Enhanced Noncontact Vital Signs Detection Method for Slightly Moving Subjects Using Tracks Catching and Parameters Estimation (TCPE)

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Abstract. A novel signal processing method based on track catching and Parameters estimation(TCPE) is proposed to detect the vital signs of slightly moving subjects, which can extract the vital signs of subjects with the influence of Gaussian noise or harmonic interference when the subject is stationary or slightly moving without much body shake. The experiment results show that the proposed method can detect the vital signs of slightly moving subjects with higher accuracy comparing with traditional methods.

1. Introduction
In recent years, the noncontact vital signs detection¹ has drawn more and more attentions. There are two main types of signals used to noncontact vital signs, Ultra-wide band(UWB) and Continuous Wave(CW). Compared to CW radar, the UWB radar has more advantages in vital detection, such as low power, good noise immunity, strong penetrability and so on. Some works have been done in the early time in detecting vital signs by UWB²³. But due to the poor performance of detection accuracy when facing breathing harmonic interference and strong noise, some useful methods are proposed to charge these challenges. However, most of these methods use discrete Fourier transform(DFT) to search the respiration and heartbeat frequencies from the processed signals and DFT may work badly when there are still some residual intervals or when signals are not long enough;

In this paper, we use the parameter estimation method(PE) to extract the vital signs from the processed signal. Besides, considering the fact that the detected subject may slightly move during experiment which will result in incorrectly extracting signals, we propose the tracks catching(TC) method to find these slight movements and eliminate their influence.

This paper is organized as follows. In section 2, the mathematical model for noncontact vital signs detection based on ultra-wideband(UWB) are mentioned. Section 3 explains the novel detection method based on TCPE. In Section 4, the effectiveness of the novel algorithm is validated with experimental results. The conclusions are presented in Section 5.

2. Mathematical model
The distance between the antenna and the human chest can be observed by the periodic variation due to respiration and heartbeat, which is expressed as:

\[ D(t) = D_0 + A \sin(2\pi ft + \phi) \]
\[ d(t) = d_0 + d_r + d_h = d_0 + A_r \sin(2\pi f_r t) + A_h \sin(2\pi f_h t) \]  
(1)

Where \( d_0 \) is the average distance between the antenna and the chest centre, \( A_r \) and \( A_h \) are the chest variation amplitudes resulting from respiration and heartbeat, \( f_r \) and \( f_h \) are the frequencies of the respiration and heartbeat. \( t \) indicates slow-time.

Thus, the change of propagation time delay of reflected signal can be indicated by:

\[ \tau_r(t) = \frac{2d(t)}{v} = \tau_0 + \tau_r \sin(2\pi f_r t) + \tau_h \sin(2\pi f_h t) \]  
(2)

Where \( v \) is the propagation speed of the radar wave, and \( \tau_0, \tau_r, \tau_h \) can be given by \( \tau_0 = \frac{2d_0}{v}, \tau_r = \frac{2A_r}{v}, \tau_h = \frac{2A_h}{v} \).

Then, the received signals by UWB can be defined as:

\[ R[m,n] = r(m\delta_r, nT_s) = a_s(m\delta_r - \tau_r(nT_s)) + \sum_i a_i s(m\delta_r - \tau_i) \]  
(3)

Where \( a_s(m\delta_r - \tau_r(nT_s)) \) represents the reflected signals by detected objects. \( a_r \) and \( \tau_r(t) \) are the amplitude and time delay. \( \sum_i a_i s(m\delta_r - \tau_i) \) is the reflections of background targets. \( a_i \) and \( \tau_i \) indicate the amplitude and time delay of the \( i \)-th static target reflection. \( T_s \) is the pulse repetition time interval, \( t = nT_s, n = 0,1,...,N-1 \), \( \delta_r \) is the sampling interval in fast time, \( m = 0,1,...,M-1 \) represents the fast-time sampling points.

3. Detection algorithms

In this section, the proposed detection algorithms are presented. We can get the respiration and heartbeat frequencies even when the received signals are suffering strong noise interfaces. Firstly, the data should be processed to suppress clutters and noises, such as time mean subtraction, linear trend suppression[4] and the fast-time filtering[5]. Then, we use tracks catching method to get the periodic vital signals. Finally, the parameters estimation method is employed to extract the respiration and heartbeat frequencies.

