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Adaptive waveform selection for maneuvering target tracking in cognitive radar

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Cognitive radar can adjust the transmitted waveform adaptively to the external dynamic environment for a better target tracking performance than the traditional radar transmitting the fixed waveform. There are two key problems in the tracking system of cognitive radar, which are how to build the transmitted waveform library and how to select the optimal waveform for target tracking in the waveform library. The problem of adaptive waveform selection for maneuvering target tracking is studied in this paper. The factors influencing the target tracking accuracy are analyzed, and the maneuvering target tracking framework in cognitive radar is proposed. Considering that the narrow pulses correspond to good delay but poor Doppler resolution capability and that the long constant-frequency pulses have the opposite behavior, we build a transmitted waveform library consisting of the waveforms with both types of properties using the fractional Fourier transform (FrFT) technique. And the criteria for waveform selection in the control theoretic and information theoretic approaches are discussed in detail. The corresponding solutions of waveform selection in the waveform library are given, respectively. The superior performance of the adaptive waveform over the fixed waveform is illustrated with simulation examples. The simulations demonstrate that the target tracking algorithm is also very important for waveform selection.

1. Introduction

Cognitive radar [1] can choose the working mode, the transmitted waveform, and the signal/data processing algorithm adaptively according to the dynamic of the external environment. It can make the best of varieties of resources to process the received echo intelligently through the closed-loop structure from the receiver to the transmitter [2]. Cognitive radar has the adaptive transmitting and knowledge-aided processing capabilities, which are the main differences from the traditional adaptive radar [3]. It has many potential advantages in the aspects of target detection, tracking and identification, etc. [4]. Hence cognitive radar has been extensively concerned once being proposed [3–6], and it is considered as an important development direction of the intelligent radar. Especially, cognitive radar has injected new intension into the area of transmitted waveform selection. It is a spot that how to adjust the transmitted waveform according to the prior information of the environment and target [7–13]. In this paper, we address the problem of adaptive waveform selection for maneuvering target tracking. And furthermore the priori information is very abundant in the process of target tracking, and it is very propitious for waveform selection. The objective of waveform selection is to attain a better tracking performance by adjusting the transmitted waveform to the target dynamic.

In recent years, adaptive waveform selection for target tracking has obtained much attention [14–25]. There are two approaches in general as follows:

The first one is finding the optimal waveform directly from the radar measurement point of view. The final tracking performance depends on two factors, the one is the prediction accuracy of target motion, and the other is the radar measurement accuracy [13]. The later is closely related to the transmitted waveform. So if the measurement accuracy is improved by choosing the waveform, the better tracking performance can be obtained correspondingly. The constant amplitude zero auto correlation (CAZAC) sequence is used for target tracking in [14], since the ambiguity function shape of the CAZAC sequence approaches to a drawing pin. It is known that the waveform whose ambiguity function peak is pointed has a good performance for estimating the target range and velocity [15]. However, the Doppler tolerance of this type of waveform is

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very poor. In this case it is hard to detect the moving target, even by the compensation of the target velocity with the minor error.

The other approach to select waveform is searching the optimal transmitted parameters based on some target tracking algorithms. The criteria for waveform selection can be categorized into two types: the control theoretic method [16] and the information theoretic method [9]. They are different in the waveform-dependent cost function. The strategy in the control theoretic method is to select the waveform by minimizing mean square error (MMSE), such as the trace of the tracking error covariance [17]. Kershaw and Evans [18] have firstly added the block of adaptive waveform selection to the traditional radar tracking system, and built the relationship between the transmitted waveform and tracking algorithm by replacing the measurement noise covariance with the inverse matrix of the Fisher information matrix. The tracking performance is optimized by waveform selection based on the Kalman filtering framework. The problems of adaptive waveform selection based on the nonlinear tracking algorithms are also studied, such as unscented Kalman filter (UKF) [19], cubature Kalman filter (CKF) [20] and particle filter [21]. In the information theoretic method, the criterion for waveform selection is maximizing the mutual information (MMI) between the target features and the corresponding radar measurement [22,23]. Niu and Willett [24] have discussed the relationship between the target maneuvering index and the sweeping frequency rate of the linear frequency modulation (LFM) signal. It is demonstrated that the predicted error ellipse should be orthogonal to the measurement error ellipse when the sweeping frequency rate is optimal. Savage and Moran [25] have rotated the ambiguity function of the waveform by the fractional Fourier transform (FrFT) to make the measurement error ellipse orthogonal to the predicted error ellipse based on the interacting multiple model (IMM) algorithm. This method has indicated the condition of minimizing the tracking error, and it has an explicit physical meaning. However, there is not the report about the theoretic analysis of this method. And the relationship between the control theoretic approach and the information theoretic approach is not clear.

