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Odd-Symmetry Template Based Three-Step Detector for IR-UWB Radar

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***Abstract*- The detection scheme for robust detection and target location in the presence of interference is presented. The problem of detecting the slow-moving target at noisy background is addressed in this paper. A novel kind of Odd-Symmetry Template Correlation (OSTC) process is developed as the first-step of the detector. The OSTC method has a better performance due to interference suppression than traditional ones. The Range-Extended Constraint and Threshold Feedback technique is proposed as the second-step for detecting range-extended target and controlling the false alarm rate. The Multi-Cycle Fusion method completes the third-step detection procedure, and improves the detection reliability by reducing false alarms. Experimental results are given to demonstrate the efficiency of this approach. Moreover, the effectiveness of this method allows for real-time execution.**

***Index Terms*- IR-UWB radar, range-extended target detection**

I. INTRODUCTION

Recent advances in the demand for search and rescue people in dangerous environments have spurred interest in using Impulse Radio Ultra-wideband (IR-UWB) radar through walls or obstacles to inspect the interiors. Other unique properties of IR-UWB radar are their high resolution, and the potential for simple and real-time implementations.

Investigating the potentials of IR-UWB radar to its desired promise, some challenges of extracting the desired signals from the noisy background must be overcome. The low operating frequencies are required for IR-UWB radar to penetrate the obscuring objects or walls, while wider bandwidth is required for high resolution sufficient to separate target from clutter. Using of bands occupied by other existing systems is necessary, thus making it more sensitive to radio frequency interference (RFI) than other high frequency and narrow-band systems. Previous approaches of RFI and clutter suppression include the adaptive FIR filtering or estimate-and-substrate[1]. These methods perform interference subtraction via the notch filters. Thereafter, all these methods raise the computational cost; suffer the deficiencies of signal distortion and unsuitable for wideband interferences.

Moreover, the influence of increasing range resolution of IR-UWB radar on the detectability of targets with dimensions greater than the resolution cell is studied in[2], the complex optimal detector for (N,K) target is obtained theoretically in[2], but more attentions have been paid to search effective quasi-optimal detectors, i.e., IPCP detector[3], energy detector[4], multichannel rank detector and by-point detector[5]. It was shown that when there are many scatterers, these noncoherent integrators give good performance, but degrades rapidly with the inappropriate choosing of integration time and with less reflecting cells exists. In[4] one detector form was derived by using the scatterer density dependent generalized likelihood ratio test (GLRT), but the spatial distribution of the target is required as a priori.

In this paper, an interference robust Three-Step detection method for range-extended targets is presented. A novel kind of Odd-Symmetry Template Correlation (OSTC) process is proposed as the first-step to suppress the interference and can significantly improve the Signal-to-Clutter ratio after accumulation. The first-step collects the energy of individual scattering point, but still not enough for reliable detection. The successive second-step is to detect the range-extended targets by using Threshold Feed-back adjustment method based on Range-Extended Constraint. It can utilize the target spatial distribution feature and controls the false alarm rate. Multi-Cycle Fusion method is the third step used to further enhance the probability of detection for targets with sufficient range extent and temporal persistence. The effectiveness and superiority of this three-step detection method is validated by simulation and real-time experimental data, respectively.

II. ODD-SYMMETRY TEMPLATE CORRELATION

A. *Odd-Symmetry Template*

Using an appropriate waveform as the receiver template match to the received signal is a vital way for the classic Matched-Filter (MF) method. The peak value after correlation of the known received signal ($s_{re}(t)$,$-T_{re}<t<T_{re}$) and echo ($p_i(t)$) is in (1), $s_{re}(t)$ is also the MF template.

$$P_{\max}(T_i) = \max\left[\int p_i(t) * s_{re}(\tau - t)dt\right] = \begin{cases} S, T_i \ge T_{re} \\ S_{partial}, T_i < T_{re} \end{cases} \quad (1)$$

Where $S_{partial}<S$, If $p_i(t)$,$-T_i<t<T_i$ contains additive white Gaussian noise (AWGN) and $s_{re}(t)$.

