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Synthesis of Evaluation Filter of Line of Sight Angle Coordinates with Maneuvering Detection on The Basis of Correction of Amplification Factor according to The Tracking Error Signal

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ABSTRACT

The tracking multi-loop target angle coordinate determination system on the missile's self-guided head only takes into account the situation of the maneuvering target with specific values of the maneuvering intensity and maneuvering frequency. Left open, the class of problems that take into account the diverse maneuverability and super-maneuverable in the reality of the target has not been solved. Therefore, when the actual motion of the target does not suitable for the hypothetical model used to synthesize the coordinate system, the error of evaluation of coordinates and their derivative components will increase. Therefore, in order to improve the coordinate determination accuracy of the angle coordinate determination system and be compatible with the target's maneuverability, the article proposes a method to evaluate the coordinates of line of sight angle with maneuvering detection on the basis of correcting the amplification factor according to the tracking error signal. Simple algorithm, small evaluation error, reliable simulation results.

Keywords: Angle of line of sight, Correction of amplification factor, Kalman filter, Target, Maneuvering, Missile.

1. INTRODUCTION

The normal acceleration model in the optimal target angle coordinate determination system is not representative of all target maneuver motions [1], [2], [3], [4]. With the application of the linear Kalman filter technique, the maneuvering frequency parameter α_{jm} and the maneuvering intensity σ_{jm}^2 are only selected by constants, so it is not representative of every maneuver motions of the target [5], [6], [7]. The tracking error will increase when the actual motion of the target does not suitable for the hypothesized normal acceleration model.

There are many adaptive filtering techniques that can be used in determining maneuver target coordinates. Single-model adaptive filtration techniques often have a simple filter structure, however the error at the time of model transfer and the error reduction time is large [1]. In addition, defining thresholds to switch between models is often imposing. Multi-model filtering technique has complex structure and large computational mass [1], [2], [8].

Therefore, in the condition of maneuvering target, in order to synthesize the target angular coordinate determination system with high accuracy, adaptive Kalman filter algorithms are used to respond to the target's maneuverability [5], [6], [7]. When the target is maneuvering, its kinematics directly affect the line of sight angle coordinate evaluation filter, so the problem of improving the accuracy of determining the target coordinates is realized when using the adaptive algorithm in the line of sight angle coordinate evaluation filter.

2. SYNTHESIS OF LINE OF SIGHT ANGLE COORDINATE FILTER

2.1 Kalman filter algorithm with intermittent processes

Considering the process described by equation of state [6], [9], [10]:

$$x(k) = \Phi(k-1)x(k-1) + \Gamma(k-1)u(k-1) + \xi_x(k-1) \quad (1)$$

The observation equation has the form:

$$z(k) = H(k)x(k) + \xi_z(k) \quad (2)$$

k - Discrete time;

$x(k)$ - State vector, size $(n\times 1)$;

$u(k)$ - Predestination input signal vector, size $(r\times 1)$;

$z(k)$ - Observation vector, size $(m\times 1)$, $(m\le n)$;

$\xi_x(k), \xi_z(k)$ - Central Gaussian discrete white noise, uncorrelated;

$\Phi(k)$ - State transition matrix, size $(n\times n)$;

$\Gamma(k)$ - Input signal amplification matrix, size $(n\times r)$;

$H(k)$ - Observation matrix, size $(m\times n)$.

The Kalman filter algorithm is determined according to the retrieval expressions, which have the form [5], [6], [9], [10]:

$$\hat{x}(k) = \hat{x}^-(k) + K(k)\left[z(k) - H(k)\hat{x}^-(k)\right] \quad (3)$$

$$\hat{x}^-(k) = \Phi(k-1)\hat{x}(k-1) + \Gamma(k-1)u(k-1); \hat{x}(0) = x_0 \quad (4)$$

$$\begin{aligned} K(k) &= D(k)H^T(k)Q_z^{-1}(k) = \\ &D^-(k)H^T(k).\left[H(k)D^-(k)H^T(k) + Q_z(k)\right]^{-1} \end{aligned} \quad (5)$$

$$D(k) = \left[E - K(k)H(k)\right].D^-(k) \quad (6)$$

$$\begin{aligned} &D^-(k) = \Phi(k-1)D(k-1)\Phi^T(k,k-1) + Q_x(k-1); \\ &D(0) = D_0 \end{aligned} \quad (7)$$

$\hat{x}$ - State evaluation;

$\hat{x}^-$ - State forecast;

K - Amplification factor matrix;

D - The posterior error correlation matrix, symmetric, positive definite;

D^- - The prior error correlation matrix, symmetric, positive definite;

Q_z - The intensity matrix of observed noise $\xi_z(k)$, positive definite;

Q_x - The intensity matrix of process noise $\xi_x(k)$, positive definite.

