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Vital Sign Signal Extraction Based on mmWave Radar

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Abstract

This research develops an algorithm for health monitoring and uses the Infineon BGT60TR13C shield 60GHz radar to build a set of software and hardware demonstration platforms for algorithm verification. The algorithm can monitor the position, breathing, heartbeat and other information of the elderly in real time, which is used to judge the health status of the elderly and improve the convenience for early warning and rescue of abnormal situations in time. However, limited by the transmission power of this radar and the number of transmitting and receiving antennas, the current detection range of the algorithm is relatively small, and the ability to distinguish between multiple persons is limited. This problem can be optimized by replacing other types of radars in the future.

Keywords

Millimeter-Wave Radar, FMCW, HR and RR Detection, Elderly Health, Real-Time Monitoring

1. Introduction

The aging problem in our country is becoming more and more serious. The number of elderly people living alone is increasing. How to support the elderly has become a social problem. At the same time, the health of the elderly is getting more and more attention. More and more families have or plan to buy equipment for detecting the physiological data of the elderly every day, in order to plan the daily diet and exercise of the elderly and prevent the emergence of diseases. Some important vital signs signals such as heart rate, respiratory rate, body temperature, blood pressure can play a role in preventing diseases. Regular testing of these vital signs helps maintain health.

Major vital signs include body temperature, heart rate, respiratory rate, and blood pressure [1]. Among them, the heart rate is a key indicator to measure the physiological and psychological state of the human body, and the change of the heart rate can reflect the major changes in the human body or spirit. The measurement methods of heart rate mainly include electrocardiography and pulse wave tracing. The former requires electrodes to be attached to the chest of the target to be measured, and the latter requires optical or pressure sensors to be attached to the skin for measurement. Respiratory rate is also an important vital sign, by breathing enough oxygen and expel carbon dioxide to maintain life, and abnormal breathing is a symptom of many diseases. The measurement of respiratory rate can be achieved by measuring the gas flow at the mouth and nose during breathing or by measuring the expansion and contraction of the chest and abdomen during breathing. Common methods such as electrical impedance plethysmography and strain measurement require electrodes or strain sensors to be attached to the chest.

In this paper, a multi-target vital sign signal extraction method based on millimeter-wave radar is proposed, which uses the high precision of millimeter-wave radar to capture the small displacement of the surface of the human chest, and extracts the frequency information of breathing and heartbeat from the displacement information to monitor the health of the elderly in real time. As an important sensing component in the field of vital sign signal monitoring, it is believed that the research content in this paper has important practical significance in the fields of home care and health monitoring for the elderly.

The rest of the paper is organized as follows. Section 2 introduces the method of the monitoring system. In Section 3, the design of offline algorithm for vital sign signal monitoring is described. In Section 4, we conduct the experiments and analyze the results. Finally, Section 5 comes to the conclusion.

2. The Method of the Monitoring System

2.1. The Basic Principle of FMCW Radar

Millimeter-wave radars can be divided into pulse radars and continuous-wave radars according to the waveforms they transmit.

The waveforms emitted by the millimeter-wave radars we use in the project are frequency-modulated continuous waves (FMCW), as shown in **Figure 1**. The frequency change linearly with time [2].

Theoretically, the shape of received signal (RX) is the same as the transmitted signal, while there is a time lag between the transmitted signal and the received signal. The time lag is caused by the distance between the radar and target. The radar mixes the TX and RX waves and output the intermediate-frequency signal (IF) $S_{IF}(t)$ as follows:

$$S_{IF}(t) = A_{IF}\exp\left\{j\left[\psi(t)+\omega(t)t\right]\right\}, t_d < t < T_r \# \tag{1}$$

$$\omega(t) = \frac{4\pi K d(t)}{c} \# \tag{2}$$

$$\psi(t) = 4\pi \frac{d(t)}{\lambda} \# \tag{3}$$

where the A_{IF}, $\omega(t)$ and $\psi(t)$ are the amplitude, frequency and phase of the IF signal. t_d is the time lag between TX and RX. K is the increasing rate of frequency of TX which is set to 0.04 GHz/μs. T_r is the frequency increasing time which is set to 128 μs. c is the speed of light. $d(t)$ is the distance between the radar and target. λ is the wavelength of the radar waveform and it is set to 5 mm.

