sec. I, the transceiver technique of the used radar system is based on the Six-Port principle [4]. Within a passive network, the emitted signal is interfered as a reference with four phase shifted versions of the received signal. These phase shifts feature multiples of $\pi/2$ amongst each other and are realized by a Wilkinson power divider and three hybrid couplers. The resulting four output signals are down-converted to the baseband by Schottky diodes. In a subsequent signal processing, the baseband voltages are interpreted as differential in-phase and quadrature components of the received radar signal. The argument σ of the resulting complex value depicts the phase difference between the reflected microwave and the reference signal. Movements of the target cause a phase modification $\Delta\sigma$ which can be converted to relative distance changes:

$$\Delta x = \frac{\Delta\sigma}{2\pi} \cdot \frac{\lambda}{2} \quad (1)$$

The parameter λ is the wavelength of the radar signal and has a value 12.5 mm for a 24 GHz signal source. The emission of the microwave is realized by a four-by-four patch antenna array that is focused on the chest of the test person. The whole radar system, including the antenna and an integrated micro-controller, is packaged in one enclosure. The micro-controller calculates the distance values and sends them via a digital serial connection to a laptop for further signal processing. A photo of the measurement system is shown in Fig. 1.

Fig. 1. Exemplary measurement system.

The heartbeat of the person under test causes electrical impulses as well as a slight expansion of the thorax in the sub-millimeter range. As the skin has a significantly higher relative permittivity in comparison to air, the electromagnetic wave is reflected off the chest and therefore, heartbeat detection by the contactless radar system is enabled. Common ECG systems exploit the electrical impulses which have a totally different signal shape, as illustrated and discussed in [4]. But these signals can be used for the validation of the proposed concept.

III. Template Matching

In this section a novel heartbeat detection algorithm, based on template matching, is proposed. The idea behind that algorithm is to sequentially determine the similarity of a cut-out of the received signal to a predefined template. The similarity of two time-discrete signals x and y can be calculated with the cross-correlation function (CCF):

$$\psi_{xy}(k) = \lim_{M \to \infty} \frac{1}{2M+1} \sum_{\nu=-M}^{M} x(\nu) \cdot y(\nu + k) \qquad (2)$$

An advantage of the CCF method is that a short observation time window is sufficient, since the width of the template can be reduced to only one heartbeat. For this reason, the proposed algorithm is able to detect single heartbeats faster than most ACF methods. Additionally, the quality of the correlation evaluation is increased as the typical signal shape of radar detected heartbeat is considered. Due to reflexions of the vasodilative blood wave at vessel walls and forks, the signal curve has not only one maximum, but a second minor local maximum called dicrotic notch. Fig. 2 exemplifies three measured heartbeat templates and emphasizes the dicrotic notch.

The complete signal processing routine for heart rate calculation is depicted in Fig. 3. For heartbeat detection, just a history of the latest seconds has to be evaluated, wherefore a *Sliding Windowing* is applied first. The window, with a recommended length of 8 s...12 s, should be updated once per second. The current cut-out is bandpass filtered (0.8 Hz...2.5 Hz) to remove the influence of the respiration and the noise of the received signal. Afterward, the cross-correlation based template matching is executed, followed by a tolerance margin included peak search. In the last step, the current heart rate is determined by the time difference between the latest detected heartbeats.

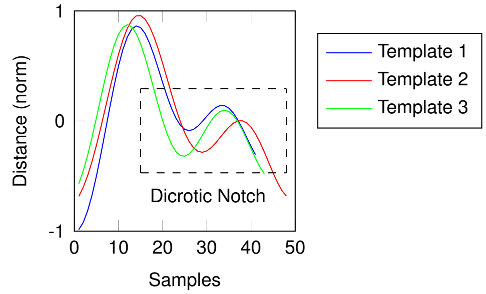


Fig. 2. Templates used for heartbeat detection which depict typical measured signal curves of a single heartbeat at a sampling rate of 50 sps (samples per second).

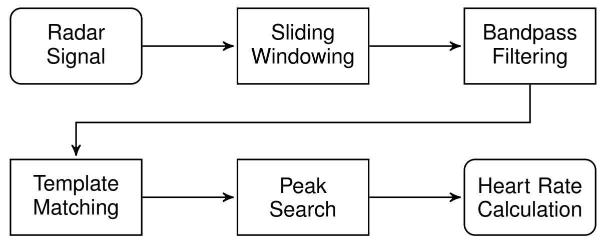


Fig. 3. Flow chart of the heartbeat analysis by cross-correlation based template matching.