The change of line of sight angle coordinate φ_m and angular speed ω_m are determined by the initial state space model, which has the form:

$$\begin{aligned} &\varphi_m(k) = \varphi_m(k-1) + \tau\omega_m(k-1), \varphi_m(0) = \varphi_{m0}; \\ &\omega_m(k) = (1-\tau\alpha_m)\omega_m(k-1) + \xi_{\omega_m}(k-1), \omega_m(0) = \omega_{m0}; \end{aligned} \quad (8)$$

The Kalman filter algorithm observation equation:

$$z(k) = z_1(k) + K_\Delta\hat{\varphi}_a(k) = K_\Delta\varphi_m(k) + \xi_{\Delta 1}(k) \quad (9)$$

τ - Discrete time step;

$\hat{\varphi}_a$ - Evaluate the angular position of the antenna;

$\xi_{\Delta 1}$ - Equivalent central Gaussian white noise with variance $Q_{\xi_{\Delta 1}}$;

$$Q_{\xi_{\Delta 1}} = Q_{\xi_\Delta} + K_\Delta^2 D_{11}^{\hat{\varphi}_a};$$

$D_{11}^{\hat{\varphi}_a}$ - The variance of the error generating the evaluation signal $\hat{\varphi}_a$.

2.2 Algorithm of the line of sight angle coordinates evaluation

One of the maneuvering detection methods is adaptive correction of the error amplification factor based on the Kalman filter algorithm with the S style variant [3]. With this method, when the actual process fits the hypothetical model to synthesize the filter, the filter works according to the usual Kalman filter algorithm (3) - (7). If the actual process does not suitable for the hypothetical model, the error amplification factor (5) will change automatically.

Consider the process described by state space models (1), (2); The tracking error in the Kalman filter algorithm is determined by:

$$\Delta z(k) = z(k) - H(k)\hat{x}^-(k) \quad (10)$$

The prior correlation matrix (7) is replaced by:

$$D^-(k) = S(k)\Phi(k,k-1)D(k-1)\Phi^T(k,k-1) + Q_x(k-1) \quad (11)$$

Weight $S(k)$ is calculated according to the results of the analysis of expression (10) on the basis of expression (11). Seeing that:

$$\begin{aligned} &\Delta z^T(k)\Delta z(k)^3 tr\left\{M[\Delta z^T(k)\Delta z(k)]\right\} \\ &= tr\left\{M\left(\left[H(k)(x(k)-\hat{x}^-(k)) + \xi_z\right]\left[H(k)(x(k)-\hat{x}^-(k)) + \xi_z\right]^T\right)\right\} \\ &= tr\left\{H(k)D^-(k)H^T(k) + Q_z(k)\right\} \end{aligned} \quad (12)$$

tr - Traces of the matrix.

If the actual process does not suitable for the hypothetical model, the evaluates of $\hat{x}$ deviate greatly from the impact value x, then the observed forecasts $H\hat{x}^-(k)$ in expressions (3) and (10) will be very different compared with the observed results $z(k)$. Therefore, the sum of squares of error in the left hand side of expression (12) will characterize the real filter error, the right hand side determines the theoretical accuracy of the process based on prior information. If condition (12) is satisfied, the actual filtering error will exceed the theoretical calculation error. Starting at that time need to correct the error amplification factor matrix (5). Replace (11) to (12) received:

$$S(k)=\frac{tr\left[\Delta z(k)\Delta z^{T}(k)-H(k)Q_{x}(k-1)H^{T}(k)-Q_{z}(k)\right]}{tr\left\{H(k)\Phi(k,k-1)D(k-1)\Phi^{T}(k,k-1)H^{T}(k)\right\}} \quad (13)$$

Using expressions (11), (13) in the evaluation algorithm (3) - (7) allows to perform adaptive filtering according to the variation of the actual process. On the basis of determining the excess of the left side (12) over its right side, the corresponding factor $S(k)$ will increase, leading to an increase in the factor of the matrices $D^{-}(k)$ and $K(k)$, so the amount of correction in the expression (3) increase. Therefore, approximation evalutions of $\hat{x}(k)$ will approach the real value of $x(k)$.

Unlike conventional filtering algorithms, in this algorithm, the factor of matrix $K(k)$ are corrected by the results of each observation. This transformation is done by defining the characteristic matrix for the actual filtering error $\Delta z(k)\Delta z^{T}(k)$. The advantage of the algorithm is that determining $S(k)$ is simple. The algorithm performs adaptive filtering according to the variation of the actual process.

When using this algorithm in maneuvering target tracking, the maneuvering start time is identified according to the condition (12), and the error amplification factor (5) is corrected according to the rule (6), (11), (13).

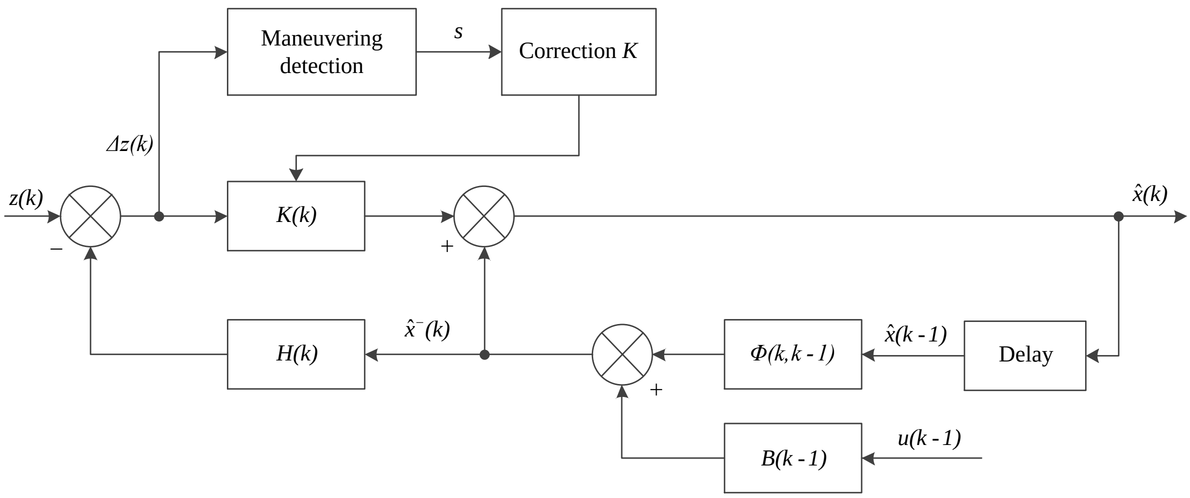

Figure 1. Structure diagram of the amplification factor correction adaptive filter

