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Pulse Modulation Method to Decrease the Blind Zone in Ultra-wideband Pulse Compression Radar Systems

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Abstract. A short penetrating distance is a drawback of traditional ultra wideband radar systems. A pulse compression technique has been used in UWB radar systems to increase the penetrating distance. However, this leads to an increase in the blind zone. The paper proposes a new method to address this issue which uses combined binary phase-coded UWB signals that are pulse-modulated by a pseudo random number (PRN). We demonstrate that this method does not cause an increase in the blind zone as long as the maximum detection range of the short pulses is longer than the minimum detection blind zone of the long pulses. The simulation results show that the theoretical analysis is correct and the proposed method can greatly decrease the radar detection blind zone. Furthermore, we demonstrate the feasibility and superiority of the proposed method in improving the performance of radar detection systems.

Introduction

The UWB opens [1-2] a new spectrum for the radar sensors with high resolution by using the UWB signal. UWB offers a promising solution to achieve fine range resolution and communication applications and high data-rate for radar [3-4] for its huge bandwidth. Applications of the UWB technology were focused on short-range high data-rate communications since the 1990s. Because of its low radiation power, UWB devices with minimal interference are allowed to coexist with current narrow band systems. Therefore, UWB is nowadays widely investigated for many applications with improved performance.

Benefiting of its wide bandwidth, UWB radar is widely used in so many fields. According to the radar theory [5-6], it is well-known that the pulse-compression techniques are widely employed inside of advanced radar systems (e.g., SAR, GPR etc.[6-8]) to increase the range resolution. Whereby the range resolution is inverse proportional with the frequency band of the transmitted signals, in the last period of time, in special literature, a lot of suitable wideband signals (e.g., chirp/LFM, short radio pulse, signals with discrete frequency or phase modulation, unsinusoidal signals etc. [7-11]) were designed and analyzed as processing performance level.

However, a wide bandwidth introduces problems such as serious signal attenuation and reduced detection distance. To increase the detection distance, many researchers use pulse compression technology [12-14] in ultra-wideband radar systems. In cases where the peak value of the transmission power is limited, the pulse transmission is broadened to increase the average power and ensure it is within the operating range [13-14]. At the receiver, a matched filter is used for pulse compression to obtain a narrow pulse signal, which improves the detection capabilities of radar without sacrificing the range resolution. This can effectively solve the trade-off between range resolution and accuracy, while reducing interference reduction and enhancing target detection capabilities [15-16].

Since the time-width of the transmission signal increases as the pulse compression coefficient increases for large time-bandwidth products, the detection blind zone of the radar also increases. In this paper, we use combined pulses as a novel transmission signal to solve this problem. In the remainder of paper, we firstly analyze the problem of the detection blind zone caused by pulse compression. Then, we describe how to generate the UWB combined pulse signals and present the radar system scheme, which is based on UWB combined pulse signals. Finally, we present the simulation and performance analysis.

This paper is organized as follows: In Section 2, the signal reflection and attenuation in various human tissues are discussed including the scattering mechanism of the multilayer biological medium. The time domain system (IR-UWB radar and PN radar) and frequency domain system with the NWA are introduced in Section 3. Section 4 provides the measurement setup of the radar and the comparison of the this system based on the measurement results. Finally in Section 5, some concluding statements and simulation results are given.

The Problem of Detection Blind Zone Caused by Pulse Compression

The radar equation can be expressed as follows [17]:

$$R_{\max}=\left[\frac{P_t G^2\lambda^2\sigma}{(4\pi)^3 kT_e BF(SNR)_{o_{\min}}}\right]^{\frac{1}{4}} \tag{1}$$

where R_{max} is the largest range that can be detected by radar, P_t is the peak transmission power, G denotes the antenna gain, λ is the wavelength corresponding to the center frequency, σ is the target cross-sectional area, $k=1.38\times10^{-23}J/K$ is the Boltzmann constant, T_e denotes the effective noise temperature denoted by K, B denotes the band-width, $F=\frac{(SNR)_i}{(SNR)_o}$ is the noise factor of the radar receiver and $(SNR)_{o_{\min}}$ is the minimum SNR which represents the radar detection threshold.