3.1. Tracks catching

When the detected subject isn’t totally unmoved, the average distance will change and the distance formula (1) will be rewritten as

\[ d(t) = d_0 + d_r + d_h + d_{\text{change}} = d_0 + A_r \sin(2\pi f_r t) + A_h \sin(2\pi f_h t) + m(t) \]  
(4)

Where the \( m(t) \) represents the moving model which defined as

\[ m(t) = \sum_{k=1}^{K} a_1 t^k + d_0 = \sum_{k=0}^{K} a_k t^k \]  
(5)

Where we use K-order polynomial to represent the movement of detection subject. \( d_0 \) is the original distance between antenna and chest.

According to our observations, we find that the variation tendency of the peak position of received impulse signals corresponds with the displacement of the detected subject. To obtain the periodic signals of chest vibration, we can use the peaks of received impulse signals to predict the subject moving model.

we can get one received impulse signal peak position by:

\[ y(n) = \arg \max_u R[n,u], n = 0,1,...,N-1 \]  
(6)

Then, We get the dataset \( \{(i, y(i)), i = 0,1,...,N-1\} \), \( y \) represents the impulse signal peak position. we use this dataset to estimate the moving tracks by:
\[
\hat{a} = \text{arg max}_{a} \sum_{i=0}^{N-1} ||m(i) - y(i)||
\]
(7)

where \(a = [a_0, a_1, \ldots, a_K]\).

After we get the tracks, we can get the periodic vital signals \(\{s[n], n = 0, 1, \ldots, N - 1\}\) by:

\[
s(t) = R\left[\sum_{k=0}^{K} a_k t^k\right], t = 0, 1, \ldots, N - 1
\]
(8)

where \([ ]\) is rounding operation.

The result is shown below. Fig.1.(a) shows the original UWB received signals. In Fig.2.(b), the left picture shows the processed signals and the right picture shows the detected subject moving curve computed by tracks catching method. Fig.2.(c) represents the vital signals extracted by traditional method comparing with the signals extracted by the trace curve in Fig.1.(d).

Fig. 1. (a) the original UWB received signals; (b) the left picture shows the data after processing and the right picture shows the detected subject moving curve computed by tracks catching method; (c) the periodic vital signals extracted by traditional method. (d) the periodic signals extracted by the trace curve.

### 3.2. Parameter estimation method

The periodic signals given by tracks catching can be represented as

\[
x[n] = A \cos(w_n + \varphi) + B \cos(w_n + \phi) + \text{noise}
\]
(10)

Where \(\varphi\) and \(\phi\) are the initial phase of respiration and heartbeat signals, we can rewrite it as:

\[
x[n] = A_r \sin(w_n) + A_{2r} \cos(w_n) + A_{4r} \sin(w_n) + A_{2n} \cos(w_n) + C
\]
(11)
The received signal above by tracks catching method is
\[ s = [s(1), s(2), \ldots, s(n)]^T \] (12)
Then, we can find the matched parameters by solving
\[ \hat{P} = \arg \min_p \sum_{i=1}^n (x[i] - s[i])^2 \] (13)

Where \( P = \{A_{ir}, A_{2r}, A_{1h}, A_{2h}, w_r, w_h, C\} \) represents the parameters. And we can rewrite equation (13) as
\[ [\hat{\theta}, \hat{w}_r, \hat{w}_h] = \arg \min_{\theta, w_r, w_h} \|H\theta - s\| \] (14)

Where
\[
H = \begin{bmatrix}
\sin(w_r) & \cos(w_r) & \sin(w_h) & \cos(w_h) & 1 \\
\sin(2w_r) & \cos(2w_r) & \sin(2w_h) & \cos(2w_h) & 1 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
\sin(nw_r) & \cos(nw_r) & \sin(nw_h) & \cos(nw_h) & 1
\end{bmatrix}
\]
\[ \theta = \begin{bmatrix}
A_{ir} \\
A_{2r} \\
A_{1h} \\
A_{2h} \\
C
\end{bmatrix} \]

We can solve the equation (14) by
\[ \hat{\theta} = (H^T H)^{-1} H^T x \] (15)
\[ g(w_r, w_h) = s^T H (H^T H)^{-1} H^T s \] (16)
\[ \hat{w}_r, \hat{w}_h = \arg \max_{w_r, w_h} g(w_r, w_h) \] (17)

