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An interacting Fuzzy-Fading-Memory-based Augmented Kalman Filtering method for maneuvering target tracking

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ABSTRACT

In this paper, the interaction and combination of Fuzzy Fading Memory (FFM) technique and Augmented Kalman Filtering (AUKF) method are presented for the state estimation of non-linear dynamic systems in presence of maneuver. It is shown that the AUKF method in conjunction with the FFM technique (FFM-AUKF) can estimate the target states appropriately since the FFM tunes the covariance matrix of the AUKF method in presence of unknown target accelerations by using a fuzzy system. In addition, the benefits of both FFM technique and AUKF method are employed in the scheme of well-known Interacting Multiple Model (IMM) algorithm. The proposed Fuzzy IMM (FIMM) algorithm does not need the predefinition and adjustment of sub-filters with respect to the target maneuver and reduces the number of required sub-filters to cover the wide range of unknown target accelerations. The Monte Carlo simulation analysis shows the effectiveness of the above-mentioned methods in maneuvering target tracking.

1. Introduction

Standard Kalman Filtering (SKF) methods such as Linear Kalman Filter (LKF) and Extended Kalman Filter (EKF) produce reasonable results for tracking non-maneuvering targets, but they may not yield desirable accuracy in presence of maneuver [1–3]. There are two main approaches to handle this problem [3]: the Input Estimation (IE) approach and the Multiple Model (MM) approach.

1.1. The Input Estimation approach

The IE approach was developed to improve the estimation accuracy of the SKF methods in presence of unknown target accelerations [4]. One method that simultaneously combines the benefits of both SKF method and IE approach is a SKF-based target tracker with IE approach [5]. This method changes the maneuvering target model to the non-maneuvering one by using a state augmentation technique to create the standard Bayesian model. By applying the LKF or EKF to this model, one yields an Augmented Kalman Filtering (AUKF) method, which can estimate the unknown target acceleration along with the original target states. The AUKF method eliminates the need for a separate maneuver detector system and provides better performance with respect to the LKF or EKF in tracking non-maneuvering and low maneuvering targets.

However, the AUKF cannot produce acceptable state estimation in presence of high maneuvers due to the poor modeling of target acceleration dynamics [6,7]. To cope with this problem, several methods have been proposed in recent years with varying degrees of success [7–13]. Unfortunately, most of these techniques have some major problems. The fading memory factor proposed in [8] and forgetting factor proposed in [9] are determined off-line and remained unvarying during the operation, so the performance of these methods is obviously degraded with the changes of target acceleration. To deal with this trouble, a soft computing approach has been proposed in [10,11], which resets the covariance matrix at each sampling time based on the values of target acceleration. However, due to the deficiency of its maneuver detector system, this method has not increased the performance of AUKF method effectively. In [12], the authors tried to handle this dilemma by proposing an intelligent approach based on the fuzzy logic for covariance matrix resetting. Unfortunately, the fuzzy system used in this approach is not accurate enough. Among the above-mentioned methods, the Fuzzy Fading Memory (FFM) technique [13] is reasonably successful. During the maneuver, the FFM technique corrects the covariance matrix using a suitable fuzzy system. This modification enables the filtering algorithm to produce reasonable state estimation in presence of unknown target accelerations.

In this paper, by choosing the EKF as the filtering algorithm, it is shown that the FFM-based AUKF (FFM-AUKF) method yields more accurate results than the standard EKF and AUKF methods for the state estimation of non-linear dynamic systems in presence of maneuver.

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1.2. The Multiple Model approach

The second approach to overcome the shortcoming of the SKF methods during the maneuver includes the MM algorithms. These approaches have been developed because a single model cannot specify the behavior of a moving target completely. Among different MM approaches [14–16], the Interacting Multiple Model (IMM) algorithm provides an excellent compromise between computational burden and performance [17]. This algorithm has been utilized to solve many important problems including tactical ballistic missile tracking [18], underwater target tracking [19], traffic forecasts [20], and ground target tracking [21].

The IMM algorithm includes a bank of sub-filters such as LKF or EKF [22] so that each sub-filter can individually estimate the target states. The major prerequisite of this algorithm is that at least one sub-filter should match the real target state at each sampling instant [23]. On the other hand, the estimation error produced by one sub-filter should be as small as possible at each time step, otherwise the IMM algorithm may diverge and the estimation error of this algorithm goes beyond the limit of acceptability. This limitation is due to the inaccurate sub-filters state estimation, which implies the choice of imprecise filtering methods [24].

Motivated by the above observations, this paper proposes a novel Fuzzy IMM (FIMM) algorithm for the combination of FFM technique and AUKF method. In this algorithm, the standard EKF method used by the sub-filters of the conventional IMM algorithm [25] is replaced by the AUKF method. This change improves the tracking accuracy of IMM algorithm in tracking non-maneuvering and low maneuvering targets. Afterward, the covariance matrix of all sub-filters is modified at each time step according to the amount of target acceleration using the FFM technique. As a result, the proposed FIMM can effectively deal with the target maneuver and reduces the number of required sub-filters to cover the wide range of unknown target accelerations. In addition, the proposed method yields more accurate results than conventional IMM algorithms with a large number of sub-filters. The Monte Carlo analysis demonstrates the effectiveness of the FFM-AUKF and FIMM methods for the state estimation of non-linear dynamic systems in presence of maneuver.