The pulse compression technique compresses the length of each long pulse from $D\tau$ to τ, meaning the pulse peak power increases by a factor D. Therefore, the maximum range of the radar in a pulse-compressed radar system ($R_{PC_{\max}}$) can be expressed as follows:

$$R_{PC_{\max}}=\left[\frac{DP_t G^2\lambda^2\sigma}{(4\pi)^3 kT_e BF(SNR)_{o_{\min}}}\right]^{\frac{1}{4}} . \tag{2}$$

This shows that the detection range of radar systems increases as the pulse compression coefficient is increased. From formula (2), we observe that the maximum detection range of radar systems is $\sqrt[4]{D}$ times greater than the uncompressed pulse.

The range resolution of radar can generally be expressed by equation (3):

$$\Delta R=\frac{1}{2}c\tau=\frac{c}{2B} \tag{3}$$

In formula (3), c denotes the speed of light, τ and B are the pulse width of the signal and the bandwidth of the signal respectively.

For a pulse signal with a single carrier frequency, $B\tau=1$. However, if pulse compression is used, then $B>>1/T$. The effective pulse width is τ after compression, so $\tau=1/B$. The ratio between the input signal width and the output of the matched filter is the pulse compression coefficient D, which measures the degree that the input and output waveforms have been compressed in time, and can be expressed by equation (4):

$$D=\frac{T}{\tau}=\frac{T}{1/B}=BT , \tag{4}$$

where T denotes the time-width of the input pulse signal of the matched filter, and τ denotes the time-width of the output pulse signal after being filtered by the matched filter. The minimum detection range of traditional pulse radar with a single carrier frequency can be denoted by equation (5):

$$R_{\min} = \Delta R = \frac{c}{2B} = \frac{cT}{2} . \tag{5}$$

The time-width of the transmitted signal after using pulse compression is D times that of the uncompressed transmission signal, and the detection blind zone $R_{PC_{\min}}$ is D times the detection blind zone of a single carrier frequency $R_{\min}$, which can be expressed by formula (6):

$$R_{PC_{\min}} = \frac{cT}{2} = \frac{cD\tau}{2} = DR_{\min} . \tag{6}$$

From formula (6), we observe that the detection blind zone of the radar system increases as the pulse compression coefficient increases. This increase in the detection blind zone reduces the performance of radar systems.

From equation (1), we conclude that the detection blind zone of radar systems after compression is D times that of the uncompressed system. When the detection blind zone of radar exceeds the maximum operating range, the radar system will not detect any signal. So the pulse compression will be meaningful only if the radar detection blind zone is below its maximum detection range, as expressed by equation (7):

$$\frac{Dc}{2B} < \left[\frac{DP_t G^2 \lambda^2 \sigma}{(4\pi)^3 kT_e BF(SNR)_{o_{\min}}} \right]^{\frac{1}{4}} . \tag{7}$$

Equation (7) can be more simply expressed by equation (8):

$$D < \frac{B}{\pi c} \left[\frac{P_t G^2 \lambda^2 \sigma}{4ckT_e BF(SNR)_{o_{\min}}} \right]^{\frac{1}{3}} . \tag{8}$$

Therefore, pulse compression technology not only keeps the original detection accuracy, but also effectively increases the operating range of pulse radar systems. However, since the detection blind zone increases as the pulse compression coefficient D increases, D should meet the requirements of formula (8) in order to guarantee that the pulse compression radar system can detect the target.

This is impossible for an ultra-wideband life-detection radar system with bandwidth 1GHz, pulse compression coefficient 256 and detection blind zone of 38.4m. Therefore, there is a requirement to find a solution to address this issue of the detection blind zone of ultra-wideband systems which use pulse compression technology.

In this paper, we propose a new method to solve the aforementioned problem based on using combined pulse signals as the transmitted waveform. We adopt a matched filter to compress the pulse at the receiver. By ensuring that the maximum detection range of the short pulse is above the blind zone of the long pulse, we successfully use the combined pulses as the transmitted waveform to prevent an increase in the blind zone in radar systems without influencing the detection accuracy.

UWB Combined Pulse Signals

There are many types of pulse compression signals, such as linear frequency modulated (LFM) signals, nonlinear frequency modulated (NLFM) signals, coded signals etc. It can be difficult to design a matched filter due to different pulse lengths. This paper addresses this difficulty by using combined pulse signals as the radar system source, which use binary phase-coded signals modulated by a pseudo-random number (PRN). The sub-pulse signals have the same bandwidth, meaning that pulses of different lengths can be filtered through the same matched filter. We define the coding length of a short pulse as $D_1\tau$, the coding length of a long pulse as $D_2\tau$, and τ is the sub-pulse length. The combined waveforms are shown in Fig 1.