The equation (16) can be called the Frequency-Component (FC) equation which expresses the frequency components existing in the received signals. The equation (17) can be solved by particle swarm optimization (PSO). To simplify the calculation, we can extract the parameter step by step. As is known that the chest vibration amplitude caused by respiration is much more strenuous than that by heartbeat, i.e., \( A_r \gg A_h \), And the FC equation (16) is mainly influenced by the respiration movement. So we can get the respiration rate by the simplified equation:
\[ [\hat{\theta}, \hat{w}_r] = \arg \min_{\theta, w_r} \|H\theta - s\| \] (18)

Where
\[
H = \begin{bmatrix}
\cos(w_r) & \sin(w_r) & 1 \\
\cos(2w_r) & \sin(2w_r) & 1 \\
\vdots & \vdots & \vdots \\
\cos(nw_r) & \sin(nw_r) & 1
\end{bmatrix}
\]
\[ \theta = \begin{bmatrix}
A_{ir} \\
A_{2r} \\
C
\end{bmatrix} \]

But in fact, the received signals may contain the respiration harmonic interferences whose amplitudes might be greater than heartbeat amplitude. Thus the received signals should be presented as:
\[ x(t) = \sum_{i=1}^\infty A_r \cos(iw_r t + \phi_r) + A_h \cos(iw_h t + \phi_h) \] (19)
Thus, before extracting the heartbeat component, we need to eliminate the respiration harmonics influences. We know the amplitudes of respiration harmonics are decreasing and the second, third or fourth respiration harmonic frequencies may be close to the heartbeat. So we just need to consider these respiration harmonics.

Firstly, we solve the equation (18) and get the respiration fundamental component, Then, we compute the $n f^r_r, n = 2, 3, 4$. If $n f^r_r$ lies in the heartbeat frequency region $[0.8 \text{Hz}, 2.5 \text{Hz}]$, we search the $n$th harmonics at the frequency region which we set is $[n f^r_r - n \Delta f_r, n f^r_r + n \Delta f_r, \text{Hz}]$, where $f^r_r$ represents the estimated respiration fundamental frequency, $\Delta f_r$ is the frequency searching scope which we set is $1/60 \text{Hz}$ (i.e., 1 beat/min). Then, we can cut off the $n$th harmonics influences by:

$$x_{\text{new}}(t) = x(t) - (A_n \cdot \cos(i \omega t + \varphi)), \quad i = n$$

Finally, we can search heartbeat frequency at the region $[0.8 \text{Hz}, 2.5 \text{Hz}]$ after eliminating the influences of respiration harmonics.

4. Experiment results
The UWB impulse radar used in this paper for data acquisition was X4M03 made in XETHRU company. Table2 show the details. The centre frequency of the radar is 7.29GHz, the fast sampling rate is 2.916GHz, and the number of fast sampling point is 1536. The slow-time sampling rate is 20Hz, and we use a segment time window of 50s, so the number of slow sampling point is 1000.

![Fig 2. (a)the original matrix with clutter on stationary object. (b)singal processed and the tracks catching result curve.](image1)

![Fig 3. (a) the respiration detection results. (b) the heartbeat detection results.](image2)
The original signals received by UWB are shown in Fig. 2(a). We can see the vital signs are masked by severe intervals. After data processing, the UWB signals are represented in the left side of Fig. 1(b), from which we can find that the detection subject isn’t stationary. The curve which indicates the motion state of the subject is shown in the right side of Fig. 2(b), and we can get the vibration signals after eliminating the influence of the slight movement. By using the Parameters estimate and respiration harmonic suppressing method proposed this paper, we can precisely obtain the respiration rate 0.340Hz and heartbeat rate 1.148Hz which proves better performance comparing with reference DFT method. In Fig. 3, the detection errors are divided three types: 1 beat/min, 2 beats/min and 3 beats/min, and TCPE method achieves higher accuracy in both respiration detection and heartbeat detection.

5. Conclusion
In this paper, a novel vital sign detection method based on tracks catching and parameter Estimate (TCPE) method is proposed this paper. This method can extract the respiration and heartbeat rate precisely when the detection object is slightly moving. Compared with the reference DFT method, our methods can obtain higher accuracy. Further efforts should be made to suppress the random shaking of the detection object, and to improve the robustness when facing more complex and diverse environments.

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