Improved ranging method for life detection using ultra-wide band impulse radar

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Abstract: This study focuses on range estimate for life detection based on the characteristics analysis of life signs by employing the ultra-wideband (UWB) impulse radar. Via analysing the standard deviation of life signs, the time of arrival (TOA) of the pulse from the radar receiver to detection target is estimated based on the calculated energy blocks. Based on the obtained TOA estimates, one area containing life information is determined, which is referred to as region of interest (ROI). Using the signals in ROI, the frequency of human breathing motion is measured more easily and accurately. Different experiments are carried out to test the performance of the new method in through-wall conditions. Results show perfect capability of detection and improving signal-to-noise ratio.

1 Introduction

Recently, researchers developed many efforts for life detection using an ultra-wideband (UWB). Various works have been presented for life detection [1–29]. In targets detection, it mainly contains two parts: time of arrival (TOA) estimate and breathing frequency (BF) estimate. However, most of the developed detection algorithms only focus on clutter suppression or BF accuracy improvement. The distance from targets to radar receiver is usually acquired from a two-dimensional matrix, which causes significant errors. In clutter suppression, many techniques have been presented and validated in different radar systems. In [2], a monitoring system is developed for human health by applying wireless communication and data processing techniques into radar system. An improved differentiate and cross-multiply technique is used to detect mechanical vibration [4]. The results of a quadrature compensation method are analysed and discussed, which can deal with the imbalance problem in radar [5]. An improved system for respiration monitor is proposed based on the hidden Markov model [8]. The curve-let transform technique is used to remove background clutters [9]. In [10], a dual-frequency UWB impulse radar is presented for eliminating the respiration-like clutters using an adaptive clutter cancellation method. The harmonics and intermodulation both heartbeat and breath signals are removed based on the logarithmic method [12]. An improved multiple signal classification method for period estimate is developed [16]. A maximum likelihood period estimator with low complexity for period estimate under additive white Gaussian noise (AWGN) [18]. An automatic detection technique is discussed based on constant false alarm rate [22]. Multiple higher-order cumulant (HOC) is used to suppress AWGN [24]. The phase shift algorithm is used to acquire life information based on the complex signal demodulation (CSD) method [25]. In [27], the state-space model is proposed to detect vital feature. These schemes show better performance in clutter suppression and frequency accuracy improvement. However, they cannot acquire accurate range estimate especially in long range. As a result, extensive efforts are required to be made in vital sign detection.

This paper proposes an improved method for TOA estimate based on the characteristic analysis of life signs. TOA is estimated based on the energy blocks from the analysed standard deviation (SD) of life signs. The corresponding frequency is obtained by adopting life signals from the region of interest (ROI). The contribution of this paper is mainly on the following points.

For removing clutters and improving signal-to-noise ratio (SNR), linear trend suppression (LTS), one effective band-pass filter and two different average extraction filters are used. Further, the autocorrelation operation is performed on eliminating non-periodic noise. TOA is estimated based on the energy blocks of the analysed SD characteristics. BF is estimated using the signals in ROI. A whole new framework for life detection is provided. The performance of the new method is tested based on the detection results in different environments.

The remainder of this paper is organised as follows. In Section 2, the model for life detection is discussed. Section 3 gives the proposed method. The adopted UWB radar is introduced in Section 4. The detection capabilities of the proposed method are validated in Section 5. Section 6 concludes the whole paper.

2 Life detection model

For life detection [28], the range bin is denoted by fast time \( r \), the collected pulse number is denoted by slow time \( t \). Fig. 1 shows TOA of the collected UWB pulse. The distance from target to radar receiver is

\[
d(t) = d_i + m_b \sin(2\pi f_b t) + m_h \sin(2\pi f_h t)
\]

(1)

where \( d_i \) is the distance from the receiver to the centre of human thorax; \( m_b \) and \( m_h \) are the amplitudes of human breathing and heartbeat movements; \( f_b \) and \( f_h \) are the frequencies of human breath and heartbeat.