However, using the known $s_{re}(t)$ to construct the odd-symmetry template of

$$g(t) = s_{re}(t - \Delta) - s_{re}(-t - \Delta) \quad (2)$$

Δ is the time offset, if choose $\Delta = T_{re}$, the width of $g(t)$ is $-2T_{re} \sim 2T_{re}$, with $g(0)=0$, $g(-t)=-g(t)$. When using $g(t)$ to

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correlate with the radar echo, the peak value of the correlation result is

$$P_{\max}(T_i)=\max\left[\int p_i(t)*\left[s_{re}(\tau-t-\Delta)-s_{re}(t-\tau-\Delta)\right]dt\right]$$
$$=\begin{cases}S^{+}-S^{-}_{partial},T_i>T_{re}\\ S^{+},T_i=T_{re}\\ S^{+}_{partial},T_i<T_{re}\end{cases} \tag{3}$$

Where S^{+}, S^{-} represent the maximum value after correlation contributed by the positive and negative part of the correlation, respectively, $S^{+}_{partial}, S^{-}_{partial}$ is the partial value of S^{+}, S^{-}.

From(3), we can know that $P_{\max}(T_i)$ exists maximum value when $T_i=T_{re}$, while the conventional matched-filter of (2) did not has such pulse width selection properties. If we model the finite length signal as sum of pulse-like signals, the difference between signal and interference lie in its pulse width parameters; then the MF template could not suppress the pulse-like interference, since it is highly correlated with signal. However, OSTC can suppress the RFI by its bipolar property, through choosing Δ according to the signal pulse width, not correlated with the different pulse width of interference. We seek not only to suppress the RFI energy, but also to minimize the effect on the target responses; so that Δ should be chosen in $0<\Delta\leqslant T_{re}$, smaller value of Δ indicates more signal miss-match when correlation, however, larger Δ also incurs aliasing between adjacent echoes.

The bipolar property of the OST offers other benefits than the monopolar MF template: i) OSTC operator has zero output to constant input, successive short pulse interference and white noise: it is a superior noise suppression capability than MF; ii) From (2), we know that OSTC process combines the correlation result by respective using the positive and negative copy of $s_{re}(t)$, provides two times of correlation length than MF.

B. IR-UWB *radar*

Typically, UWB signal has a nonsinusoidal waveform that can change shape during transmission and propagation, thus making the term $s_{re}(t)$ difficult to estimate. MF method, highly depend on the construction of $s_{re}(t)$, did not suitable for the processing of IR-UWB signals. However, the OSTC method is still effective even with $s_{re}(t)$ unknown.

We often approximate UWB pulse signal as second derivative of the Gaussian (Doublet) Pulse[6], as

$$g_2(t)=\frac{A}{t_{au2}}\left[1-4\pi\left(\frac{t}{t_{au2}}\right)^2\right]\exp\left[-2\pi\left(\frac{t}{t_{au2}}\right)^2\right] \tag{4}$$

While, interferences with finite length can be approximated as pulse-like signals, i.e., the wideband interference also can be approximated by (4), only with time parameter t_{au2} different. Narrow band interference (NBI) $I(t)$ often being represented by L sinusoids with amplitudes A_i, phases Φ_i, normalized frequencies ω_i; it also can be written by a series sum of half period sine $p(t)$ with finite length K in time, $p(-t)=p(t)$

$$I(t)=\sum_{i=1}^{L}A_i\sin\left(\omega_i t+\Phi_i\right)=\sum_{i=1}^{L}\sum_{j=1}^{K}A_{i,j}\,p(\omega_i t+j\frac{\pi}{2}+\Phi_i) \tag{5}$$

If $s_{re}(t)$ is unknown, we can use Gaussian Monocycle pulse to approximate the OST, the pulse width parameter t_{au1} can be chosen by the bandwidth of the system, is

$$g_1(t)=A\frac{t}{t_{au1}}\exp\left[-2\pi\left(\frac{t}{t_{au1}}\right)^2\right] \tag{6}$$

When considering the signal and wideband interference, the Odd-Symmetry template correlation result is

$$A(\tau)=\int_{-\infty}^{\infty}g_2(t)g_1(t-\tau)dt=A^{'}\exp\left[-E\tau^2\right]\times\left[-F\tau^3+G\tau\right] \tag{7}$$

Have $a=2\pi/\left(t_{au1}\right)^2$ $b=2\pi/\left(t_{au2}\right)^2$ $d=\sqrt{\pi}(a+b)^{-\frac{3}{2}}$, $A^{'}=A/(t_{au2}t_{au1})$, $E=ab/a+b$, $F=\frac{2a^2b^2d}{\left(a+b\right)^2}$, $G=\frac{3abd}{a+b}$.

