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Synthesis of Line of Sight Angle Coordinate Filter on the Basis of Interactive Multi-Model Evaluation Algorithm

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Abstract— *The article has selected and proposed an interactive multi-model adaptive filter algorithm to improve the quality of the target phase coordinate filter, on the basis of the tracking multi-loop target angle coordinate system. The interactive multi-model evaluation algorithm is capable of adapting to the maneuverability of the target as the evaluation process progresses to the most suitable model. In which, the 3 models selected to design the line of sight angle coordinate filter; Constant velocity (CV) model, Singer model and constant acceleration (CA) model, characterizing 3 different levels of maneuverability of the target. As a result, the evaluation quality of the target phase coordinates is improved because the evaluation process has redistribution of the probabilities of each model to suit the actual maneuvering of the target. The structure of the filters is simple, the evaluation error is small and the maneuvering detection delay is significantly reduced. The results are verified through simulation, ensuring that in all cases the target is maneuvering with different intensity and frequency, the line of sight angle coordinate filter always accurately determines the target angle coordinates. The method of synthesizing the target coordinate determination system used in the article can be extended and applied to the target tracking systems in the fire control radar station under the ground.*

Keywords— *Missile, Target, Maneuvering, Angle of line of sight, Interactive multi-model.*

I. INTRODUCTION

In the missile, the target angular coordinate determination system is actually the tracking system that determines the target coordinate parameters. In angle measuring device, the directional device generates signals that are proportional to the target tracking error according to the angle. This error in the vertical plane is determined by angle $\Delta\varphi_d$, between the signal balance direction of the antenna and the target direction [1], [15], [16]. Figure 1, O_a and O_t - the position of the control object (missile) and the target in the non-rotation coordinate system $X_0 O_a Y_0$, attached to the missile.

where: $O_a X_{oy}$ - Longitudinal axis of the missile;

$O_a X_a$ - The signal balance directional of the directional device;

ε_d - Angle of the line of sight to target in the inertial coordinate system $X_0 O_a Y_0$;

φ_t - Angle of the line of sight compared to the longitudinal axis of the missile;

φ_{ad} - The angle of rotation of the antenna compared to the longitudinal axis of the missile (the directional angle of the antenna);

$\Delta\varphi_d$ - Angle difference between the signal balance line and the line of sight.

ϑ - Missile nodding angle;

$O_a O_t$ - The missile line of sight;

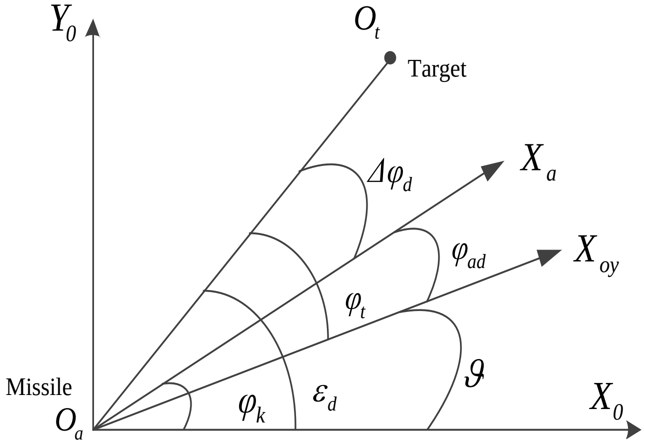

Fig. 1. Motion correlation between the missile and the target.

The task of the problem determines the coordinates of the target angle: Generates angle ε_d and ω_d speed coordinate evaluations of the line of sight. On the current missile control systems, the determination of ε_d and ω_d is done by the tracking one-loop angular coordinate determination system [1]. With this method, ε_d and ω_d are received using directly the signals from antenna transmission system φ_{ad} and from gyros measure the longitudinal axis angle ϑ. The evaluation error ε_d and ω_d of this method will be large, especially in the case of the maneuvering target, due to the antenna has large inertia [3].

Based on the application of optimal control theory and optimal filtration theory, the target angle coordinate determination system on current missile is built with the tracking multi-loop [4], [5]. This coordinate determination system has a smaller error than the tracking one-loop system, especially in the case of a maneuvering target, because ε_d and ω_d are evaluated by a separate tracking loop without using directly the φ_{ad} signal as an evaluation signal [6].

However, in the tracking multi-loop coordinate determination system, it only takes into account the maneuvering target situation with specific values of maneuvering intensity ($\sigma_{j_t}^2$) and maneuvering frequency (α_j). That is, it remains unresolved for the class of the problem taking into account the diverse maneuverability in reality of the target. Therefore, when the actual maneuvering of the target is not consistent with the hypothetical model used to synthesize the coordinate system, the evaluation error ε_d and ω_d will increase.