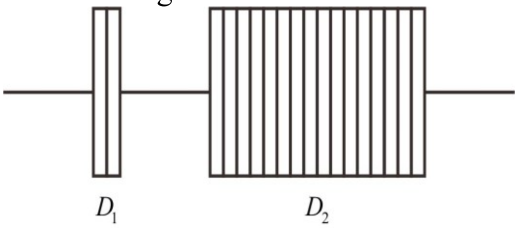

Fig.1 Combined pulse waveforms

Since the long and short pulses are both binary phase-coded signals which are modulated by PRN, they have the same bandwidth and detection accuracy. The time-width of the short pulse and long pulse is reduced by D_1 and D_2 respectively after the echo signals are filtered through the matched filter. According to equation (6), the detection blind zone of the short pulse is

$$R_{PCD_{1\min}} = \frac{D_1 c}{2B} \quad (9)$$

and the detection blind zone of the long pulse is

$$R_{PCD_{2\min}} = \frac{D_2 c}{2B} \quad (10)$$

The maximum operating range of the short pulse can be ensured to be greater than the blind zone caused by the long pulse by using equation (11), which is obtained from formula (2) and (6):

$$\left[\frac{D_1 P_t G^2 \lambda^2 \sigma}{(4\pi)^3 k T_e B F (SNR)_{o_{\min}}}\right]^{\frac{1}{4}} > \frac{D_2 c}{2B} \quad (11)$$

At the receiver, the short pulse signal resolves the large blind zone issue, which is caused by long pulse signals due to a large compression coefficient, as given by formula (11). The blind zone using the combined pulse compression signals can be expressed by equation (12):

$$R_{CPPC_{\min}} = R_{PCD_{1\min}} = \frac{D_1 c}{2B} \quad (12)$$

This blind zone is much smaller than $R_{PCD_{2\min}} = \frac{D_2 c}{2B}$, since it uses pulse compression directly. The combined waveforms can therefore solve the blind zone problem in cases with a large pulse compression coefficient.

Radar System Based on UWB Combined Pulse

The radar system based on UWB combined pulse signals is now described. Fig. 2 shows the schematic diagram of the radar system with combined pulses. In this monostatic system, we use the combined pulses as the transmitting signal source, which includes the short pulse and the long pulse after modulation by pseudorandom sequences. The combined signal is split into the detection signal and the reference signal. Although it is a combined signal, the long pulse and the short pulse are transmitted and received separately. The detection signal is sent to the transmitter system and transmitted by the transmitting antenna. The reference signal is sent to the matching network after a time delay. The echo signal is received by the two receiving antenna. We use a matching network which is matched with the transmitting signal spectrum at the receiver. We separate the long pulse and the short pulse from the echo combined signal. The long pulse performs long-range target detection and the short pulse is used for close-range target detection. Therefore, it is possible to reduce the detection blind area without the loss of detection precision. The signal then undergoes analog-to-digital conversion for real time visualization or off-line processing to detect the human body and 2D imaging.

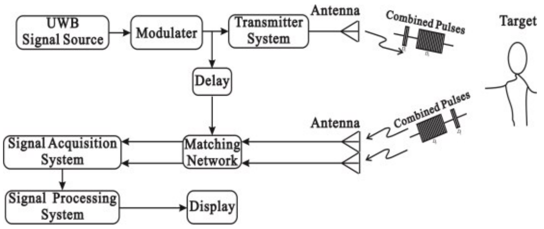

Fig. 2 Principle diagram of radar system with combined pulses

Simulation and Performance Analysis

The pulse sequences of the binary-phase signals modulated by the pseudo random number (PRN) are used for the pulse compression detection signal. The simulation parameters were set as follows: the peak transmission power was 15W, the center frequency was 2GHz, the radar cross section (RCS) was 0.1m2, the signal band-width was 1GHz, the noise reduction was 3dB, the radar loss was 6dB and the radar detection threshold was set to 0dB. Fig. 3 shows the relationship between the pulse compression coefficient and the maximum detection range. It was found that the maximum detection range of radar increases as the pulse compression coefficient is increased. Therefore, pulse compression increases the maximum detection range of radar.