The maximum value of (7) is achieved when

$$\tau^2_{\max}=\pm\sqrt{\frac{\left[(2EG+3F)^2/8EF-G\right]}{2EF}}+\frac{\left(2EG+3F\right)}{4EF} \tag{8}$$

$A_{\max}$ reach the maximum value when correlate with the signal($t_{au1}=t_{au2}$), like (3), while obtain lower value with the RFI($t_{au1}\neq t_{au2}$). So, OSTC just like the pulse width selection filter, selects the desired signal with the similar pulse width, while suppresses the wideband RFI with $t_{au1}\neq t_{au2}$.

For the narrowband RFI ($-T\sim T$), with $p(-t)=p(t)$, and the odd-symmetry properties of $g_1(t)$, the OSTC result is

$$A(\tau)=\int_{-T}^{T}I(t)g_1(t-\tau)dt$$
$$=\int_{-T}^{T}\sum_{j=1}^{K}A_{i,j}\,p(\omega_i t+j\frac{\pi}{2}+\Phi_i)g_1(t-\tau)dt=0 \tag{9}$$

MF method could not obtain the result of (9), so it can illustrates the interference suppressing abilities of OSTC method.

Just like Canny transform [7] of edge detection in image processing, the OSTC method also can intensify the edge of the desired signal that can be the indictor of the target present.

III. THREE-STEP DETECTOR FOR IR-UWB RADAR

A. First-step: Odd-Symmetry Template Correlation detector

After sampling, the received signal is $x[n]=s[n]+w[n]+I[n]$, where $s[n]$ is target return signal, $\mathbf{S}=[s[1], s[2],\ldots,s[N]]$, and power is P_S, $w[n]$ is AWGN, $g[n]$ is the OST, with power $4P_S$, and length of M. $I[n]$ is NBI, its covariance matrix is $\mathbf{R}$, with element of $r_{ij}[i,j]$ of

$$r_{ij}[i,j]=\sum_{n=1}^{L}A_i^2/2\bullet\cos\left(\omega_n(t_i-t_j)\right) \tag{10}$$

Then the result of N period accumulation and OSTC process can be shown as

$$T(\mathbf{x})=\sum_{n=0}^{N-1}\left(\sum_{m=0}^{M-1}x[m]g[m]\right) \tag{11}$$

After OSTC, since each individual sample is a random variable and N is large, their sum is Gaussian distribution according to Central Limit Theory; so that we assume the distribution of $T(\mathbf{x})$ after OST correlation is approximate to Gaussian distribution, have $T\sim N(\mathrm{a,b})$. Then we can have

$$E(T;H_0)=E(T;H_1)=E\left(\sum_{n=0}^{N-1}\left(\sum_{m=0}^{M-1}x[m]g[m]\right)\right)=0$$

$$\mathrm{var}(T;H_0)=\mathrm{var}\left(\sum_{n=0}^{N-1}\left(\sum_{m=0}^{M-1}(w[m]+I[m])g[m]\right)\right)$$

$$=N\left[\sigma^2\sum_{m=0}^{M-1}g^2[n]+\mathbf{SRS}^T\right]=4N\sigma^2P_S+N\mathbf{SRS}^T=\varepsilon_1 \quad (12)$$

$$\mathrm{var}(T;H_1)=\mathrm{var}\left(\sum_{n=0}^{N-1}\left(\sum_{m=0}^{M-1}(s[m]+w[m]+I[m])g[m]\right)\right)$$

$$=2NP_S+4N\sigma^2P_S+N\mathbf{SRS}^T=\varepsilon_2+\varepsilon_1$$

The mean and variance obtained in (12) is different from conventional MF method, also leads a different definition of signal to noise ratio (SNR) as

$$SNR=\left(\mathrm{var}(T;H_1)-\mathrm{var}(T;H_0)\right)/\mathrm{var}(T;H_0)=\varepsilon_2/\varepsilon_1 \quad (13)$$

Accumulates the energy in length M, using the logarithm likelihood ratio test (log-LRT), yields the form of

$$Z(\mathbf{y})=\sum_{m=0}^{M-1}T(\mathbf{x})^2>\gamma' \quad (14)$$

It is like the conventional Energy-based method using sliding window with length M to integrate the energy in different range resolutions, where $Z(\mathbf{y})$ approaches the chi-squared distribution χ_M^2, its PDF is in[8]. The false alarm probability is

$$P_{FA}=\int_{\frac{\gamma'}{\varepsilon_1}}^{\infty}\frac{1}{2^{M/2}\Gamma(\frac{M}{2})}x^{\frac{M}{2}-1}\exp\left(-\frac{1}{2}x\right)dx=Q_{\chi_M^2}(\gamma) \quad (15)$$