For the process (8) and observation (9), it is necessary to synthesize the algorithm to create the evaluations $\hat{\varphi}_m$, $\hat{\omega}_m$ according to (3) - (7) with the detection of target maneuverability according to the rule (12) automatic correction of the error amplification factor according to the stated rules.

Transform (9) to simple form, for use in the Kalman filter algorithm:

$$z(k)=z_{1}(k)+K_{\Delta}\hat{\varphi}_{a}(k)=K_{\Delta}\varphi_{m}(k)+\xi_{\Delta 1}(k) \quad (14)$$

$\hat{\varphi}_a$ - Evaluate the angular position of the antenna;

$\xi_{\Delta 1}$ - Equivalent central Gaussian white noise, variance $Q_{\xi_{\Delta 1}}$;

$$Q_{\xi_{\Delta 1}}=Q_{\xi_{\Delta}}+K_{\Delta}^{2}D_{11}^{\hat{\varphi}_{a}};$$

$D_{11}^{\hat{\varphi}_a}$ - The variance of the error generates the evaluating signal $\hat{\varphi}_a$.

Compare models (8), (14) with models (1), (2), received:

$$\Phi(k-1)=\begin{bmatrix}1 & \tau\\ 0 & 1-\tau\alpha_{m}\end{bmatrix};\ B=\begin{bmatrix}0\\ 0\end{bmatrix};\ x=\begin{bmatrix}\varphi_{m}\\ \omega_{m}\end{bmatrix};\ \xi_{x}=\begin{bmatrix}0\\ \xi_{\omega}\end{bmatrix};$$
$$Q_{x}\approx\begin{bmatrix}0 & 0\\ 0 & Q_{\xi_{\omega m}}\end{bmatrix};\ H=[K_{\Delta}\ 0];\ Q_{z}=Q_{\xi_{\Delta 1}}; \quad (15)$$

Applying (15) to (13), S is determined by:

$$S(k)=\begin{cases}\dfrac{\Delta z^{2}(k)-Q_{\xi_{\Delta 1}}(k)}{K_{\Delta}^{2}\left[D_{11}(k-1)+2\tau D_{21}(k-1)+\tau^{2}D_{22}(k-1)\right]} & when\ S>1\\ 1 & when\ S\le 1\end{cases} \quad (16)$$

The tracking error $\Delta z(k)$ is determined by:

$$\Delta z(k)=z_{1}(k)-K_{\Delta}\left[\hat{\varphi}_{m}^{-}(k)-\hat{\varphi}_{a}(k)\right] \quad (17)$$

The prior correlation $D^{-}(k)$ is calculated according to (11):

$$
\begin{aligned}
&D^{-}_{11}(k) = S(k-1).[D_{11}(k-1) + 2\tau D_{21}(k-1) + \tau^2 D_{22}(k-1)],\\
&D_{11}(0) = D_{110}\\
&D^{-}_{21}(k) = D^{-}_{12}(k) = S(k-1)\{(1-2\tau\alpha_m)[D_{21}(k-1) + \tau D_{22}(k-1)]\},\\
&D_{21}(0) = 0\\
&D^{-}_{22}(k,k-1) = S(k-1).\{(1-\tau\alpha_m)^2[D_{22}(k-1) + Q_{\xi_{\omega m}}(k-1)]\},\\
&D_{22}(0) = D_{220}
\end{aligned}
\tag{18}
$$

The posterior correlation $D(k)$ is determined according to (6):

$$
\begin{aligned}
&D_{11}(k) = (1 - K_1 K_\Delta)D^{-}_{11}(k)\\
&D_{21}(k) = D_{12}(k) = D^{-}_{21}(k) - K_2 K_\Delta D^{-}_{11}(k)\\
&D_{22}(k) = D^{-}_{22}(k) - K_2 K_\Delta D^{-}_{21}(k)
\end{aligned}
\tag{19}
$$

Amplification factor are received according to (5):

$$
K_1 = D_{11}(k)K_\Delta / Q_{\xi_{\Delta I}};\ K_2 = D_{21}(k)K_\Delta / Q_{\xi_{\Delta I}} \tag{20}
$$

Substitution (15), (17) and (20) to (3) and (4), received:

$$
\begin{aligned}
&\hat{\varphi}_m(k) = \hat{\varphi}^{-}_m(k) + K_1 \Delta z(k);\ \hat{\varphi}_m(0) = \varphi_{m0}\\
&\hat{\omega}_m(k) = \hat{\omega}^{-}_m(k) + K_2 \Delta z(k);\ \hat{\omega}_m(0) = \omega_{m0}
\end{aligned}
\tag{21}
$$

$$
\begin{aligned}
&\hat{\varphi}^{-}_m(k) = \hat{\varphi}_m(k-1) + \tau\hat{\omega}_m(k-1)\\
&\hat{\omega}^{-}_m(k) = (1-\tau\alpha_m)\hat{\omega}_m(k-1)
\end{aligned}
\tag{22}
$$