2.2. The Principle of Heartbeat and Respiration Monitoring

The detection of human heart rate and breathing frequency can be realized by detecting the movement of the human chest. The combined action of breathing and heart beating makes the human chest rise and fall. When a person breathes smoothly, the breathing will cause the regular rise and fall of the human chest. During the beating process of the heart, the contraction and relaxation of the heart are transmitted to the chest wall to move the chest cavity. Using the high precision of the millimeter-wave radar to capture the tiny displacement of the chest cavity, and extract the frequency information from the displacement information, the monitoring diagram is shown in **Figure 2**.

When the human body remains as still as possible, the non-contact sensor is used to detect the distance of the chest relative to the sensor. And the simplified calculation formula of $d(t)$ is as follows [3]:

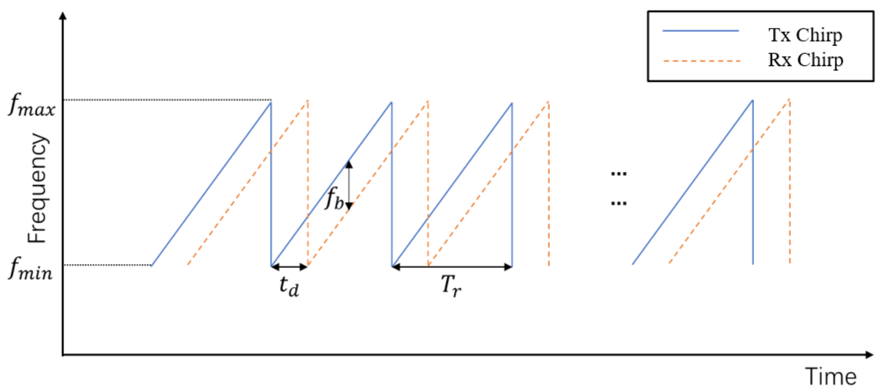

Figure 1. Relationship between *Rx* and *Tx* chirp of FMCW radar.

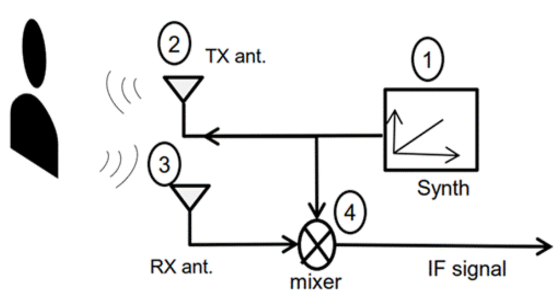

Figure 2. Schematic diagram of heartbeat and respiration monitoring.

$$d(t) = d_0 + d_R + d_H = d_0 + A_R \sin(2\pi f_R t) + A_H \sin(2\pi f_H t) \# \quad (4)$$

In Equation (4), d_0 is the average distance of the human chest relative to the sensor. d_R and d_H are the changing distance of the chest relative to sensor caused by respiration and heartbeat. f_R and f_H are the respiratory rate and heartbeat rate. The general range of A_H is 0.1 - 2 mm, the range of A_R is 3 - 10 mm, the range of f_R is 0.2 - 0.9 Hz, the range of f_H is 0.9 - 2 Hz [4].

3. Algorithm for Vital Sign Signal Monitoring

3.1. Noise Filtering

When millimeter-wave radar is actually used for monitoring, complex monitoring scenarios will generate noise clutter in radar data. In addition to the human body in the room, static objects such as beds, wardrobes, and walls will reflect radar waves, which will greatly interfere with the monitoring results. A large number of static objects in the scene make the obtained spectrum have strong zero components, which interfere with the display and identification of normal spectrum waves [5]. How to filter out the interference of static furniture on radar data is a key point and difficulty of our algorithm.

In practice, we found that the IF of the obtained intermediate frequency signal is very noisy, and the time domain and frequency domain diagram is shown in **Figure 3**:

We can find that the signal is mixed with:

1) Linear noise component

2) Low frequency noise component

3) High frequency noise component

Noise sources are from:

