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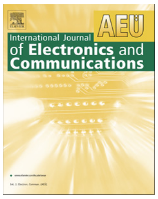

Short communication

Dynamic programming based adaptive step integration method for maneuvering fluctuating target detection

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ABSTRACT

An adaptive long time integration method based on dynamic programming (DP) is proposed for the detection of high speed maneuvering fluctuating targets. The proposed method is aimed at detecting a target with an unpredictable range migration and fluctuating echoes by jointly applying three main ideas: the improved DP procedure that could search the maneuver position and velocity at each frame; the multi-pulse integration that could suppress the influence of fluctuation; and the adaptive step with fading factor that could allow the integration time to be suitable for each searching velocity. Compared with the existing methods, the target energy could be integrated along its trajectory using the proposed method without estimating the specific motion parameters, which makes the proposed method applicable to a target with arbitrary motion. Simulation results and performance comparisons show the superiority of the proposed method.

1. Introduction

Target fluctuation is a common phenomenon in radar target detection [1]. The complex motion and high velocity of a maneuvering target inevitably brings about range migrations, Doppler ambiguities and radar cross section (RCS) fluctuations, which impairs the detection performance of the traditional methods, and could even make them invalid [2]. In this regard, an improved fast Hough transform (FHT) [3] has been proposed, which amounts to a long time integration with range distance compensation. The FHT could successfully detect a target with uniform motion in a straight line, but it is incapable of detecting maneuvering targets with nonlinear displacements. An elliptical Hough transform (EHT) [4] for weak ballistic target detection has been presented. The EHT could detect and track a target with a bent track that follows an elliptical orbit. The limitation of EHT is that the prior information of the exact motion model must be obtained, which is not applicable for other motion models. The generalised Radon-Fourier transform (GRFT) [5] could integrate the energy along the track by compensating the posterior Doppler and range migration with the estimated motion parameters. The Radon-Lv's distribution (RLVD) [6] can remove the range migration via jointly searching along range, velocity and acceleration directions, while eliminating the Doppler spread and achieving the coherent integration via the LVD. The Keystone transform (KT) with generalized dechirp process (GDP) (KTGDP) [7] can first correct the range migration via KT and fold factor searching, and then compensate the Doppler spread via GDP with the acceleration and jerk estimated, finally perform the coherent integration via Fourier transform. However, coherent methods are helpless to the phase fluctuations caused by attitude change, angular glint and complex noise.

A generalized likelihood ratio (GLR) detector has been proposed for detecting a fluctuating target [8], but this method is only suitable for orthogonal frequency division multiplexing (OFDM) radars. A fuzzy clustering [9] method and a truncated quadrature Kalman filtering [10] method could accurately track maneuvering targets, but the prior distribution must be obtained first. DP based track before detect (DP-TBD) [11] method could detect and track weak targets without prior distribution information. An improved DP-TBD method in Ref. [12] introduced a stable factor into the recursion process, which could increase the tracking efficiency. Using the position information of the data of three adjacent frames, an improved DP-TBD method in Ref. [13] performed direction weighting to reduce the energy diffusion, which could increase the integration efficiency. However, TBD methods are usually used in a frame-to-frame scenario, which are not suitable for the long time integration in a pulse-to-pulse scenario. And the DP-TBD methods are not applicable to targets with strong maneuverability.

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The polynomial time series prediction based DP-TBD method [14] could distinguish target from disturbance more effectively without prior knowledge about target motion, but the probability distribution information is necessary. The non-coherent integration and generalized likelihood ratio test based DP-TBD (GLRT-DP-TBD) methods [15] have been proposed for range distributed target detection in compound-Gaussian clutter. The GLRT-DP-TBD method has good performance but it still need the prior or indirectly estimated distribution information. The logarithm of the complex measurement based likelihood ratio based DP-TBD method [16] used the phase information besides the amplitude information, which could significantly improve the detection ability. And the fast implementation remarkably reduced the computational complexity. But when the radar echo is not coherent, the phase information will be useless.

To tackle the above problems, the DP based adaptive step integration (DPAI) method is proposed, which could well handle the fluctuation and maneuver problems without estimating the motion parameters of the target. The proposed method that needs no prior distribution information, could significantly improve the maneuvering target detection performance without change of radar system hardware.

2. System model

Consider that a radar that transmits K pulses with a pulse repetition interval (PRI) T_r to observe a target with a variable radial velocity. Due to the phase fluctuation of a high speed maneuvering target, or the time limitation of the radar coherent processing interval, only the amplitude information is useful. Assume that in the Rayleigh noise, the RCS follows the Swerling II fluctuation model. The echo at time k in cell n is given by

$$z_k(n) = \begin{cases} A_k(n) + w_k(n) & \text{target in cell} \\ w_k(n) & \text{no target in cell} \end{cases} \tag{1}$$

where $A_k(n)$ is the fluctuating amplitude and $w_k(n)$ is the Rayleigh noise. All the measurements in the whole N range cells at frame k are given by $Z_k = [z_k(1), z_k(2), \ldots, z_k(N)]^T$.