Equations (16) - (22) determine the filter synthesis algorithm to evaluate the coordinates of the line of sight angle with maneuvering detection and automatic correction of the tracking process. K_M is determined

$$
K_M = 1/\left\{K_\Delta^2\left[D_{11}(k-1) + 2\tau^2 D_{21}(k-1) + \tau^2 D_{22}(k-1)\right]\right\}
$$

The diagram of the filter structure of figure 2 is different from that of the Kalman filter in the additional loop, for maneuvering detection, weight $S(k)$ is calculated and analyzed. If the target is not maneuvering then $S(k) = 1$, the filtering effect is performed according to the usual Kalman algorithm. When the target is maneuvering, the law of transformation of angle φ_m and angular speed ω_m will not suitable for the model (8).

Forecast of the quantities φ_m and ω_m will be biased, causing $S(k)$ to increase, i.e. increasing the factor s K_1 and K_2. Therefore, increase the amount of correction for tracking error in the evaluation results. The evaluations $\hat{\varphi}_m$, $\hat{\omega}_m$ will asymptote to the real values φ_m and ω_m.

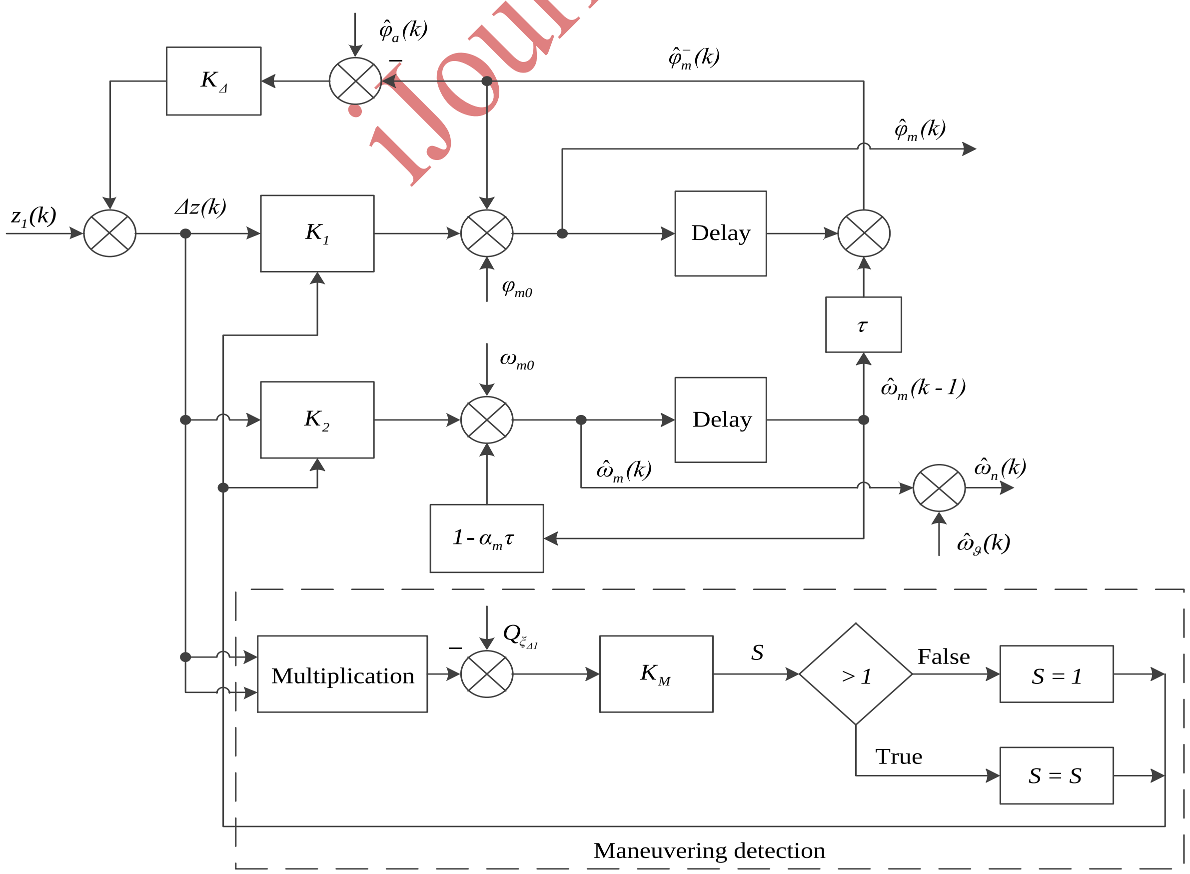

Figure 2. Structure diagram of the amplification factor correction adaptive filter used to evaluate the coordinates of the line of sight angle

3. SIMULATION RESULTS AND ANALYSIS

- The sample trajectory is generated from the following kinetic model:

$$\begin{aligned} &\varphi_m(k) = \varphi_m(k-1) + \tau\,\omega_m(k-1) \\ &\omega_m(k) = (1-\tau\,\alpha_m)\,\omega_m(k-1) + \alpha_m \tau\, u \\ &z(k) = \varphi_m(k) + \xi_{z\varphi}(k) \end{aligned} \quad (23)$$

- Parameters for creating line of sight trajectory: $\tau = 0{,}001(s)$, $\alpha_m = 0{,}6\,(1/s)$, $\varphi_{m0} = 0\,(rad)$, $\omega_{m0} = 0\,(rad/s)$, $\sigma^2_{\xi_z} = 0{,}05^2\,(o^2)$, simulation time $t_\Sigma = 15(s)$, $u\ (^O/s) = \begin{cases} 0{,}5 & when\ t < 5\,s \\ 5 & when\ t \geq 5\,s \end{cases}$.