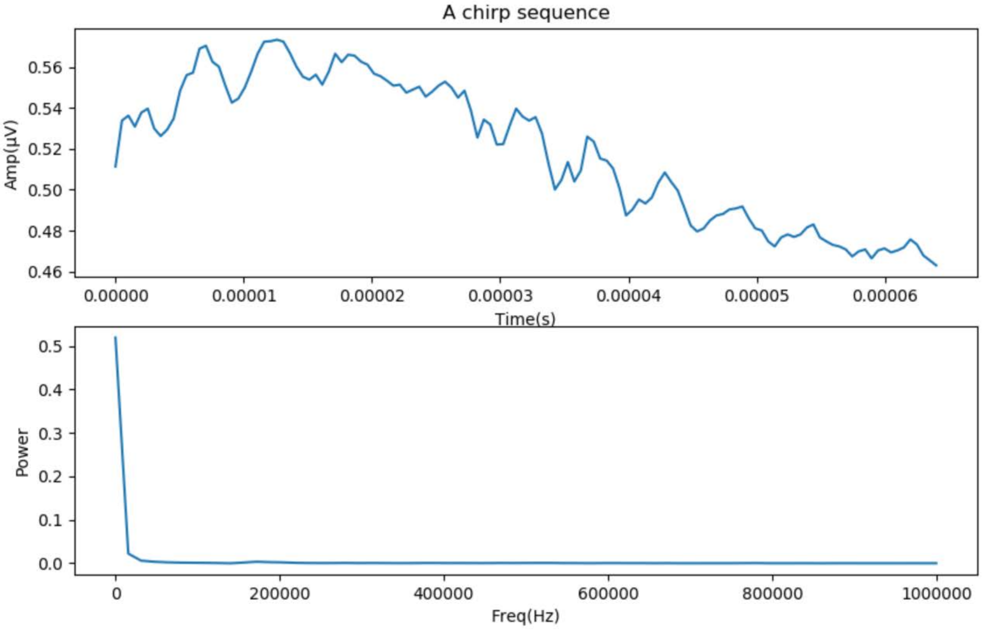

Figure 3. IF signal time domain frequency domain diagram.

1) External DC signal component [6]

2) Local oscillator leakage

3) Nonlinearity of the mixer [7]

According to the modulation and demodulation theory of RF signals, a trigonometric function can decompose the IQ signal as follows:

$$x(t) = I\cos(2\pi f_c t) - Q\sin(2\pi f_c t)\# \tag{5}$$

This project requires reverse demodulation. Our solution is to use carrier demodulation. The flow chart is shown in **Figure 4**:

Ideally the sinusoidal signal IQ decomposition should be a circle in the complex plane with the center of the circle at the origin of the complex plane. However, the original signal contains a DC bias that deforms the signal, and this component can significantly affect the accuracy of phase extraction in vital signs signal measurements [8]:

$$\phi = \arctan\left(\frac{I(t)+c_1}{R(t)+c_2}\right) \neq \psi\# \tag{6}$$

so we use the method of DC offset, which means normalizing the amplitude and translating the center of the circle to the origin as shown in **Figure 5**.

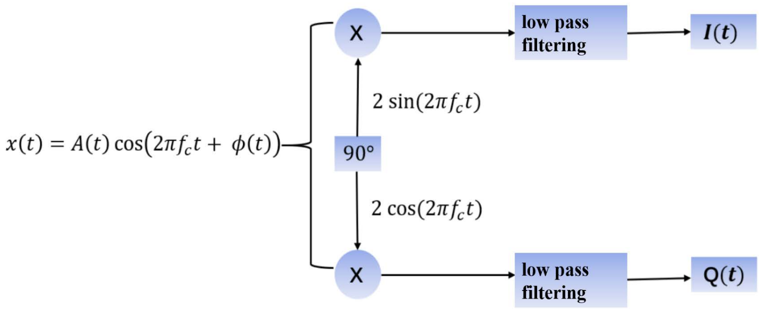

Figure 4. Schematic diagram of carrier demodulation principle.

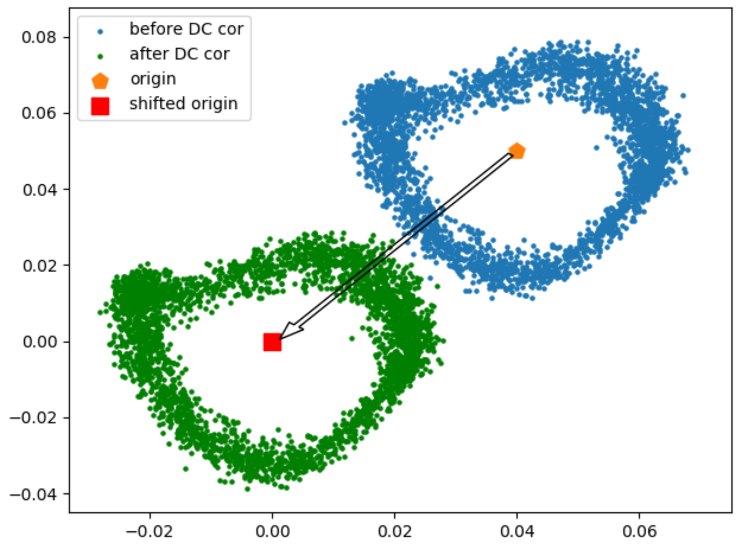

Figure 5. Schematic diagram of DC offset.