Therefore, the task set out for the article: On the basis of the tracking multi-loop coordinate determination system, building an algorithm to improve the accuracy of the target angle coordinates in maneuvering target conditions.

When applying optimal control theory and optimal filter theory, the problem of synthesizing systems to determine the target angle coordinates can be divided into two problems, namely:

The antenna control problem so that the signal balance line ($O_a X_a$) coincides with the direction of line of sight ($O_a O_t$). This problem has been solved [14] or the optimal control technique [2] can be used to synthesize the control law, so the article does not set out, but only applies the results when necessary.

The problem of evaluating the phase coordinate of the line of sight ε_d, ω_d takes into account the interaction of other parameters (ϑ, φ_{ad} ...) and the maneuvering of the target. This problem is solved by the article in the direction of synthesizing the adaptive system to improve the accuracy of the target angle coordinates in maneuvering target conditions.

The general method to improve the evaluation ε_d, ω_d in maneuverable target conditions is to use adaptive Kalman filtering techniques. Single-model adaptive filtering techniques perform the adaptation on the corrected phase or predictive of the Kalman filter algorithm [7]. With these methods, the structure of the filter is relatively simple, however the evaluation accuracy is not high and the maneuvering detection time is kept slow compared to the multi-model adaptive filtering techniques. In the multi-model adaptive filtration technique, with the assumption that the process follows one of the N known models, the evaluation accuracy is higher and the maneuvering detection delay is significantly reduced [12].

II. THE ALGORITHM TO EVALUATE THE COORDINATES OF THE LINE OF SIGHT ANGLE

The purpose of the line of sight angle coordinate filter is to evaluate the line of sight angle, line of sight angle speed and target normalization acceleration in order to provide the information required for the flying equipment guide law. With the optimal target angular coordinate system, this filter is designed with Singer model with fixed parameters.

On the basis of this idea, the article adds 2 other models, characteristic for the small and large degree of maneuverability of the target. Model with constant velocity (CV model) and almost constant acceleration model (CA model) to build the interactive multi-model (IMM) evaluation algorithm for the line of sight angle coordinate filter. This choice is derived from the point of view, these 3 models are suitable for 3 different levels of maneuverability of the target.

Thus, the line of sight angle coordinate filter includes 3 linear Kalman filters running in parallel using 3 models, respectively, CV model, Singer model and CA model. The final state evaluation is a combination of component filters with weighting on the exact probabilities of each model. As a result, the evaluation quality of the target phase coordinates is improved because the evaluation process has redistribution of the probabilities of each model to suit the actual maneuverability of the target.

On the basis of the interactive multi-model filtering algorithm [8], [9], [10], we have a general block diagram describing the evaluation algorithm of line of sight angle coordinates shown in Figure 2.

- Call p_{ij}, ($i, j = 1,2,..., N$) - probability of changing from model i at time $(k-1)$ to model j at time k. This probability constant throughout the evaluation process. We choose the model transfer probability matrix as follows:

$$\boldsymbol{\Pi} = \begin{bmatrix} 0,9995 & 0,0001 & 0,0004 \\ 0,0004 & 0,9995 & 0,0001 \\ 0,0001 & 0,0004 & 0,9995 \end{bmatrix}$$

In which, model 1 is CV, model 2 is Singer and model 3 is CA.

Call $\mu_j(0)$ - model probability at the time of initialization. At the beginning, the true probabilities of the 3 models are equal, so:

$$\mu_{CV}(0) = \mu_{SINGER}(0) = \mu_{CA}(0) = \frac{1}{3}$$

- Calculate the mixing probability, that is, the appear probability of the i^{th} model at time $(k-1)$ with the j^{th} model condition at time k.

$$\mu_{i|j}(k-1) = \frac{1}{\overline{c}_j} p_{ij}\mu_i(k-1);\ with\ i, j = 1,2,3 \qquad (1)$$

$$\overline{c}_j = \sum_{i=1}^{3} p_{ij}\mu_i(k-1);\quad with\ j = 1,2,3$$

- Mix the first condition for the j^{th} filter:

+ Input status, after mixing:

$$\hat{\boldsymbol{x}}^{0j}(k-1) = \sum_{i=1}^{3} \hat{\boldsymbol{x}}^{i}(k-1)\mu_{i|j}(k-1);\ With\ j = 1,2,3 \qquad (2)$$