The collected pulses are

\[
r(t, r) = \sum_i A_i p(t - \tau_i) + A_p p(t - \tau_d(t))
\]

(2)

where \( p(t) \) is the transmitted pulse; \( A_i \) is the amplitude of multipath component; \( \tau_i \) is the time delay; \( A_p \) is the amplitude of the received pulse; and \( \tau_d(t) \) is TOA of the transmitted pulse, which is given by

\[
\tau_d(t) = 2d(t)/c = \tau_0 + \tau_a \sin(2\pi f_a t) + \tau_b \sin(2\pi f_b t)
\]

(3)

where \( \tau_0 = 2d_i/c \), \( \tau_a = 2m_a/c \), and \( \tau_b = 2m_b/c \).

Usually, multipath components can be eliminated based on the background subtraction algorithm. The ideal signals are
The collected pulses are usually stored in digital form, which is given by

\[ R_m, n = r_m, n = mT_s, \tau_n = nT_f = h_m, n + c_m, n + a_m, n + w_m, n + g_m, n \]  

(5)

where the sampling period in slow time and range are \( T_s \) with index \( n = 0, \ldots, N - 1 \) and \( T_f \) with \( m = 0, \ldots, M - 1 \); \( h_m, n \) is the life signs; \( c_m \) is static clutter; \( a_m, n \) is linear trend; \( w_m, n \) is AWGN; and \( g_m, n \) is some unwanted clutter.

### 3 Proposed detection method

The developed method for life detection is analysed in this section.

#### 3.1 Linear trend suppression

The background subtraction algorithm is used to remove static clutter, and we acquire

\[ A = R - \frac{1}{M \times N} \sum_{m=1}^{M} \sum_{n=1}^{N} R[m, n] \]  

(6)

LTS is used to eliminate the linear trend, which is

\[ W = A^T - X(X^T X)^{-1}X^T A^T \]  

(7)

where \( X = [x_1, x_2], x_1 = [0, 1, \ldots, N - 1]^T, \) and \( x_2 = [1, 1, \ldots, 1]_{N \times 1}. \)

#### 3.2 SNR improvement

To improve SNR, one-fifth-order band-pass filter and two averaging filters are developed. The results after applying the band-pass filter are given by

\[ B[m, n] = \alpha_1 W[m, n] + \alpha_2 W[m - 1, n] + \cdots + \alpha_6 W[m - 5, n] - \beta_1 W[m - 1, n] - \cdots - \beta_6 W[m - 5, n] \]  

(8)

where \( \alpha \) and \( \beta \) are filter coefficients.

The first averaging filter is performed on \( B \) in slow time, the results are given by

\[ \tilde{B}[k, n] = \frac{1}{\lambda} \sum_{m=\lambda k}^{\lambda k + 1 - 1} B[m, n] \]  

(9)

where \( k = 1, \ldots, \lfloor M/\lambda \rfloor \), \( \lfloor M/\lambda \rfloor \) is the maximum integer less than \( M/\lambda \).

The second averaging filter is performed on \( \tilde{B} \) in fast time, the results are given by

\[ D[m, k] = \frac{1}{\lambda} \sum_{n=\lambda k}^{\lambda k + 1 - 1} B[m, n] \]  

(10)

where \( k = 1, \ldots, \lfloor N/\lambda \rfloor \), \( \lfloor N/\lambda \rfloor \) is the maximum integer less than \( N/\lambda \).

Further, the autocorrelation is used to eliminate non-periodic noise and acquire the result \( C \).

#### 3.3 TOA estimate

To estimate the distance from target to receiver, we develop a new method based on the acquired energy blocks from SD of life signs in slow time, which is given by [30, 31]

\[ SD[n] = \sqrt{\frac{\sum_{m=1}^{M} (c_m(n) - \mu)^2}{N - 1}} \]  

(11)

where \( \mu \) denotes the mean of \( c_m(n) \).

