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Life Signal Extraction in Through-the-Wall Surveillance

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Abstract—Technology of Through-the-Wall Surveillance (TWS) is explosively developing in recent years and widely interested. This paper proposes the general TWSR system architecture and the whole signal processing units, both of which help researchers to design or improve the system performance conveniently. We also analyze the selection of radar signal and filter, and their influences on the system performance. Finally, our simulation demonstrates that our solution can successfully distinguish the breathing and heartbeat information from the echo signal of one stationary person.

I. Introduction

TWS technology which combines radar and biomedical engineering, emits electromagnetic waves through the wall, and then receives the target echo, as is shown in Fig. 1. After signal processing, we can obtain the information of lives behind the wall, such as breathing, heartbeat, the number of people, and the position, etc. Therefore, TWSR is helpful to military reconnaissance, fire-fighting, monitoring of special patient, and rescue after earthquake, etc due to its non-contact, long-distance and detecting ability.

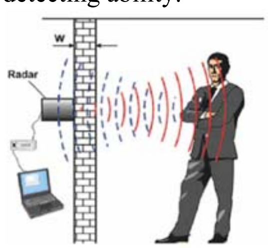

Fig.1 Through-the-wall surveillance

CW-TWSR (Continuous Wave TWS-Radar) and UWB-TWSR (Ultra-Wideband TWSR) are two major kinds of TWSR [1]. The former began in the early 1980s and the later study has been done for over ten years. In 2000, Professor K.M.Chen designed a kind of dual-antenna CW-TWSR which can distinguish breathing and heartbeat successfully. In February 2002, the Federal Communications Commission (FCC) allowed UWB technology to commercial purposes, and then many companies began to research UWB biological radar in various fields. As one of famous hand-held UWB-TWSR, DKLLifeGuardTM played a significant role in the earthquake rescue in Wenchuan, China, 2008.

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In spite of the rapid development, there are still many disadvantages in the traditional TWSR for the further applications in the near future. So we focus on the extensible system design which can accelerate to design or improve a TWSR system. For this purpose, this paper is organized as follows. Section II introduces the two major kinds of TWSR, and analyses their similarities and differences. Section III devises the general modular system architecture. Section IV completes the whole signal processing of TWSR. The simulations on the distinguishment of breathing and heartbeat information are presented in section V. Finally, the main conclusions are summarized in section VI.

II. CW-TWSR & UWB-TWSR

In order to design a general, modular system architecture, first and foremost is to compare the architecture and principle between different TWSRs.

A. CW-TWSR

The traditional CW-TWSR emits continuous wave, and then receives the target echo reflecting the motion information due to micro-Doppler effect.

Assume the radar signal is $s(t)$, and the distance from antennas to target is $r(t)$. They are respectively expressed as

$$\begin{aligned} s(t) &= U_0 \exp(j\omega_0 t) \\ r(t) &= r_0 + \Delta r(t) \quad \Delta r(t) = \Delta_1 \sin(\omega_1 t) + \Delta_2 \sin(\omega_2 t + \phi_2) \end{aligned} \tag{1}$$

where U_0 and ω_0 are amplitude and frequency of radar signal. r_0 is the fixed distance between radar and human body and $\Delta r(t)$ is the tiny body movement. Δ_1 Δ_2 ω_1 ω_2 are the amplitude and frequency of breathing and heartbeat respectively. ϕ_2 is the phase of heartbeat signal related to the breathing. The echo signal at receiver can be written as [2].

$$s_r(t) = \mu U_0 \exp(j\left[\omega_0 t - 2kr(t) - \phi_0\right]) \tag{2}$$

where μ is attenuation factor. k is

$$k = 2\pi / \lambda \tag{3}$$

where λ is radar signal wavelength. ϕ_0 is the change of phase caused by the wall.

After low-pass filter (LPF), we can get the $S_r(t)$ [3].

$$S_r(t) = \mu U_0 \exp(-j\left[2kr(t) + \phi_0\right]) \tag{4}$$

From the expanded form of (4), we can get the different frequency components which are $m_1\omega_1 + m_2\omega_2$, and the filter can help us to extract the useful components.

Equation (1)-(4) show that radar wave is modulated by life signal, and the echo which can be regarded as a phase modulation (PM) signal is demodulated by the mixer and filter.

B. UWB-TWSR

UWB-TWSR and CW-TWSR which are both based on the micro-Doppler effect, have the similar signal transmission process except the radar signal [4].

The echo signal of UWB-TWSR can be considered as a Pulse Phase Modulation (PPM) signal, and finally be demodulated by the correlator and filter [5].