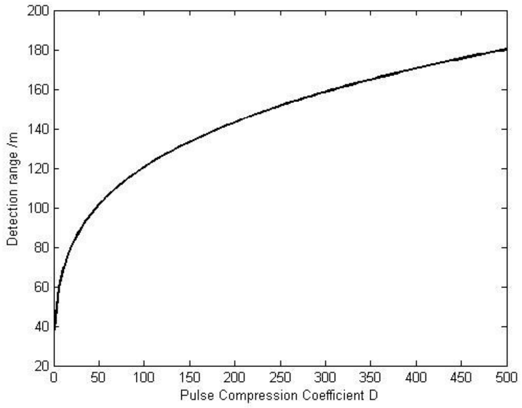

Fig. 3 The relationship between the pulse compression coefficient and the maximum detection range

In Fig. 4, the dotted line indicates the maximum detection distance, the solid line represents the minimum detection range of radar, and the area below the solid line is the detection blind zone of the radar system. Area I denotes the detection zone of the radar based on pulse compression technology. The blind zone range may exceed the maximum detection range when the pulse sequence is too long, which may mean that the pulse compression signals do not detect any signal. Therefore, the pulse compression coefficient of the traditional radar systems should meet the conditions of formula (11) in order to ensure that the radar systems can detect the target.

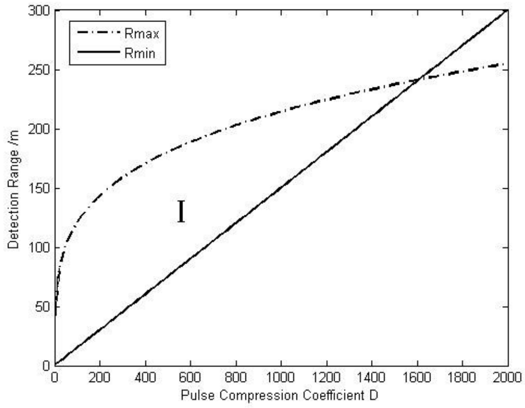

Fig. 4 the variation of the detection range with the pulse compression coefficient, The area I denotes the radar detection zone based on pulse compression technology. The bottom of the curve $R_{\max}$ denotes the blind zone.

Assuming that the encoded length of the short pulse is $D_1\tau$, the encoded length of long pulse is $D_2\tau$, and $D_2 >> D_1$,then in order to eliminate the blind zone of the detection area, the condition $R_{2\min} < R_{1\max}$ must be met. The pulse compression coefficient can be seen in Fig.5 when D_2, D_1 meet equation (11). The abscissa axis shows the pulse compression coefficient of the short pulse D_1 and the ordinate axis shows the pulse compression coefficient of the long pulse D_2 .The area II presents the desirable pulse compression coefficient combination for the short and long pulses required to ensure the radar detection zone.

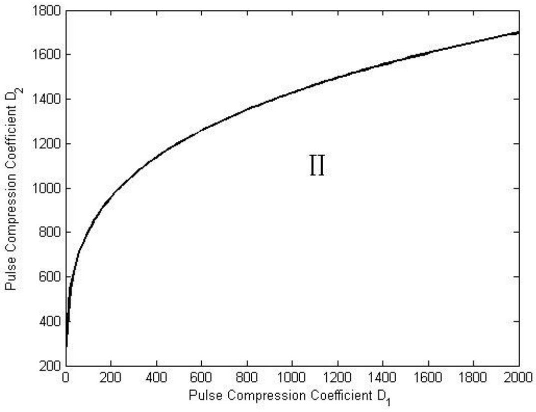

Fig. 5 The range of pulse compression coefficients of the long and short pulses. Area II presents the desirable pulse compression coefficient combination for the short and long pulses required to ensure the radar detection zone.

In Fig. 6, the horizontal axis shows the pulse compression coefficient of the long pulse D , the vertical axis refers to the detection region. Equation (2) $R_{PC\max}$ shows that the maximum detectable range of the pulse combination is similar to conventional pulse compression signals. From Fig.6, we can see that if the longest detection distance of a single short pulse is longer than the shortest blind zone of the long pulse, $R_{CPPC\min}$ of the blind area of the combined pulse waveform of radar system can be maintained at 0.15m, as calculated by equation (12). However, $R_{\min}$ of the blind area of traditional pulse compression methods increases as the pulse compression coefficient increases, as calculated from equation (10), and the blind area can be as great as 38.4m when the pulse compression coefficient is 256.