In this paper, we analyze the factors determining the target tracking accuracy, and propose a maneuvering target tracking framework in cognitive radar. Based on the IMM algorithm, a method of adaptive waveform selection for maneuvering target tracking is proposed. The major contributions of this work are twofold:

(1) The transmitted waveform library: Considering that the constant-frequency (CF) signal corresponds to a good Doppler resolution but poor delay resolution capability and that the narrow pulse has the opposite resolution capability, we build a rotation waveform library consisting of the waveforms with both types of capabilities by the FrFT technique. The waveforms in the library are conducive to engineering implementation, and their measurement capabilities are easy to depict.

(2) The criteria for waveform selection: We use the criteria of MMSE and MMI to select the waveform for maneuvering target tracking in the rotation waveform library, respectively. The corresponding solutions of waveform selection are given. The equivalent relationship between the MMSE and MMI criteria is discussed in detail, and some applied cost functions are proposed.

The rest of the paper is organized as follows. In Section 2, the target dynamic model and the radar measurement model are introduced. A method of adaptive waveform selection for maneuvering target tracking is proposed in Section 3, which focus on the transmitted waveform library and the criteria for waveform selection. The simulations are presented in Section 4 to show the effectiveness of the proposed method, followed by concluding remarks in Section 5. The mathematical derivations of some equations are detailed in Appendix A and Appendix B.

2. System model description

It is known that there are two main factors influencing the target tracking performance. One is the prediction accuracy of target motion, which is defined by the dynamic model and the tracking algorithm [26]. And the other is the radar measurement accuracy, which is dependent on the signal-to-noise ratio (SNR) in the receiver and the delay and Doppler resolution capabilities of the transmitted waveform [13].

2.1. Target dynamic model

Without loss of generality, the one-dimensional tracking scenario is considered. The target model is a discrete-time dynamic motion model of the form

$$\mathbf{x}_{k+1} = \mathbf{F}_{k+1|k}\mathbf{x}_k + \mathbf{w}_k \tag{1}$$

where $\mathbf{x}_k$ is the target state vector at time $k = 1, 2, \ldots$. Here we employ two models for the target motion, i.e. the constant-velocity (CV) model with a low level of noise covariance corresponds to the target non-maneuvering motion and the constant-acceleration (CA) model with a high level of noise covariance corresponds to the target maneuvering motion. $\mathbf{x}_k = [r_k\ \dot{r}_k]^{\mathrm{T}}$ in the CV model, and $\mathbf{x}_k = [r_k\ \dot{r}_k\ \ddot{r}_k]^{\mathrm{T}}$ in the CA model, where r_k, $\dot{r}_k$ and $\ddot{r}_k$ denote the target range, velocity and acceleration, respectively. $\mathbf{w}_k$ represents the process noise of target motion, an additive Gaussian noise vector with a covariance matrix $\mathbf{Q}_k = E(\mathbf{w}_k\mathbf{w}_k^{\mathrm{T}})$. The corresponding state transformation matrix $\mathbf{F}_{k+1|k}$ and the process noise covariance matrix $\mathbf{Q}_k$ in the CV model are as follows:

$$\mathbf{F}^{(1)}_{k+1|k} = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix}, \qquad \mathbf{Q}^{(1)}_k = q_v \begin{bmatrix} \Delta t^3/3 & \Delta t^2/2 \\ \Delta t^2/2 & \Delta t \end{bmatrix} \tag{2}$$

where the superscript "1" denotes the CV model, Δt is the sampling interval, and q_v is the process noise intensity and controls the size of the deviations of the predicted velocity from the actual one. The matrices $\mathbf{F}_{k+1|k}$ and $\mathbf{Q}_k$ in the CA model are given by

$$\mathbf{F}^{(2)}_{k+1|k} = \begin{bmatrix} 1 & \Delta t & \Delta t^2/2 \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix},$$

$$\mathbf{Q}^{(2)}_k = q_w \cdot \begin{bmatrix} \Delta t^5/20 & \Delta t^4/8 & \Delta t^3/6 \\ \Delta t^4/8 & \Delta t^3/3 & \Delta t^2/2 \\ \Delta t^3/6 & \Delta t^2/2 & \Delta t \end{bmatrix} \tag{3}$$

where the superscript "2" denotes the CA model, q_w corresponds to the level of target maneuver and controls the size of the deviations of the predicted acceleration from the actual one.

2.2. Radar measurement model

The radar observation equation at time k is given by

$$\mathbf{z}_k = \mathbf{H}\mathbf{x}_k + \mathbf{v}_k \tag{4}$$

where $\mathbf{z}_k$ is the two-dimensional measurement vector of target state, consisting of the target range and velocity. $\mathbf{H}$ is the measurement matrix, and its forms are

$$\mathbf{H}^{(1)} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \qquad \mathbf{H}^{(2)} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \tag{5}$$

in the CV model and CA model, respectively. $\mathbf{v}_k$ represents the measurement error with its covariance matrix $\mathbf{R}_k$, which is dependent on the SNR and the transmitted waveform. We let the matrix

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