In this study, we assume the target is single, stationary and the TWSR is a single antenna system. Analysis results show that two kinds of radar have the similar phase modulation, filtering system and signal preprocessing system. So we can establish the modular according to the similarities and differences between different TWSRs.

III. ARCHITECTURE OF TWSR

Comparing the architecture of many different TWSRs, and classify the components according to their functions. We can obtain the basic TWSR system architecture, which consists of the signal processing unit, antenna and control system, as are shown in Fig. 2. This paper focuses on the signal processing unit, which consists of the first five blocks as follows.

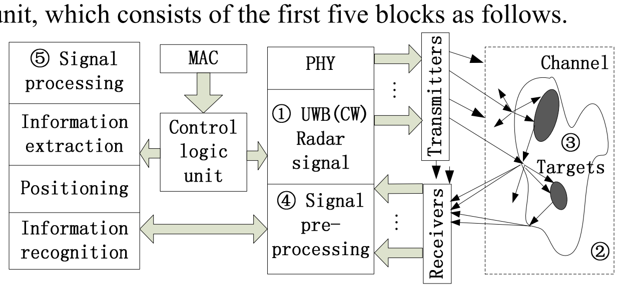


Fig. 2 The basic system architecture of TWDR

1) Designing radar signal.
2) Through-wall channel model.
3) Human reflection model.
4) Received signal preprocessing.
5) Information extraction and recognition.

These blocks can give us the whole signal processing flow which will be shown in next section. Thus system level design will be more convenient.

IV. SIGNAL PROCESSION OF TWSR

According to the signal processing unit and the order of signal flow shown in Fig. 2, we can get the whole signal processing as shown in Fig. 3.

A. Designing Radar Signal

Radar signal design is the first signification block in Fig. 3. It's necessary to balance the resolution and penetrability during choosing radar signal. The measurement results from Hughes Advanced Electromagnetic Technology Center (HAETC) shows that, 1GHz-10GHz is the best TWSR working frequency band, and the lower frequency, the less attenuation [9], [10].

We will analyze the optimal radar signal in terms of performance on distinguishing breathing and heartbeat signal in next section.

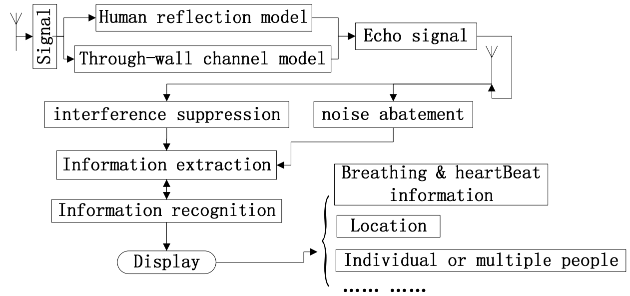


Fig. 3 The basic signal processing flow chart of TWDR.

B. Through-wall Channel Mode

This paper initiatively establishes the through-wall channel model by SEMCAD which can give us the distorted received signal.

C. The Human Reflection Model

TWSR works based on the micro-Doppler effect shown in (2), and the echo can be considered as a phase-modulation signal. Therefore, the human reflection model in any TWSR system is the same [7], [8].

D. Received Signal Preprocessing

As is shown in Fig. 3, the roles of preprocessing are the suppression of interference and noise [11]. In this part, digital filter design is the most effective way, and we will analyze the influence of filter choice on the performance of TWSR in the following section.

With the consideration of the noise and interference, the echo can be rewritten as.

$$s_r'(t) = s_r(t) + I(t) + n(t) \tag{5}$$

where the $s_r(t)$ is shown in (2), $I(t)$ is the reflection signal from the non-target objects, $n(t)$ is the noise. After preprocessing (LPF), we can get the baseband signal $S_r'(t)$ with limited noise and interference.

$$\begin{aligned} S_r'(t) &= S_r(t) + I'(t) + n'(t) \\ &= \mu U_0 \exp(-j(\phi_0 + 2kr_0)) \exp(-2jk\Delta r(t)) + I'(t) + n'(t) \end{aligned} \tag{6}$$

where $S_r(t)$ is shown in (4), $I'(t)$ and $n'(t)$ are noise and interference in baseband.

E. Information Extraction and Recognition

The main work of information extraction is to extract the life signal from the baseband signal after preprocessing, and to select extractable characteristics in life signal. The information recognition mainly estimates the spectrum of life signal, and provides the information of the number, location and physiological parameters of targets [12].

Because the noise and interference are random signals, we use time accumulation and phase compensation algorithm to wipe off the useless baseband components, and correct the frequency offset in this paper.