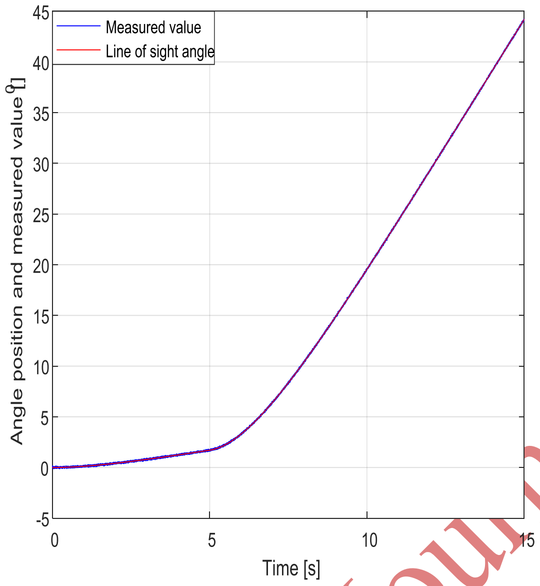

Figure 3. Line of sight angle and measured value

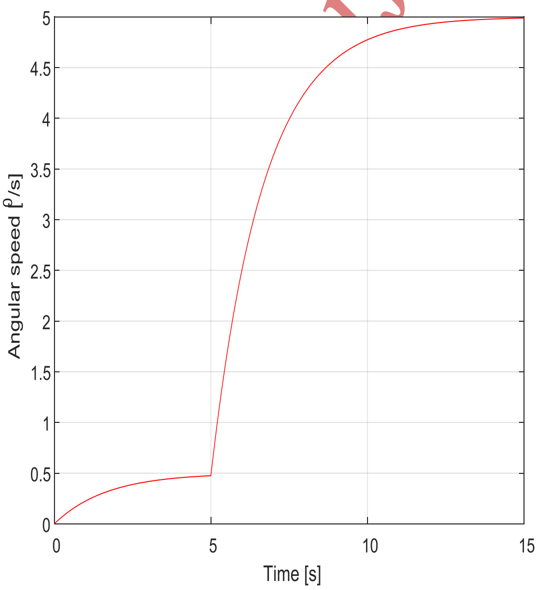

Figure 4. Line of sight angle speed

u - Characterizes the magnitude of the line of sight angle speed. When there is a change in the value of u, the angular speed of the line of sight will change from the current value to the new value of u;

α_m - Parameter that characterizes the speed of change of angular speed (angular acceleration); α_m greater, the larger the angular acceleration.

3.1 Survey the influence of the model's parameters on the evaluation error of the line of sight angle coordinates

Use Kalman filter algorithm to evaluate states φ_m and ω_m. The model used for synthesis has the form (23) with $\sigma^2_{\xi_{\omega m}} = 2\,\alpha_m\,\sigma^2_{\omega_m}\,\tau$;

To see the effect of parameters $\sigma^2_{\omega_m}$ and α_m on the evaluation error of the filter, it is necessary to conduct a filter survey with different parameters $\sigma^2_{\omega_m}$ and α_m.

- The case of changing $\sigma^2_{\omega_m}$ when $\alpha_m = const$.

Choose $\alpha_m = 0{,}6\ (1/s)$, fiting the target's maneuverability parameters (model (23));

Choose $\sigma^2_{\omega_m}$ with 3 different values: $0{,}0012^2\,(rad/s)^2$, $0{,}012^2\,(rad/s)^2$ and $0{,}0006^2\,(rad/s)^2$.