3.2. Separation of Breathing and Heartbeat—EMD

Empirical Mode Decomposition (EMD) is a new time-frequency analysis method system based on the intrinsic mode function. It jumps out of the traditional Fourier framework and can be used to deal with non-stationary and nonlinear signals. EMD decomposes an unknown signal into a series of signal components and the sum of a remainder, each signal component is completely obtained through the local time scale of the signal, which makes the empirical mode decomposition (EMD) decomposition highly adaptable [9]; In contrast, such as wavelet analysis, the choice of basis function is selected at the beginning, the wavelet basis may be the best globally, but the local may not be, lack of adaptability.

From **Figure 6** we can see that the original signal is decomposed into components containing various frequency ranges, including respiration and heartbeat curves.

3.3. Multi-Target Monitoring

Millimeter-wave radar can not only measure the target distance, but also measure the target angle according to the arrangement of the receiving antennas. If multi-target health monitoring is to be carried out, some methods proposed by the current research are to detect the target position based on the angle, and cooperate with beam forming technology [10] [11] or beam steering technology [12] to detect the azimuth of each target, and then extract vital signs signals for each target. But these two technologies require multi-transmission and multi-reception radars to obtain multiple sets of data for analysis. The radar used in

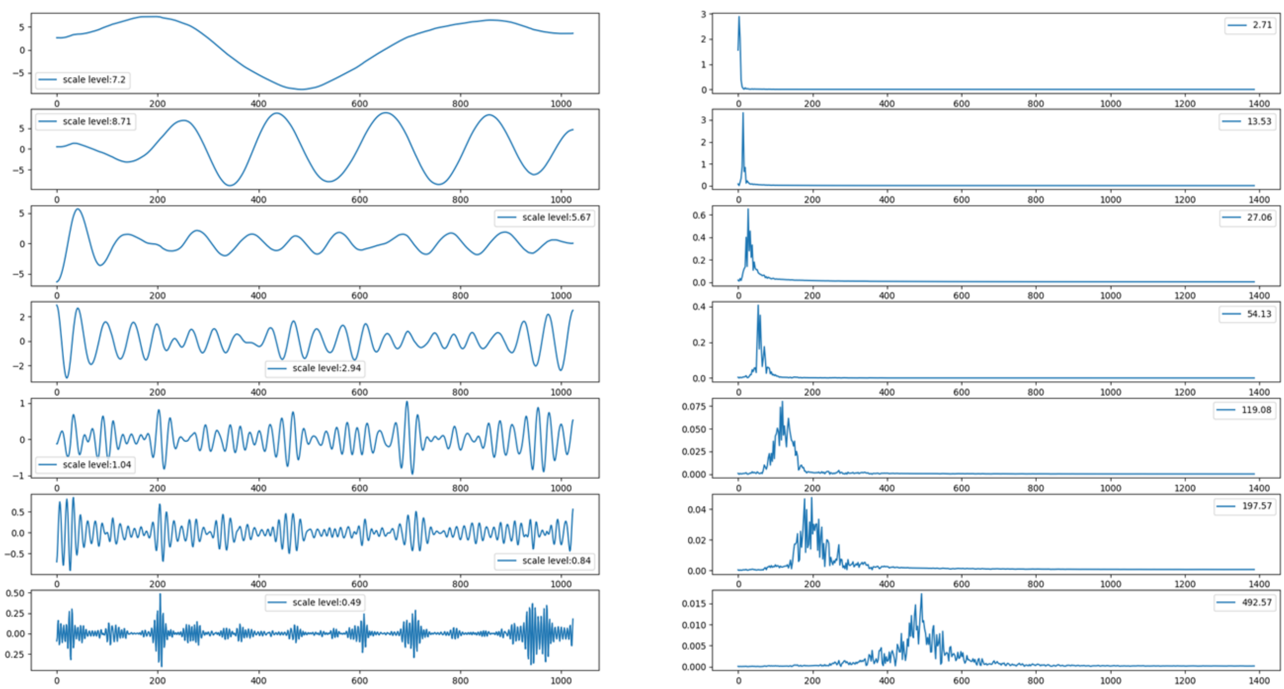

Figure 6. Results of EMD.

the project can only obtain three sets of data with one launch and three receptions, and the receiving antennas are arranged in an L shape. That is to say, the angle detection in the horizontal direction and the vertical direction can only be analyzed based on two sets of data, so we use mathematical methods to improve frequency bandwidth with algorithms. The diagram is shown as **Figure 7**.