The signal after time cumulation is (7).

$$S_r''(t)=\sum_{i=1}^{N}S_r'(t)=\sum_{i=1}^{N}S_r(t) \quad (7)$$

where N is the cumulative number of sample points.

The final signal after phase compensation is shown in (8).

$$\hat{S}_r(t)=\frac{1}{2\pi}\int S_r''(\omega)\exp[j(\omega t-\phi)]d\omega$$
$$=\sum_{i=1}^{N}\mu U_0\exp(-2jk\Delta r(t)) \quad (8)$$

where $S_r''(\omega)$ is the spectrum of (7), and ϕ is the estimate of ϕ_0+2kr_0 in (6). Finally, $\hat{S}_r(t)$ is the relatively ideal life signal which can be seen in Fig. 6 (a).

As a whole, the first block determines the performance of TWSR, and the last two blocks play significant roles in signal processing system. The next section, we will focus on the influence of these blocks on the detection result.

V. SIMULATION

The system model in the simulation is based on the CW-TWSR with single antenna, and the frequency of radar is 1GHz. Suppose there is a stationary, single person behind the wall at 0.5 meters, whose breathing and heartbeat frequency are 0.4Hz and 1.2Hz respectively, with a uniform breathing in the environment without strong noise. The whole simulation system works as shown in Fig. 4.

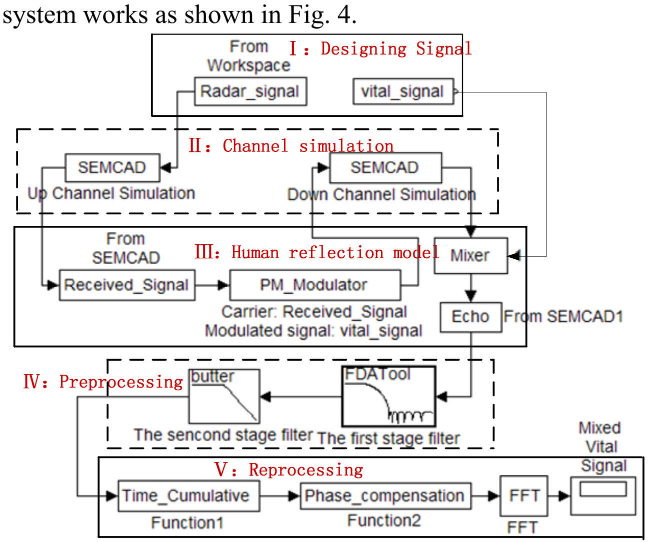
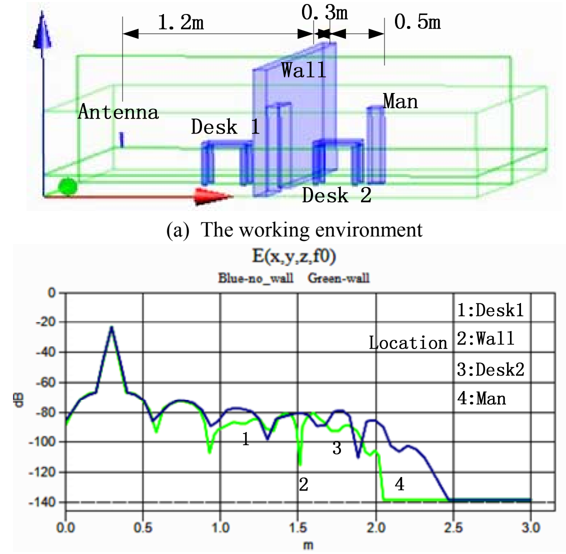


Fig. 4 The simulation system of CW-TWSR based on Matlab 7.0

Fig. 4 includes all the five blocks which are introduced in section IV, and we focus on the second, the fourth and the fifth block.

In the second block, the channel model, which is shown as Fig. 5 (a), is simulated by SEMCAD. It can give us not only the locating information of wall and person, but also the phase offset ϕ_0 in (2) and (6).

Filter design in the fourth block is most important; here we design a two-stage filter. The first stage filter is a four-order Direct-form FIR LPF that can filter out the components whose frequencies are higher than audio frequency, and the second stage filter is an eight-order Bessel LPF which can extract life signals. Fig. 6 compares five kinds of LPF, and shows that Bessel LPF is more effective than others to remove the useless $m_1\omega_1+m_2\omega_2$ components, such as the waves whose frequencies are 1.667Hz, 2.381Hz and 3.095Hz in Fig. 6 (b).