Based on data obtained indoors at 10 m, the skewness and kurtosis are given in Figs. 2a and b. The area in red ellipse denotes the target area containing life information. It is challenging to extract life signs only depending on the skewness or kurtosis due to clutters in short range with strong amplitude. Fig. 2c shows SD.
considered as $\varphi(\tau)$ with normalised amplitude. The SD values in target area follow a periodic distribution with larger amplitude than that in non-target area. The periodicity in target area can be proved based on the results from fast Fourier transform (FFT) as shown in Fig. 3.

To estimate distance from target to receiver, the SD values are employed. The calculated energy blocks from $\varphi(\tau)$ are given by

$$z[n] = \int_{\varphi \in [T_{b} \times [0 \times T_{f}]} \varphi(\tau)^2 \, d\tau, \quad n = 1, 2, ..., \left\lfloor M \times T_{b}/T_{f} \right\rfloor$$

where $T_{b} \geq T_{f}$ is the integration period, $\lfloor \ldots \rfloor$ denotes maximum integer less than $M \times T_{b}/T_{f}$.

TOA can be estimated as centre of maximum energy block in (12), which is [33]

$$\hat{\tau} = \arg \max_{1 \leq n \leq \lfloor M \times T_{b}/T_{f} \rfloor} \{n | z[n] = 1\} \times T_{b}$$

The range is

$$L = v \times \hat{\tau}/2$$

In this paper, the integration period is considered as 1 ns to validate the developed method. Fig. 4 shows the error is 10 cm (1 ns), 10 cm (2 ns), 35 cm (3 ns), and 20 cm (4 ns).

### 3.4 Frequency estimate

The frequency of human breath movement is usually within 0.2–0.4 Hz [26]. Fig. 5a shows all signals from $C$ in slow time, which indicates life signs are covered by clutters with strong strength and it is challenging to estimate BF. How to choose ROI is the key to estimate BF. The signals within $\epsilon \in [\nu_1, \nu_2]$ which correspond to maximum energy block are considered as ROI as shown in Fig. 5b, which is 30 cm in range. Fig. 5b indicates that the signals in ROI are modulated by life activity obviously. It is more effective to acquire frequency information compared with Fig. 5a.

In our radar system, $4096 \times N$ data are acquired. However, only $60 \times N$ data (named as $\xi$) are used to estimate the frequency of human breathing movement. As a result, the defined ROI area reduces data size and improves SNR, which is the key to achieve life detection in real time. To estimate BF, one window $\kappa$ within 0.1–0.8 Hz is added to remove clutters, which gives

$$\Omega = \text{FFT}(\xi) \otimes \kappa$$
To remove harmonics, the frequency accumulation method is used as

\[ H = \sum_{i=1}^{21} \Omega_i \]  

(16)

The frequency is

\[ f_r = H[\mu_r] \]  

(17)

where \( \mu_r \) is the index of the maximum (16).

### 4 Data acquisition

#### 4.1 UWB radar

The radar used for acquiring data is controlled by a wireless personal digital assistant. The key parameters for this radar are indicated in Table 1. About 4096 sampling points are obtained in range. In slow time, it takes 17.6 s to obtain 512 pulses for one time measurement.

#### 4.2 Experimental setup

To test the range estimate method, different experiments are carried out as shown in Fig. 6.

The first experiment was conducted in Chinese Academy of Sciences. Four volunteers including two boys and two girls served as detection targets at four distances (3, 6, 9, and 11 m). The radar is 1.5 m in height and 48 data are acquired finally.

The second experiment was conducted in China National Fire Equipment Quality Supervision Centre. One male volunteer served as volunteer at four distances (4, 7, 10, and 12 m). The radar is about 1.3 m in height and finally 12 data are acquired.