2. Problem statement

This paper deals with the state estimation of systems with non-linear dynamics. Most target tracking methods have been developed based on the mathematical models. The model considered in this article has the following discrete state-space equation with additive noise [26]:

$$X(k+1) = f\big(X(k), k\big) + w(k)$$
$$z(k) = h\big(X(k), k\big) + v(k) \tag{1}$$

where the (possibly non-linear) functions $f(.)$ and $h(.)$ are system transition and measurement functions, respectively. In this model, $X(.)$ and $z(.)$ are the state and the observation vectors. The initial state $X(0)$ is assumed to be a Gaussian random variable with $E\{X(0)X^T(0)\} = \psi$ and $E\{X(0)\} = 0$. The measurement noise $v(.)$ and the process noise $w(.)$ are mutually uncorrelated zero-mean white Gaussian processes with covariance matrices R and Q, respectively.

$$E\big\{v(k_1)v^T(k_2)\big\} = R(k_1)\delta(k_1 - k_2)$$
$$E\big\{w(k_1)w^T(k_2)\big\} = Q(k_1)\delta(k_1 - k_2)$$
$$E\big\{w(k)\big\} = E\big\{v(k)\big\} = 0 \quad \text{for all } k$$

where the signs T and δ represent the transpose and Kronecker delta function. In the non-maneuvering mode, the state vector of a moving target in a two-dimensional plane at time step k is:

$$X(k) = \big[x(k)v_x(k)y(k)v_y(k)\big]^T \tag{2}$$

where $x(k)$, $v_x(k)$ and $y(k)$, $v_y(k)$ are target positions and velocities in x and y directions, respectively. In presence of maneuver, a new term is added to (1) and modifies this model as follows:

$$X(k+1) = f\big(X(k), u(k), k\big) + w(k)$$
$$z(k) = h\big(X(k), k\big) + v(k) \tag{3}$$

where $u(k)$ denotes the unknown target acceleration, which is shown by the following vector:

$$u(k) = \big[u_x(k)u_y(k)\big]^T \tag{4}$$

The linear counterpart of model (3) has the following set of equations [26]:

$$X(k+1) = F(k)X(k) + C(k)u(k) + G(k)w(k)$$
$$z(k) = H(k)X(k) + v(k) \tag{5}$$

At time step k, $F(k)$, $C(k)$, and $G(k)$ are the Jacobian matrices of the partial derivatives of f with respect to X, u, and w, respectively, and $H(k)$ is the Jacobian matrix of the partial derivatives of h with respect to X.

3. Fuzzy Fading Memory technique

Tracking a maneuvering target is difficult due to the uncertainty of unknown acceleration vector in Eq. (3). To solve this problem, Khaloozadeh and Karsaz have proposed a new scheme based on the combination of Bayesian and Fisher uncertainty models [5]. This so-called AUKF method provides better tracking accuracy in comparison with the SKF methods such as LKF and EKF in tracking non-maneuvering and low maneuvering targets. Unfortunately, the AUKF method cannot produce desirable performance in presence of high maneuvers. This problem is due to the limitation of this estimator to model the target acceleration dynamics correctly and completely, which causes the covariance matrix ($\hat{P}_{Aug}(n \mid n)$) becomes small after a few iterations. In recent years, several techniques have been proposed to deal with this trouble [7–13]. Among them, the fading memory method [9] is noteworthy because of its efficiency and easy implementation. This method uses the fading memory factor (α, $\alpha \geqslant 1$) to correct the covariance matrix in the filtering algorithm. Unfortunately, this factor is determined off-line so that it stays constant during the process. This dilemma leads to the over fading information in non-maneuvering mode or imperfect compensation in presence of maneuver. To solve this problem, a FFM technique has been proposed by Bahari et al. [13], which modifies the covariance matrix with respect to the amount of target acceleration in each iteration. During the maneuver, this technique aids the AUKF method to estimate the unknown target acceleration suitably.

In this section, the FFM-AUKF method is presented for the state estimation of non-linear system (3), where the EKF has been chosen as the filtering algorithm. In this method, the maneuvering model (3) is converted to a non-maneuvering model to construct a standard Bayesian model. In this method, the unknown deterministic term $u(k)$ is added to the state vector, which forms an augmented state-space equation as described below.

$$X_{Aug}(k+1) = f\big(X_{Aug}(k), k\big) + W_{Aug}(k)$$
$$Z_{Aug}(k) = h\big(X_{Aug}(k), k\big) + V_{Aug}(k)$$
$$X_{Aug}(k) = \begin{bmatrix} X(k) \\ u(k) \end{bmatrix} \tag{6}$$