(a) The working environment

(b) Static electric field distribution

Fig. 5 The channel model in SEMCAD

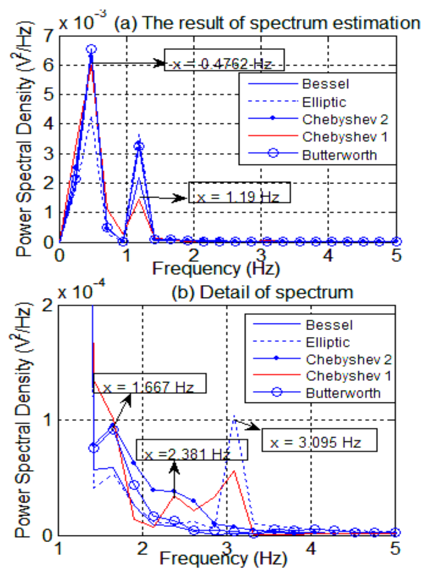


Fig. 6 Five kinds of LPF with cut-off frequency of 30Hz on Matlab 7.0. (a) The result of spectrum estimation. (b) The detail of (a).

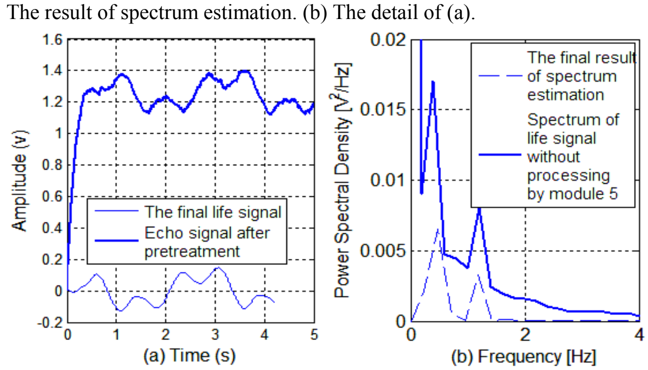


Fig. 7 The echo after two-stage filter and the final signal after time cumulation and phase compensation. (a) The time-domain forms of two signals. (b) The spectrum of (a).

After preprocessing, the information extraction and recognition in the fifth block are simulated by functions in Matlab. Useless baseband signals are wiped off by time cumulative algorithm, and frequency offset can be corrected by phase compensation technique. Fig. 7 illustrates the effecting of these algorithms which are effective, especially during a long simulation time.

Fig. 8 shows the whole signal processing procedure as follows: mixing, two-stage filtering, signal truncation and STFT spectrum estimation. The SNR increases by 15.9021 dB after signal processing. The heartbeat frequency in Fig. 9 (d) can be looked as the same as the measured value. However, the breathing frequency is slightly higher than the measured value since the simulation time is too short, only 5s.

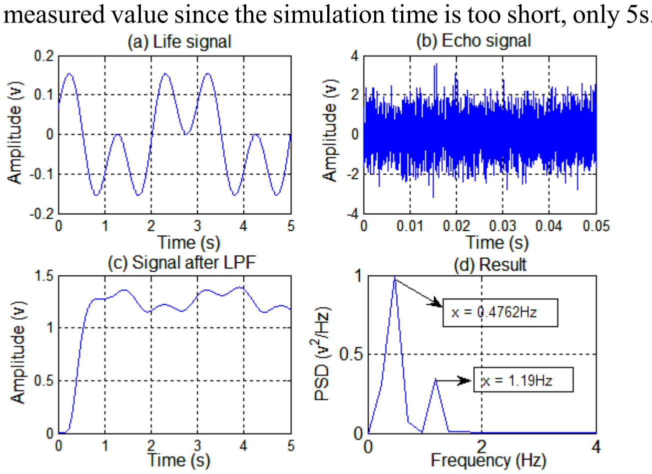


Fig. 8 (a) Simulated life signal in the human body. (b) Echo signal at receiver. (c) The signal after preprocessing. (d) The result of distinguishment of breathing and greathearted information.

Above is the simulation of CW-TWSR where we pay attention to filter design and information extraction algorithm. Now we analyze the relations among the detectable distance, wavelength of radar signal, phase shift, and the spectrum of signal after signal processing.