Through the above operations, we can easily find the location of multiple targets on the cloud map as shown in **Figure 8**.

4. Experiment and Analyze

Our experimental scene is shown as **Figure 9**. The tested person faces the radar, wears a breathing sensor and a heart rate sensor as a result comparison, and the computer displays the result.

During the experiment of breathing monitoring, a total of 24 test samplings were performed. The sampling distance was 0.3 m~3.1 m, and each sampling time was 1 minute. And we got the breathing rate monitoring result shown as **Figure 10**.

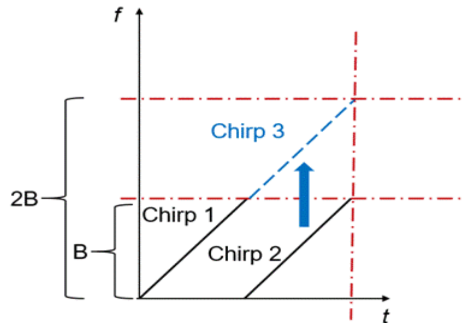

Figure 7. Principle of resolution enhancement algorithm.

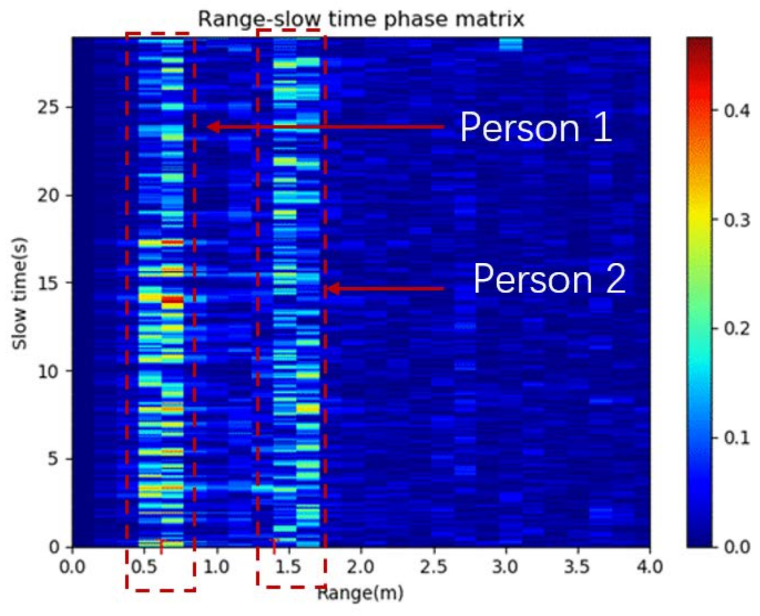

Figure 8. The cloud map of mutliple targets.

In the experiment of heartbeat monitoring, 2 subjects were sampled 30 times at different times of the day. The sampling distance was 0.5 m - 1 m, and each sampling time was 1 minute. The subjects were required to rely on limb movements to adjust the heart rate variation, and the heart rate variation range was about 60 - 90 BMP, which basically covered the static heart rate range of the human body. The heartbeat monitoring result is shown as **Figure 11**.

From the above results, it can be seen that the vital sign signal extraction method proposed in this study can obtain good monitoring accuracy. The heartbeat monitoring error does not exceed 7 bpm, and the respiration monitoring error does not exceed 3 bpm.

5. Conclusions

In this article, we developed an effective and practical multi-target vital sign signal extraction method using a 60 GHz FMCW radar. The overall system includes a

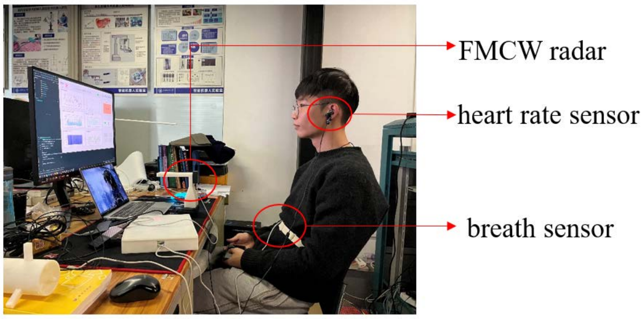

Figure 9. The experimental scene.