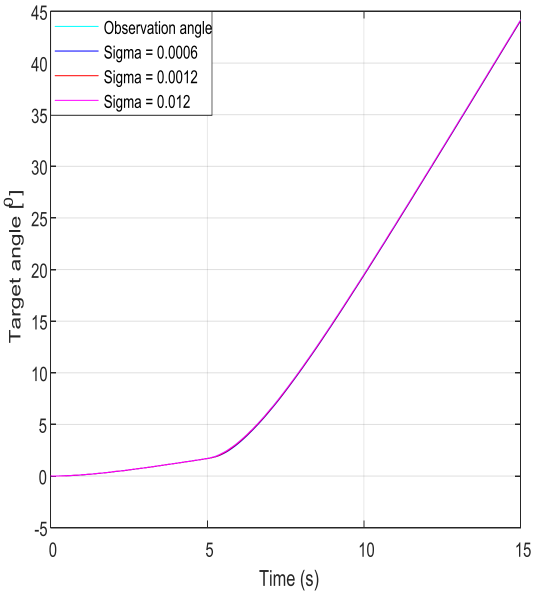

Figure 5. Evaluation of angle coordinates $\hat{\varphi}_m$

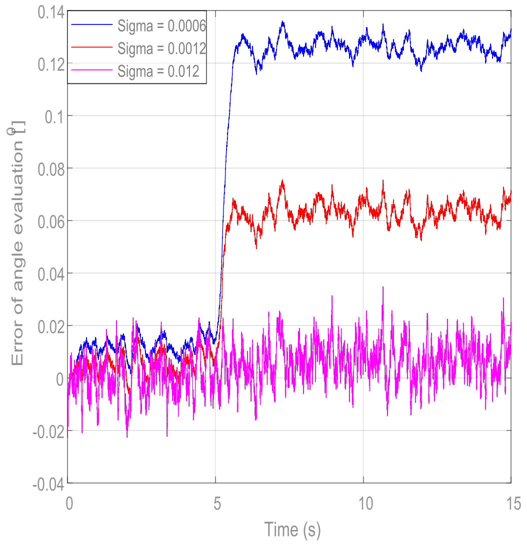

Figure 6. Error of evaluation of angular coordinates

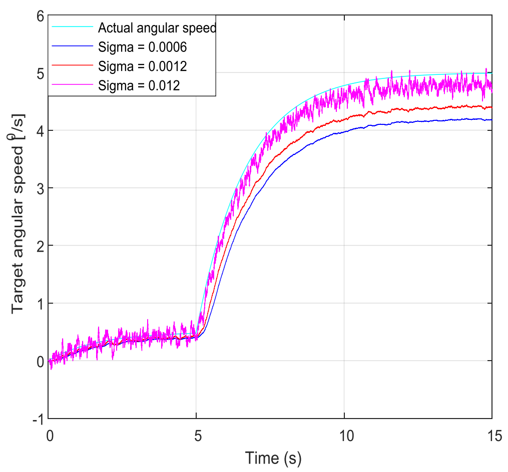

Figure 7. Evaluation of angular speed $\hat{\omega}_m$

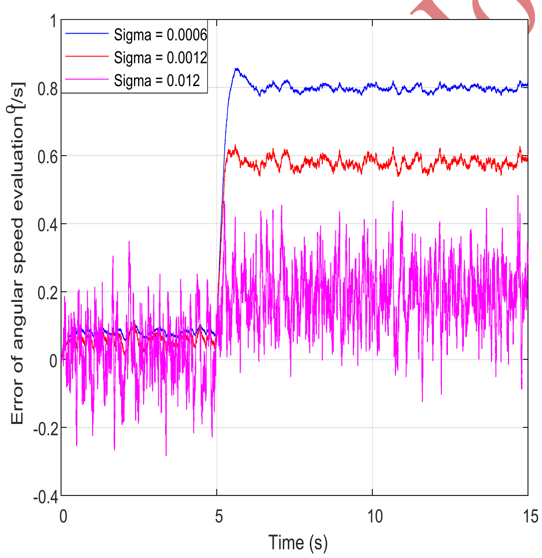

Figure 8. Error of angular speed evaluation

+ When choosing $\sigma^2_{\omega_m}$ large, the error of angle coordinate evaluation and angular speed decrease;

+ Increasing the value of $\sigma^2_{\omega_m}$ will increase the fluctuation error of the evaluations;

In case u is unknown, $\sigma^2_{\omega_m}$ is usually chosen according to the magnitude of u_{max}. Therefore, if the error is guaranteed in the case of the target moving with the maximum angular speed, a large error must be accepted in the case of the small target angular speed.

- The case of changing α_m when $\sigma^2_{\omega_m} = const$.

Choose $\sigma^2_{\omega_m} = 0,0012\ (rad/s)^2$;

Choose α_m with 3 different values: $0,12\ (1/s), 0,6\ (1/s)$ and $1,2\ (1/s)$.