In this model, the target speed is high and time-variant, which leads to nonlinear displacements and rapid fluctuations. It is difficult to either estimate the uncertain motion or to compensate the range migration, thus making it difficult to fulfil the detection task with traditional methods.

3. Proposed algorithm

In order to integrate the energy along the protean target trajectory, the idea of the DP method [11] is used to search the current position and velocity of the target. In addition, to allow the integration time to be suitable for each searching velocity, the adaptive step is introduced in the multi-pulse integration process.

Define a target track as a sequence of successive states $X_k = [x_k, \dot{x}_k]^T$ from time 1 to K. A target track is defined as $\boldsymbol{X}_K = \{X_1, X_2, \ldots, X_K\}$. The proposed algorithm is as follows.

3.1. DP based searching procedure

Assume that the maneuvering target produces an uncertain range migration during the observation. From frame $k-1$ to k, using the DP method for position searching and energy accumulation, we have

$$I(X_k) = \max_{X_{k-1}} [I(X_{k-1})]_3 + Z_k \tag{2}$$

$$\Psi(X_k) = \arg\max_{X_{k-1}} [I(X_{k-1})]_3 \tag{3}$$

where $I(\cdot)$ denotes the merit function that stores the integrated energy after the DP searching process, and the expression of $I()$ is amplitude. $\Psi(\cdot)$ denotes the transit function that records the state transition procedure at the current frame. The maximization is performed over the transiting candidates of X_{k-1} for which a transition to X_k is possible.

Since the PRI time is short, it needs more than one pulse for the target to move across one range cell. The state transition from frame $k-1$ to k is obviously one of the three circumstances: moving one cell forward, standing still or moving one cell backward. Therefore, there are three transiting candidates of each state X_k to be maximized, which brings about the subscript of 3.

3.2. Multi-pulse integration

The DP process in (2) amounts to two pulses integration, and to reduce the effects of RCS fluctuations, the following L pulses are utilized. Due to the inertia, the velocity varies slightly between the adjacent PRIs. The step L lies on the pulse number that it takes for the target to stride over one range cell at the maximal velocity $V_{\max}$. L is set to

$$L = \mathrm{round}(\rho / V_{\max} / T_r) \tag{4}$$

where ρ denotes the range cell size and round$(\cdot)$ means fixing to the nearest integer. The recursion run time is revised to $2 \le k \le K\text{–}L$, and then (2) is modified to

$$I(X_k) = \max\nolimits_{X_{k-1}} \left[I(X_{k-1}) + \sum_{l=1}^{L} Z_{k+l} \right]_3 + Z_k \tag{5}$$

3.3. Adaptive step length

Both the improved process (5) and the original (2) could estimate the transition speed but not the moving speed. To estimate the actual target velocity, we use the modified DP method for velocity searching.

Suppose that the maximal velocity of the target is $V_{\max}$. Dividing the possible speed range $[-V_{\max}, V_{\max}]$ into M equal parts, the feasible searching velocities are $\{v_m, m = 1{:}M\}$. The dividing number M rests with the velocity estimation accuracy required. The arithmetic sign of v_m relates to the moving direction of the target, so each candidate v_m corresponds to two possible position transitions. The subscript of max$[\cdot]$ is hence $2M$.

In a multi-pulse integration procedure, a large L is useful for a low speed target but not for a high speed one, and vice versa. Therefore, the adaptive step is introduced according to the variable searching velocity. The adaptive steps are set by

$$L_m = \mathrm{round}\left(\frac{\rho}{v_m T_r} \right), \quad m = 1:M \tag{6}$$

When v_m approaches 0, L_m will approach infinity. To limit the step length in low searching velocity condition, let each searching step be equal or less than twice the length of the step at $V_{\max}$, i.e. the longest step $L_{\max} = \mathrm{round}(2\rho/V_{\max}/T_r)$. The adaptive steps are modified to

$$L_m = \mathrm{round}\left[\min\left(\frac{\rho}{v_m T_r}, L_{\max} \right) \right], \quad m = 1:M \tag{7}$$

A fading factor is introduced to assign weights for the following L_m pulses. The longer the interval time of the following pulse, the smaller the contribution to the integration. So the weighting rule is that the further the separation, the smaller the weight. The fading factor W_m is given by

$$W_m(l) = \left(\frac{L_m - l}{L_m} \right)^{\frac{1}{10}}, \quad l = 1, 2, \ldots, L_m \tag{8}$$