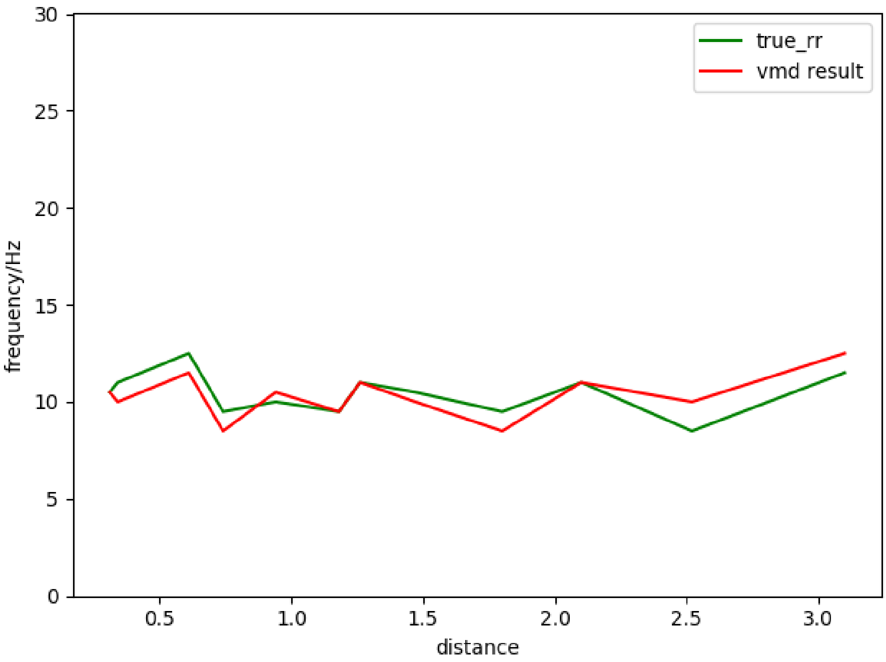

Figure 10. Respiratory monitoring results compared with the true results.

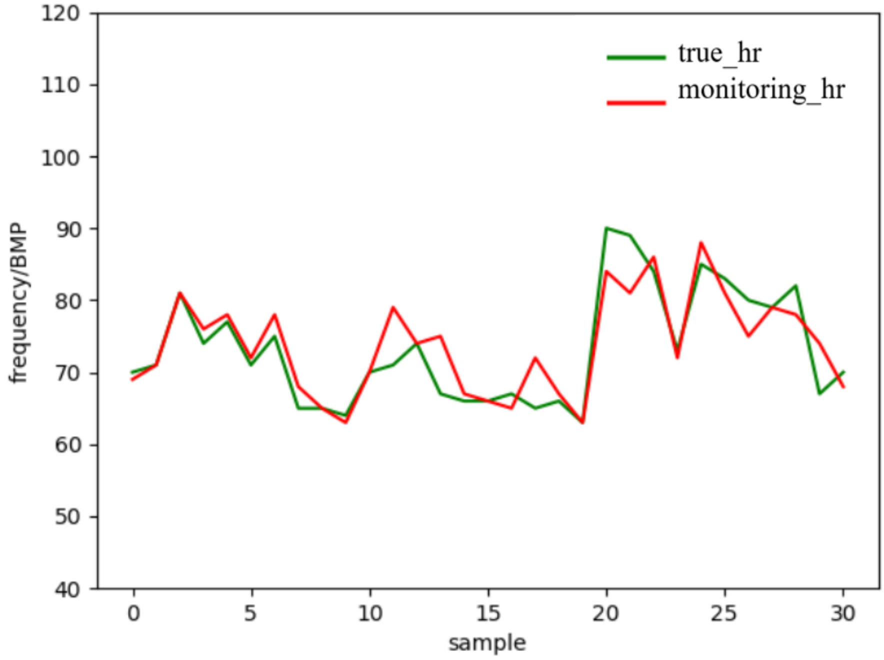

Figure 11. Heartbeat monitoring results compared with the true results.

distance measurement part, a clutter filtering part, and a breathing and heartbeat curve extraction part. We adopt DC offset method to filter the noise clutter in radar data, which is caused by the static objects in the scene. In order to separate the breathing and heartbeat, we develop EMD method to decompose the signal with various frequency ranges. The heartbeat monitoring error range is less than 7 bpm, and the respiration monitoring error range is less than 3 bpm.

In the future, we will improve the stability and robustness of the algorithm. Also, we will use higher power radar to complete more accurate monitoring of weak heartbeat signals.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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