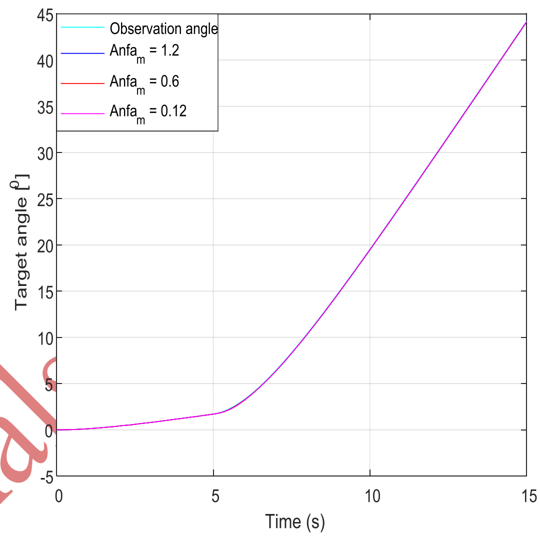

Figure 9. Evaluation of angle coordinates $\hat{\varphi}_m$

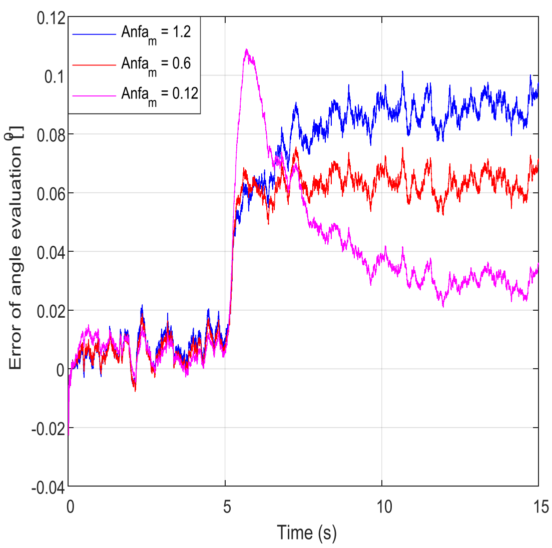

Figure 10. Error of evaluation of angle coordinates

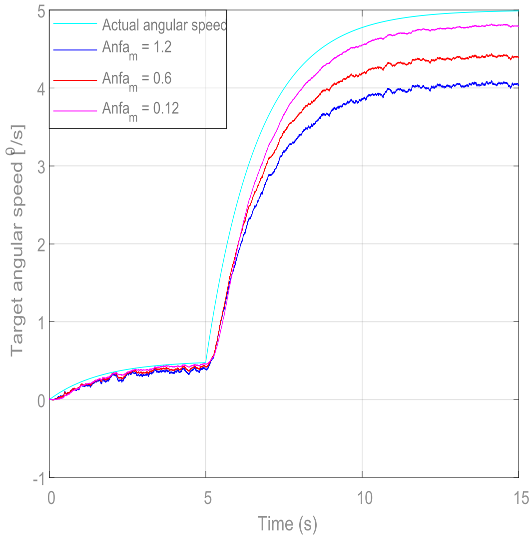

Figure 11. Evaluation of angular speed $\hat{\omega}_m$

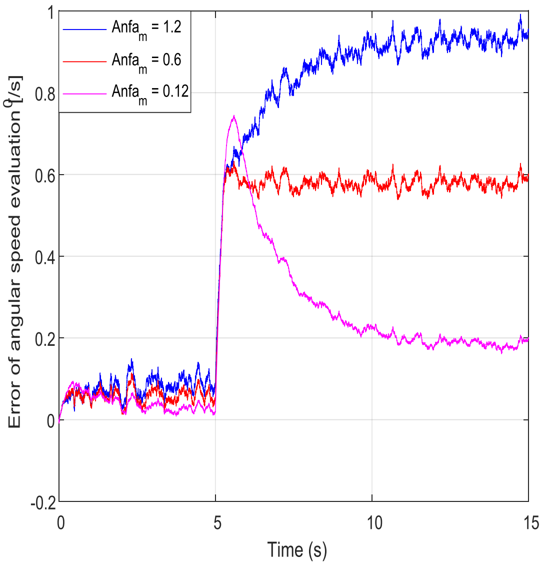

Figure 12. Error of angular speed evaluation

+ When the α_m value is suitable for the trajectory model parameter ($\alpha_m = 0,6\ (1/s)$), the algorithm will give a small angular coordinate and angular speed evaluation error in the target time period of speed change. However, if the target has a large speed and little change, the evaluation error will be large. Because the hypothetical model used to synthesize the filter does not fit the actual motion of the target; specifically, in the model does not take into account the effect of u (in practice the value of u cannot be known in advance).

+ When $\alpha_m = 1,2\ (1/s)$, the evaluation error is large because the filter synthesis model is too deviated from the actual motion of the target.

+ When $\alpha_m = 0,12\ (1/s)$, the evaluation error is small in the case of large target speed and little change. Because, when α_m is small, the synthetic model will closely resemble the white noise acceleration model (constant velocity model), the state forecast of this model will be more accurate. However, when the target has a large speed change (target acceleration appeared), the evaluation error will be large.

From the simulation results, it can be seen that:

It is not possible to select a fixed value of parameters α_m and $\sigma^2_{\omega_m}$, suitable for all actual movements of the target.

In order to ensure coordinate evaluation accuracy, it is necessary to use adaptive algorithms. The adaptive algorithm changes the parameters (or structure) of the model to fit the actual movement of the target.

In a particular case can adaptive α_m or $\sigma^2_{\omega_m}$ or both α_m and $\sigma^2_{\omega_m}$; The general case can adaptive the transition matrix or amplification factor of the filter.

3.2 Survey the filter evaluates the coordinates of the line of sight angle

Simulation parameters are selected:

$\alpha_m = 0,6\ (1/s)$ and $\sigma_{\omega_m} = 0,0012\ (rad/s)$.

Choose a small parameter σ_{ω_m} to ensure small fluctuation errors when the angular speed of the line of sight is small. When the angular speed of the line of sight is large or the angular speed changes, the adaptation process will reduce the evaluation error.