The detection probability can be written as

$$P_D=\int_{\frac{\gamma'}{\varepsilon_1+\varepsilon_2}}^{\infty}\frac{1}{2^{M/2}\Gamma(\frac{M}{2})}x^{\frac{M}{2}-1}\exp\left(-\frac{1}{2}x\right)dx$$
$$=Q_{\chi_M^2}\left(\frac{\gamma}{\varepsilon_2/\varepsilon_1+1}\right)=Q_{\chi_M^2}\left(\frac{\gamma}{SNR+1}\right) \quad (16)$$

$Q_{\chi_M^2}(x)=\int_x^{\infty}p(t)dt$ is the right-tail probability of a central chi-squared PDF in[8], and $\gamma'/\varepsilon_1=\gamma$ is the threshold.

B. Second step: Range-Extend Constraint and Multi-Cycle Fusion

We effectively suppresses the interference and accumulates the energy in a single scattering point; however, the desired multiple target return is spatially distributed, collecting the energy in different range resolutions of the each target, needs the second-step detection.

With no prior information of scatterer distribution, the range-extended length of target can only be estimated by the physical size[5]. Echoes surpassing the threshold of the first-step detector are used as the input of the second detector, and we can cluster it by its range extend—so multiple target can be determined. Set L_1,L_2 as the minimum and maximum value of the range-extended length. $C(x)$ performs clustering: peak value as the initial group center x_{m1}, the range of adjacent point that surpassing the first threshold is $N_{n1}\sim N_{n2}$. The procedure is shown in (17), x_{mn} is the weighted-center of group, n is the group index, $\mathbf{L}_c$ is the final result and contain all the groups.

$$\begin{aligned}&if\left((N_{n1}-nL_1)<0\|(N_{n2}+nL_1)>N\right)\quad stop\\&else\,\forall i\in(N_{n1}-nL_1,N_{n1}),x_i-x_{mn}<L_1\quad i\in G_n,n=n+1\\&\qquad\forall i\in(N_{n2},N_{n2}+nL_1),x_{mn}-x_i<L_1\quad i\in G_n,n=n+1\end{aligned} \quad (17)$$

Such bifurcate clustering method can resolve multiple target, also reduces the total time of computation. The estimated maximum group number $N(\mathbf{L}_c)_{\max}$ is M_C.

Further, the maximum and minimum value, group number of $\mathbf{L}_c$ can be indicator of the threshold in the first-step. We can adapt the threshold γ according to the logic of

$$\gamma=\begin{cases}\gamma-\Delta,\left(\max(\mathbf{L}_c)>L_2\ \&\ \min(\mathbf{L}_c)>L_1\right)\|N(\mathbf{L}_c)>M_c\\\gamma+\Delta,\min(\mathbf{L}_c)<L_1\ \&\ \max(\mathbf{L}_c)<L_2\\\gamma,otherwise\end{cases} \quad (18)$$

If the detection result of last period indicates more points crossing the threshold, improve the threshold can decrease the false alarm rate, and vice versa. Such iterative procedure eliminate the fluctuation of false alarm rate caused by interference and clutter, also completes the second-step detection by returns the target number and each occupied resolution cells as the input of the final-step detector.

C. Third step: Multi-Cycle Fusion

To even decrease the false alarm rate, we use Multi-Cycle Fusion method as the third-step, it memorizes the resolution cells in which the target are present. After that, the cells in which the signals emerge repeatedly are determined. It utilizes N out M criterion to ensure that the test result with a sufficient persistence and range extent to be declared a target, and return the weighted center as the target's position, and its occupied ranges. The detection probability and false alarm rate is[5]

$$F=\sum_{i=N_P}^{M_P}C_{M_P}^iP_{FA}^i(1-P_{FA})^{M_P-i},D=\sum_{i=N_P}^{M_P}C_{M_P}^iP_D^i(1-P_D)^{M_P-i} \quad (19)$$

P_{FA}, P_D is the false alarm and detection probability in (15),(16).