+ Correlation of input errors, after mixing:

$$\boldsymbol{P}^{0j}(k-1)=\sum_{i=1}^{3}\mu_{i|j}(k-1)\Big\{\boldsymbol{P}^{i}(k-1)+$$
$$\left[\hat{\boldsymbol{x}}^{i}(k-1)-\hat{\boldsymbol{x}}^{0j}(k-1)\right]\left[\hat{\boldsymbol{x}}^{i}(k-1)-\hat{\boldsymbol{x}}^{0j}(k-1)\right]^{T}\Big\}\ \hat{\boldsymbol{x}}^{0j}(k-1) \tag{3}$$
$$=\sum_{i=1}^{3}\hat{\boldsymbol{x}}^{i}(k-1)\mu_{i|j}(k-1);\ With\ \ j=1,2,3$$

Due to the state vector size in the CV model is 2, and the Singer model and the CA model are 3, in this case, we need to solve the problem of mixing three models with different state vector sizes. In [11], [12], [13] has proposed a number of ways to solve the problem. Here, we simply choose that when mixing for the CV model (model with smaller state space size), we only mix the corresponding state components in the Singer and CA model, ignoring the states remaining. When mixing for Singer and CA models (the model with larger state space size), we consider the missing state components in the CV model to zero.

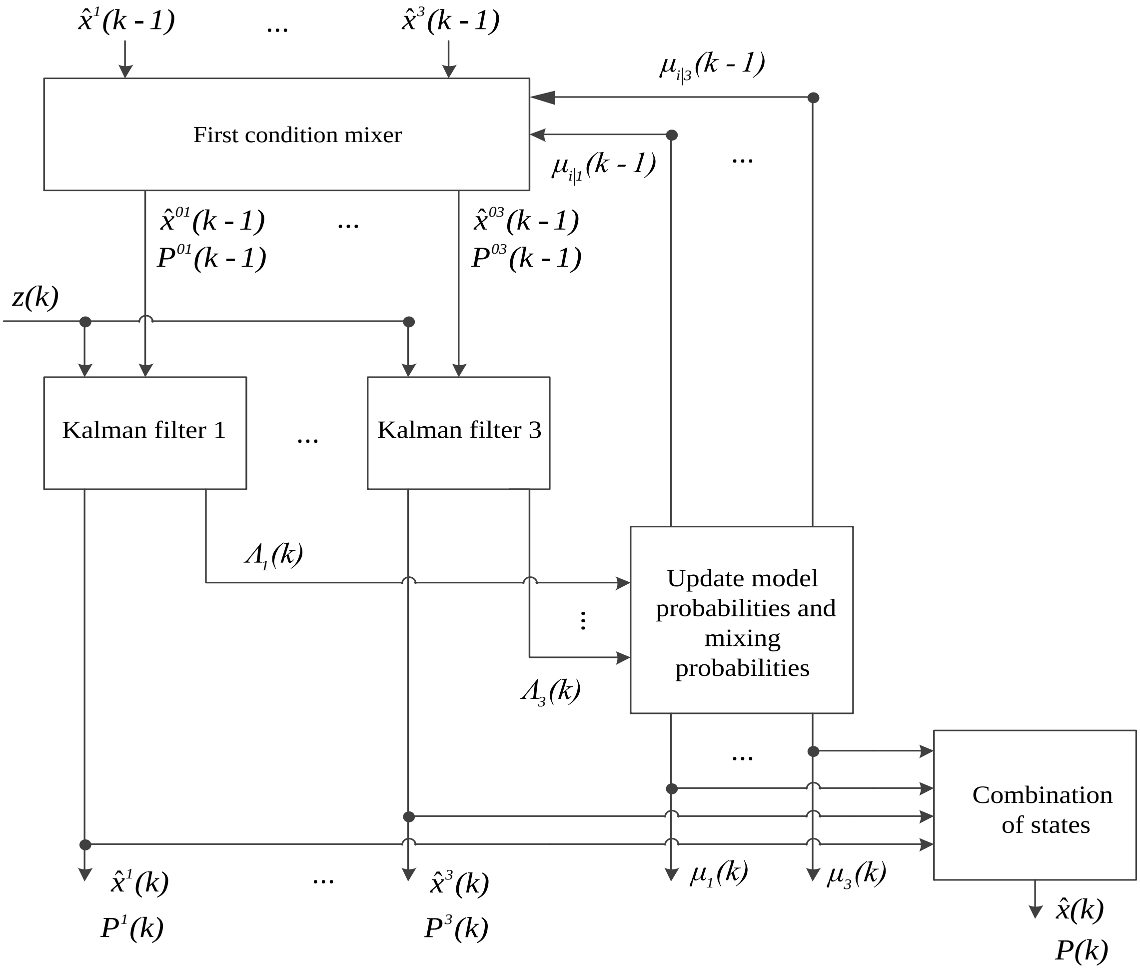

Fig. 2. Block diagram of line of sight angle coordinate filter with 3 component Kalman filters.