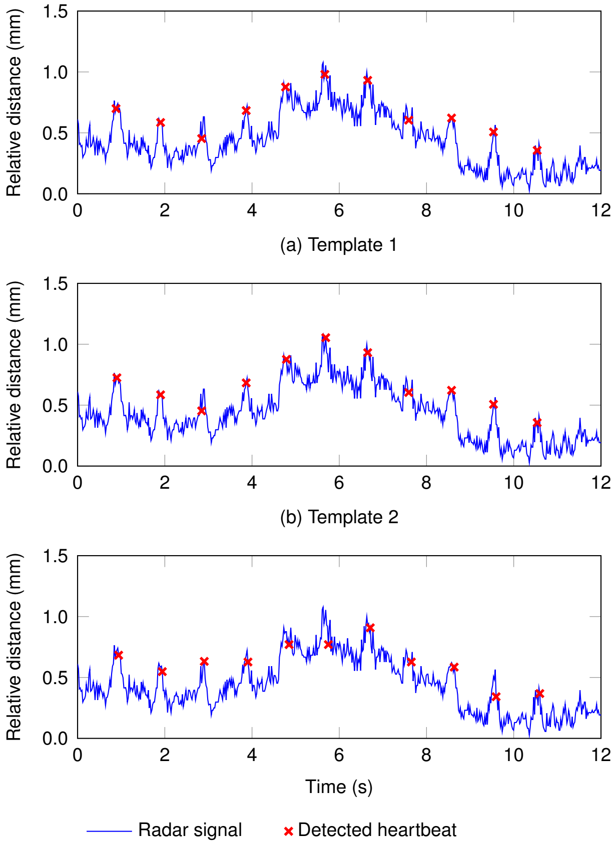
IV. Measurement Results

In this section the performance of the novel algorithm is evaluated. For a comparison of the different heartbeat templates (Fig. 2) the chest vibrations of a person-under-test were measured and recorded while holding the breath. For a signal length of 12 s the processing routine of Fig. 3 was executed with three different templates. In Fig. 4 the detected heartbeats are marked at the maxima of the CCF for all templates. No heartbeat was missed and the detected position for the different templates varies only slightly.

To underline the system performance, the measured radar signal was compared to a common two-channel ECG chest belt, too. For heartbeat detection in the ECG signal the Pan-Tompkins-Algorithm [14] was used. This real-time algorithm exploits the typical shape of a ECG signal and detects the QRS complex. A comparison of the radar system with template matching to the reference ECG is depicted in Fig. 5.

V. Conclusion

Instantaneous heartbeat detection is extremely important for proper vital sign monitoring. Nowadays, ECG systems are still widely-used to accomplish this task, but contactless measurement systems are desired for reasons of comfort. In this paper, a novel algorithm has been proposed to achieve live heartbeat detection with CW-radar systems. A cross-correlation based template matching has been introduced to rapidly detect a heartbeat by exploiting its typical signal shape. The functionality of the algorithm has been tested for different templates and proved its higher quality results in comparison to a common ECG chest belt.

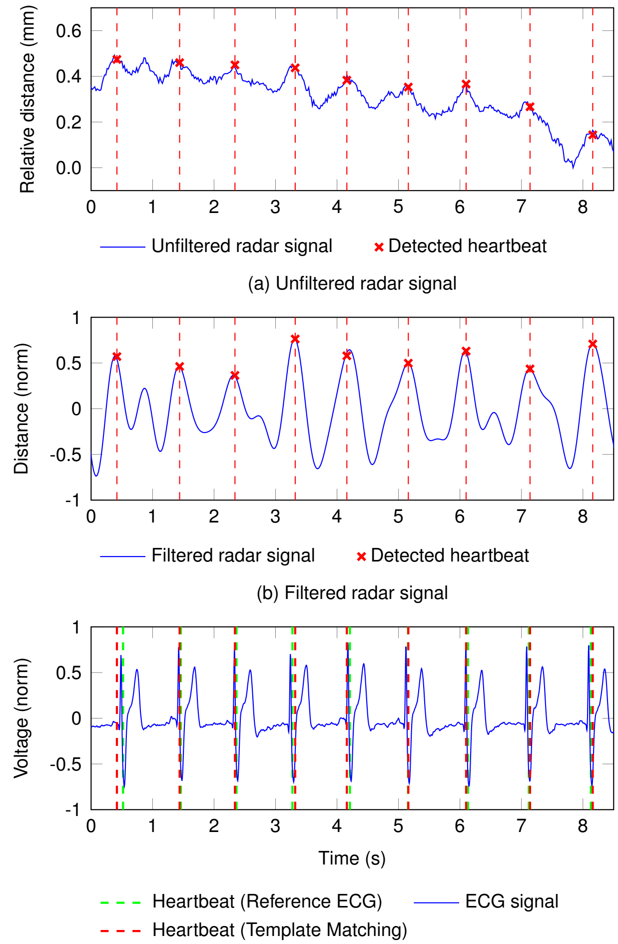


(a) Template 1

(b) Template 2

(c) Template 3

Fig. 4. Comparison of the heartbeat detection for three different templates.



(a) Unfiltered radar signal

(b) Filtered radar signal

(c) ECG reference

Fig. 5. The unfiltered (a) and filtered (b) radar signal and the detected heartbeats by template matching using *Template 1*. A comparison to a reference ECG (c) illustrates the precision of the proposed algorithm.

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