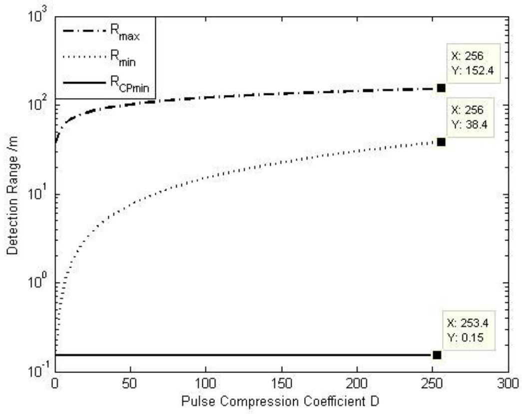

Fig.6 The contrast of blind zone between the combined waveform and the normal waveform. $R_{\max}$ is given by equation (2), $R_{\min}$ is given by equation (10), $R_{CP\min}$ is given by equation (12).

In the following paragraphs, we show a computer simulation result to detect four targets at different distances using combined pulse signals. The width of each code element is 2ns, D_1 is 256 and D_2 is 2048.We set four targets at positions [0.50,0.55,40000,40050] km with SNR of[20,10,20,10] dB. The noise was 3dB in all cases. The echo signal is shown in Fig.7.

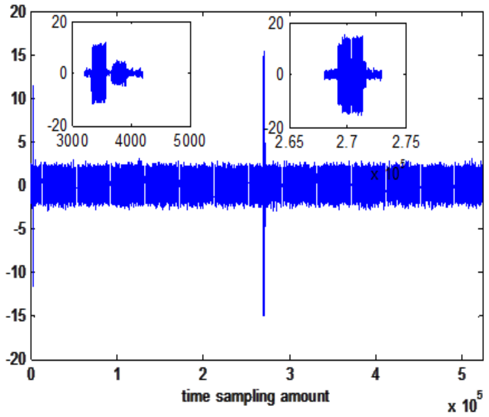

Fig. 7 A sample of the return signal from four targets, which includes the 3dB noise; the figure on the top left is the return sample signal of the short pulse which detected the close range target at [500,550] m, the figure on the top right is the return sample signal of the long pulse which detected the long range target at[40,40.05] km.

The simulation result is shown in Fig8. Four targets were found, including the targets in the range [500,550] m, which verifies that the short pulse can decrease the blind zone. We also conclude that the short pulse has the same range resolution as the long pulse. Therefore, the proposed method can solve the problem of the radar detecting blind zone effectively compared with traditional pulse compression radar.

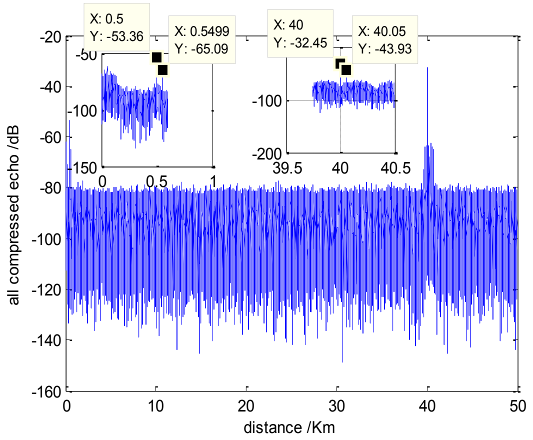

Fig.8 The output result of detecting four targets after the matched filter, the horizontal axis is the detection distance of the combined pulse; the figure on the top left is the correlation response in target detection at [500,550] m, the figure on the top right is the correlation response in target detection at [40,40.05] km.

Results and Conclusions

In this paper, we analyze the problem of the detection blind zone of ultra-wideband radar system based on pulse compression. An equation for the maximum pulse compression coefficient of the effective detection range is obtained for the pulse compression radar system. We conclude that the detection blind zone of pulse compression radar increases as the pulse compression coefficient is increased. In order to solve the problem of the detection blind zone, we presented a detailed analysis of the performance of combined pulse waveforms and then used the combined pulse waveform modulated by pseudo random number as the radar signal emission source. The simulation results show that the proposed scheme is feasible for ultra-wideband pulse compression radar to solve the issue of the detection blind zone by using a combination of pulses. This study has important implications for ultra-wideband radar pulse compression to improve the overall performance, and can further promote the development of ultra-wideband radar technology.

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