- Perform evaluation algorithm of each component filter, with the first conditions is mixed:

+ Evaluate the a priori of each filter:

$$\hat{\boldsymbol{x}}^{-j}(k)=\boldsymbol{\Phi}_{k}^{j}\hat{\boldsymbol{x}}^{j}(k-1)+\boldsymbol{G}_{k}^{j}\hat{\boldsymbol{u}}^{j}(k-1) \tag{4}$$

Inside: $\boldsymbol{\Phi}_{k}^{j}$ - State transition matrix corresponding to model j;

$\boldsymbol{G}_{k}^{j}$ - Control matrix corresponding to the model j.

Calculate the a priori error correlation matrix of each filter:

$$\boldsymbol{P}^{-j}(k)=\boldsymbol{\Phi}_{k}^{j}\boldsymbol{P}^{0j}(k-1)[\boldsymbol{\Phi}_{k}^{j}]^{T}+\boldsymbol{Q}_{k}^{j}(k-1)$$

Calculate the Kalman amplification matrix:

$$\boldsymbol{K}^{j}(k)=\boldsymbol{P}^{-j}(k)\boldsymbol{H}_{j}^{T}(k)\times\left[\boldsymbol{H}_{j}(k)\boldsymbol{P}^{-j}(k)\boldsymbol{H}_{j}^{T}(k)+\boldsymbol{R}_{k}^{j}(k)\right]^{-1} \tag{5}$$

Inside, $R_{k}^{j}(k)=\sigma_{z}^{2}$ - variance of observed channel noise. Here, we consider the variance of the measurement noise in all three models to be equal.

With CV model, the Kalman amplification coefficient is only 2:

$$K_{1}^{1}(k)=\frac{P_{11}^{-1}(k)}{P_{11}^{-1}(k)+\sigma_{z}^{2}}$$

$$K_{2}^{1}(k)=\frac{P_{12}^{-1}(k)}{P_{11}^{-1}(k)+\sigma_{z}^{2}}$$

The Singer and CA model are respectively:

$$K_1^j(k) = \frac{P_{11}^{-j}(k)}{P_{11}^{-j}(k) + \sigma_z^2}$$

$$K_2^j(k) = \frac{P_{12}^{-j}(k)}{P_{11}^{-j}(k) + \sigma_z^2}$$

$$K_3^j(k) = \frac{P_{13}^{-j}(k)}{P_{11}^{-j}(k) + \sigma_z^2}$$

+ Evaluate the posterior state (after measurement update) of each filter:

$$\hat{\mathbf{x}}^j(k) = \hat{\mathbf{x}}^{-j}(k) + \boldsymbol{K}^j(k)\left[\mathbf{z}(k) - \boldsymbol{H}^j(k)\hat{\mathbf{x}}^{-j}(k)\right] \tag{6}$$

+ The posterior correlation matrix of each filter:

$$\boldsymbol{P}^j(k) = \left[\boldsymbol{I} - \boldsymbol{K}^j(k)\boldsymbol{H}^j(k)\right]\boldsymbol{P}^{-j}(k)$$

- Calculate the logical function for filter j^{th}:

$$\Lambda_j(k) = N\begin{bmatrix} \mathbf{z}(k); \hat{\mathbf{z}}^j\left[k \mid k-1; \hat{\mathbf{x}}^{0j}(k-1 \mid k-1)\right], \\ S^j\left[k, \boldsymbol{P}^{0j}(k-1 \mid k-1)\right] \end{bmatrix} \tag{7}$$

It mean, $\Lambda_j(k) = N\left[e^j(k); 0; S^j(k)\right]$, inside;

$$e_j(k) = \mathbf{z}(k) - \boldsymbol{H}^j\hat{\mathbf{x}}^{-j}(k-1)$$

$$S_j(k) = \boldsymbol{H}_j\left[\boldsymbol{\Phi}_k^j\boldsymbol{P}^{0j}(k-1)[\boldsymbol{\Phi}_k^j]^T + \boldsymbol{Q}_k^j\right]\boldsymbol{H}_j^T + \boldsymbol{R}_k^j$$

$$\Lambda_j(k) = \frac{1}{\sqrt{2\pi S_j(k)}}exp(-\frac{1}{2}e_j^T(k)S_j^{-1}(k)e_j(k))$$

$$\Lambda_j(k) = \frac{1}{\sqrt{2\pi S_j(k)}}exp(-\frac{1}{2S_j(k)}e_j^2(k))$$

- Updated j^{th} model probabilities:

$$\mu_j(k) = \frac{1}{c}\Lambda_j(k)\overline{c}_j \tag{8}$$

$$c = \sum_{j=1}^{3}\Lambda_j(k)\overline{c}_j \quad \text{- normalized constants.}$$

- Combination of evaluation states and error correlation matrix after updating the correct probabilities of each model.