D. Complete structure of Three-step detector

Complete structure of Three-step detector is shown in Fig. 1

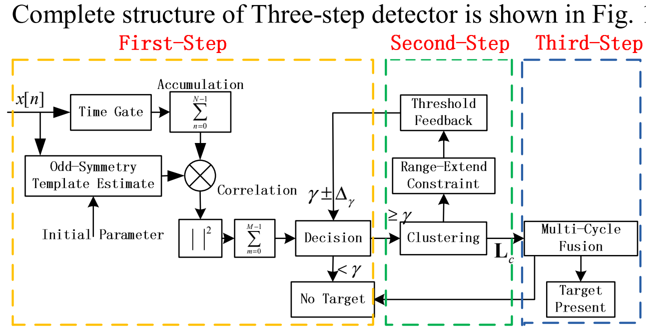


Fig. 1. Complete structure of the three-step detector

The Time Gate above is to select the interested-range. Complete three-step detection contains OSTC, Clustering process, threshold feedback calibration, examine of the Range-Extend Constraint and Multi-Cycle Fusion method. Though three steps involved, it is still suitable for real-time implementation, for its no need of high-computational operation such as adaptive and estimation.

IV. NUMERICAL AND EXPERIMENTAL VALIDATION

A. *Numerical Result*

Fig. 2 shows the performance comparison of the conventional Energy Method (EN), OSTC method, proposed complete three-step method (TS) and Matched-Filter (MF) for its detection probability vs. SNR. We use 10^5 times Monte-Carlo simulation. From Fig. 2, our proposed Three-Step (TS) method is effective for its superior performance than other one-step method in almost all the SNR values.

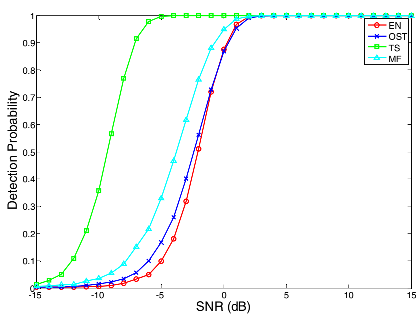
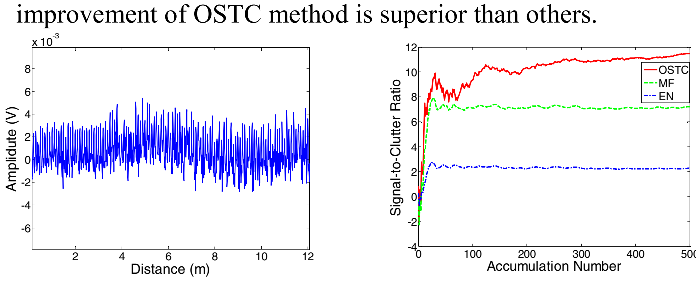


Fig. 2. Detection probability vs. SNR of different detector, false alarm rate: 10^{-3}; In TS, M_P =10, N_P=8.

B. *Experimental validation*

We get two situations of people's backscattering echoes in typical outdoor environment: the low Signal-to-Clutter ratio (SCR) case and multi-person case. The first case has lower transmit peak power 8.5dBm; the single target is 7 meters away from the antenna, system operating band is 1~2GHz. Then SCR improvement after accumulation based on EN, quasi-Matched Filter (using Gaussian second derivative (GSD) template) and our OSTC method were given in Fig. 3(b). The empirical SCR expression is using in [1].

From Fig. 3, since the clutter, narrow band and wide band interference can be partially suppressed by OSTC method, but could not be canceled by accumulation, so the SCR improvement of OSTC method is superior than others.



(a) (b)

Fig. 3 Radar echo (a) and SCR improvement (b) after accumulation of different accumulation number

The second case is the multi-person situation, with transmit power 28.5dBm; three targets are in 4.2, 7.5, 9.1 meters, respectively. The detection result with each target's extended range and weighted-center is shown in Table. 1.

Table. 1 Detection result and estimated position of target by TS and EN method

Method	Target	Start-distance	End-distance	Weighted-center
TS	1	4.2225m	4.3200m	4.2714m
	2	7.3275m	7.7250m	7.5520m
	3	9.0825m	9.4425m	9.2698m
EN	1	7.3800m	7.6200m	7.4977m

The obtained weighted-center can be used as the position estimate of the target. It is shown that TS method is effective, and the detection result is very close to the real situation, three targets can all be detected, while the conventional EN method using sliding window can only resolve one target.

V. CONCLUSION

A three-step scheme for detection of slow-moving and range-extended target in the presence of interference has been developed. The interference and signal can all be modeled as pulse-like signals, with scale parameter as distinction. OSTC method can suppress the interference component and increase the SCR after accumulation. The first step detection combines the OSTC with EN method, and the detection statistic has the chi-square distribution so that the detector threshold is easily calculated for a given probability of false alarm. The following two steps utilize the range extent and temporal persistence of targets to even improve the detection reliability. Finally, the simulation and real measured data validation illustrates the effectiveness of our OST based Three-Step method.

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