To further survey the method, an actuator is served as a reference to imitate human breath movement. The vibration frequency is 0.3333 Hz with the amplitude 3 mm. This range is 4, 7, and 10 m in China National Fire Equipment Quality Supervision Centre. Among these experiments, the wall is 1 m in thickness. All volunteers facing radar kept stationary and breathed normally.
Detection performance

5.1 Pre-processing performance

The capability of removing clutters and improving SNR is analysed and discussed in this section based on the data from a girl at 9 m outdoors. Fig. 7a shows the reflected pulses, the result after suppressing the linear trend is shown in Fig. 7b, Fig. 7c shows result after the band-pass filter. Fig. 7d shows the result after performing two averaging filters. Life sign becomes more visible by comparing with Figs. 7a–c.

5.2 Outdoor detection performance

The ability to improve SNR can be analysed and discussed based on the results at different distances [26]. The obtained 48 data are used to show the effectiveness of improving accuracy. Using data obtained from the female volunteer (158 cm, 48 kg), the SD is given in Fig. 8. Fig. 9 shows the energy blocks at different distances. The calculated errors from the developed method are 15 cm (3 m), 30 cm (6 m), 15 cm (9 m), and 25 cm (11 m). The errors are 56 cm (3 m), 26 cm (6 m), 7.71 m (9 m), and 8.1 m (11 m) using FFT method. Forty eight range estimates are shown in
Table 2 based on the proposed algorithm. The presented method can provide high accuracy in range estimate (Table 3). All results indicate the better capability of improving accuracy.

### 5.3 Indoor detection performance

The data obtained from subject V are used to test the proposed algorithm. Fig. 10 shows the skewness, kurtosis, and SD calculated from the data at 10 m. The SD values at four distances are shown in Fig. 11. Fig. 12 shows range estimates based on the presented method. The errors are 10 cm (4 m), 15 cm (7 m), 15 cm (10 m), and 15 cm (12 m). By employing FFT, the errors are 12 cm (4 m), 34 cm (7 m), 7.03 m (10 m), and 10.5 m (12 m). As a result, the presented algorithm shows better performance and effectiveness in range estimate.

### 5.4 Actuator detection performance

The results acquired from actuator based on the presented algorithm are analysed and discussed. Fig. 13 shows the characteristics, and the estimated ranges are shown in Fig. 14 with errors 25, 25, and 25 cm. The ROIs at different distances are given.
in Fig. 15. The pulses are modulated due to the periodic vibrations. Fig. 16 and Table 4 show the rate estimates with deviations 2.49, 2.49, and 2.49%. Compared with results using FFT, the presented method provides higher accuracy in frequency estimate.

6 Conclusion

This paper proposes an improved TOA estimate algorithm for target detection based on the impulse UWB radar. The range between human subject and the radar receiver can be estimated based on the energy blocks calculated from the analysed SD of life signals. Based on the range estimate, the ROI is determined to remove clutters and estimate BF based on the accumulation method in the frequency domain. Results are presented to show the better performance of the presented method in through-wall conditions.

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Table 4  Rate estimates using different methods

| Method | Estimate | 4 m  | 7 m  | 10 m |
|--------|---------|------|------|------|
| proposed | rate, Hz | 0.3416 | 0.3416 | 0.3416 |
|          | deviation, % | 2.49 | 2.49 | 2.49 |
| FFT     | rate, Hz | 0.12 | 0.37 | 0.12 |
|          | deviation, % | 64 | 11.01 | 64 |
| CSD     | rate, Hz | 0.12 | 0.46 | 0.12 |
|          | deviation, % | 64 | 38 | 64 |
| HOC     | rate, Hz | 0.12 | 0.56 | 0.42 |
|          | deviation, % | 64 | 68 | 26 |

Fig. 13  Calculated characteristics at 7 m
(a) Skewness, (b) Kurtosis, (c) Standard deviation

Fig. 14  TOA estimates using data at
(a) 4 m, (b) 7 m, (c) 10 m

Fig. 15  Signals in ROI at
(a) 4 m, (b) 7 m, (c) 10 m
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