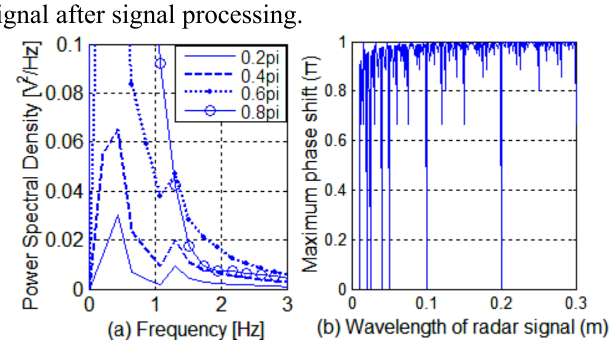


Fig. 9 (a) The influence of phase shift on the spectrum estimation. (b) The change of maximum phase shift by the wavelength of radar signal when the detectable distance range from 10m to 50m.

Fig. 9 (a) shows the influence of phase shift, which is $4\pi r(t)/\lambda$ in (4), on the result of spectrum estimation. When the phase shift is less than 0.6 π, it is easy to distinguish the breathing and heartbeat signals, and the less phase shift is, the easier to be distinguished. Fig. 9 (b) shows the change of maximum phase shift caused by different radar signals when detectable distance range from 10m to 50m. In order to have less phase shift, we observe the radar signals whose wavelengths locate around 0.2m, 0.1m and 0.05m, etc, namely the signals, whose frequencies are around 1.5GHz, 3GHz and 6GHz, are appropriate.

Therefore, based on the analysis this section and the part A of section IV, the optimal radar signal frequency is 1.5GHz or 3GHz or ones in a small range around them. Meanwhile, we observe that distance between the radar and the target influences the signal attenuation and time delay, but not necessarily affect the structure of spectrum.

In conclusion, the choices of radar signal and filters are important to the performance of TWSR. They are the keystones of TWSR design.

VI. Conclusion

Based on the former achievements, we propose the general modular system of TWSR, as well as the whole signal processing unites, both of which help future researchers to design or improve the TWSR performance more conveniently. Meanwhile, we pursuit the appropriate radar signal and filter design, both of which are basic and significant to TWSR systems. Though the whole process of life signal extraction and recognition is complex, the CW-TWSR simulation on Matlab can separate breathing and heartbeat signal successfully according to our solution.

References

[1] Guo Shan-hong, Sun Jin-tao, Xie Ren-hong, Rui Yi-bin. “Technology of Through-the-Wall Surveillance”. Journal of Nanjing University of Science and Technology. Vol. 4, pp. 186-188, 2005.

[2] Luo Jing-zhou, Yi Da-fang. “Discussion on the Mechanism of Vital Sign Detection with CW Radars”. Telecommunication Engineering. Vol. 7, pp. 29-33, 2008.

[3] Anders Host-Madsen, Nicolas Petrochilos, Olga Boric-Lubecke, Victor M.Lubecke, Byung-Kwon Park, Qin Zhou. “Signal Processing Methods for Dopper Radar Heart Rate Monitoring”. Paper for US National Science Foundation. 2007.

[4] Lu Guo-hua. “Experimental study on the technology of recognizing the target inoformation based on bioradar”. Xi’an, China, Fourth Military Medical University, 2005.

[5] Maria-Gabriella Di Benedetto, Guerino Giancola. “Understanding Ultra Wide Band Radio Fundamentals”. Prentice Hall PTR. Upper Saddle River, New Jersey 07458. pp. 241-368, 2004.

[6] Li Shu-wei, Gao Mei-guo, Fu Xiong-jun. “Processing and Simulating of Radar Echo Signal Through Wall for Detecting Life”. ACTA ARMAMENTARII. Vol. 29, pp. 756-758, June, 2008.

[7] Zhang Shi-bing, Zhang Li-jun. “The Modeling and Simulation of UWB Channel”. Journal of Nanjing University of Posts and Telecommunications. Vol. 25, pp. 50-53, Mar, 2005.

[8] Liang Lu-lu. “The study of UWB signal waveform distortion after the signal comes through wall”. China Science and Technology Information. pp. 263-264, June, 2008.

[9] David D Ferris Jr. Nicholas C Currie. “A Survey of Current Technologies for Through- The-Wall Surveillance (TWS)” [A]. SPIE Conference on Sensors, Information, and Training Technologies for Law Enforcement (SPIE Vol: 3577) [C]. Massachusetts: pp.62-72, Boston, 1998.

[10] Zhang Shuang-shi. “The application of pseudo-random code pulse in searching and rescuing UWB radar”. Cheng Du, China, Chengdu University of Technology, 2006.

[11] Zhang Yang. “Research for controlling methods of interference on non-contact life parameter detecting system”. Xi’an, China, Fourth Military Medical University, 2006.

[12] Niu Ben. “Recognition Methods Researching for Life-detection Radar”. Xi’an, China, Xi Dian University, 2006.