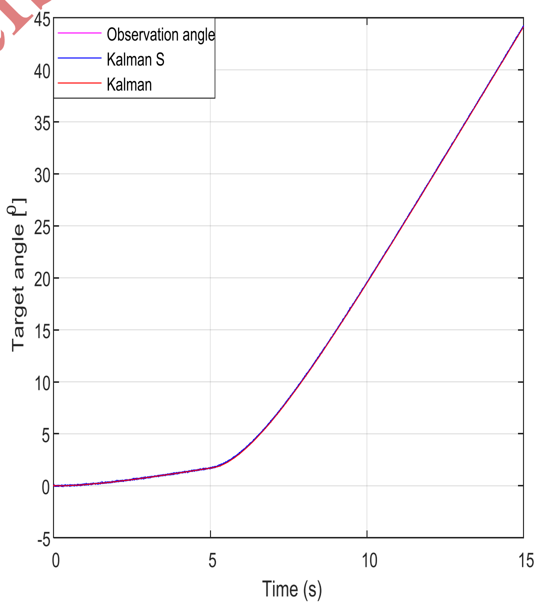

Figure 13. Evaluation of angle coordinates $\hat{\varphi}_m$

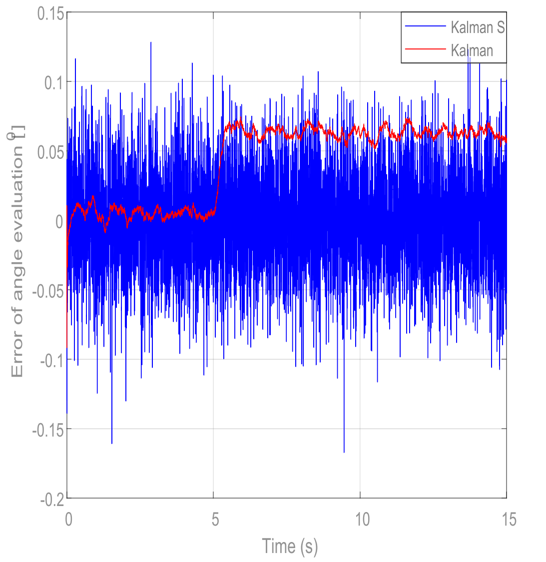

Figure 14. Evaluation error of angle coordinates

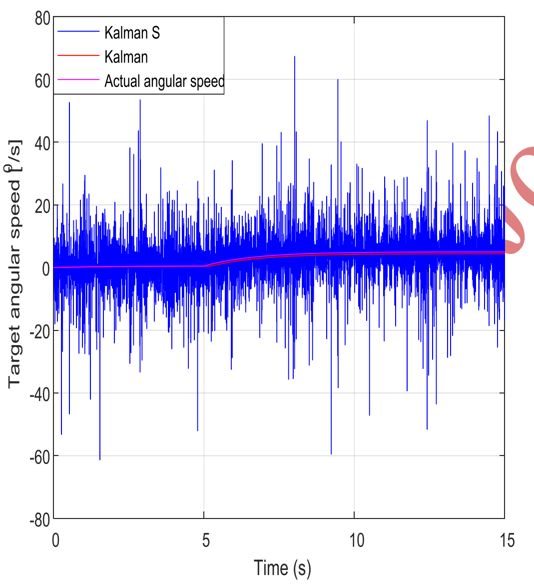

Figure 15. Evaluation of angular speed $\hat{\omega}_m$

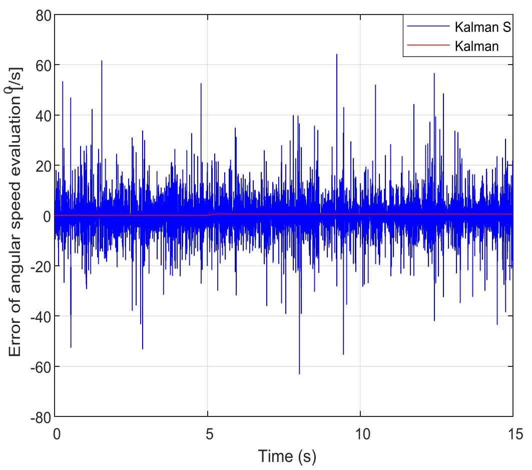

Figure 16. Evaluation error of angular speed

+ The algorithm is capable of reducing angular coordinate evaluation errors. However, the fluctuation error in the evaluation of angular coordinates also increased too large (figures 13, 14).

+ The error of angular speed evaluation is very large, which reduces the angular speed evaluation accuracy (figures 15, 16).

4. CONCLUSION

In the tracking multi-loop optimized target angle coordinate system, using the adaptive Kalman filter algorithm, the target's maneuverability is taken into account by the target normal acceleration model. This model is characterized by maneuvering frequency α_{jm} and maneuvering intensity σ^2_{jm}. In this angle coordinate system, the accuracy is advanced by not using direct the signal balance direction as the target coordinate evaluation signal, but using a separate line-of-sight angle coordinate evaluation filter; At the same time, the related states are evaluated by the Kalman filter algorithm in the tracking loop.

Simple adaptive algorithm in maneuvrability detection and eliminate the non-convergence of the filter caused by the target maneuvering, with high accuracy of the line-of-sight angle coordinates evaluation. However, the algorithm should not be used in systems that require high accuracy in the speed evaluation of tracking coordinates or in order to be usable, necessary improvements are required. When increasing the amplification factor, will increase the influence of noise to the coordinates are evaluated. In addition, the determination of $S(k)$ is approximate, because by replacing $M\{\Delta z(k)\Delta z^T(k)\}$ by $\Delta z(k)\Delta z^T(k)$, the value of $S(k)$ fluctuates greatly.

The target angle coordinate system uses the adaptive Kalman filter algorithm to significantly reduce the tracking error when the target changes the maneuvering style. Capable of adapting to the target maneuvering as the evaluation process progresses the most suitable model.

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