+ Combination of evaluation states:

$$\hat{\mathbf{x}}(k) = \sum_{j=1}^{3}\hat{\mathbf{x}}^j(k)\mu_j(k) \tag{9}$$

+ Combination of error correlation:

$$\boldsymbol{P}(k) = \sum_{j=1}^{3}\mu_j(k)\left\{\boldsymbol{P}^j(k) + \left[\hat{\mathbf{x}}^j(k) - \hat{\mathbf{x}}(k)\right]\left[\hat{\mathbf{x}}^j(k) - \hat{\mathbf{x}}(k)\right]^T\right\}$$

III. SIMULATION RESULTS AND ANALYSIS

To survey the quality of the tracking multi-loop target angle coordinate system using the interactive multi-model filtering algorithm, we will simulate the angular coordinate system with different maneuvering style of the target in the horizontal plane. Then, compare with the quality of the optimal angular coordinate system (with fixed parameters based on Singer model) according to the criteria of mean square error (MSE).

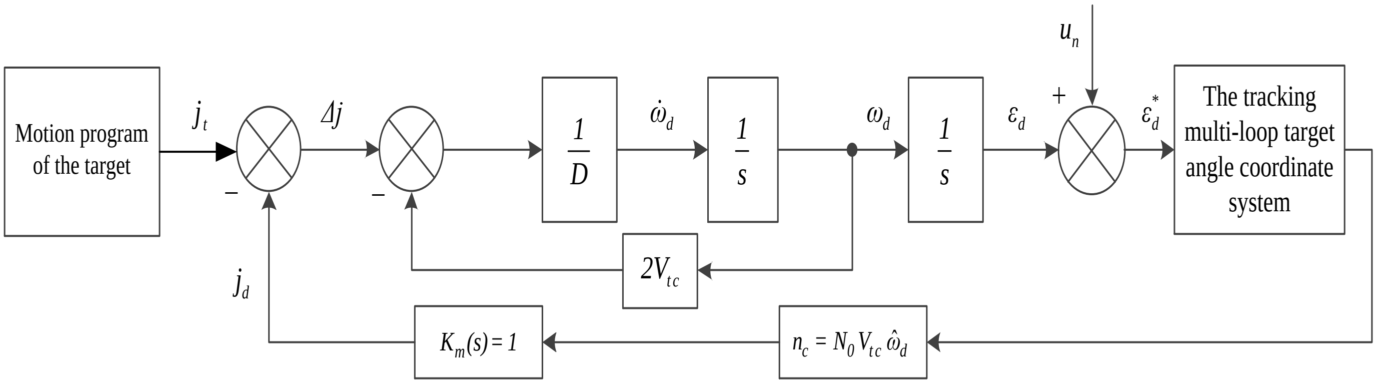

Fig. 3. Diagrams simulation of the target angle coordinates system in the ideal missile control loop.

- The target's initial position: $x_t(0) = 40\ (km)$; $y_t(0) = 0(km)$.
- The missile initial position: $x(0) = 0(km), y(0) = 0(km)$.
- The target flies in at velocity: $350\ (m/s)$.
- Missile velocity: $1000(m/s)$.
- The target's initial trajectory tilt angle: $\theta_t = 0^o$.

3.1. In the case of a ladder type maneuvering target

- Normal acceleration of the target:

$$j_t = \begin{cases} 0 & when \quad t < 20s \\ 30\ (m/s^2) & when \quad t \geq 20s \end{cases} \tag{10}$$

With this model, initially, the target evenly straight movement. After 20 seconds, the target suddenly maneuvers continuously with constant normal acceleration $30(m/s^2)$. Thus, the target has a change from non-maneuverable model to maneuverability with constant normal acceleration. This motion model has uncertainty in maneuvering moment and maneuvering intensity.

Figure 4 shows that from 0 to 20 seconds, the CV model dominates, but after about 22 seconds (the transition time of the IMM algorithm is about 2 seconds), the probability of the CA model is clearly dominant compared to the other 2 models.

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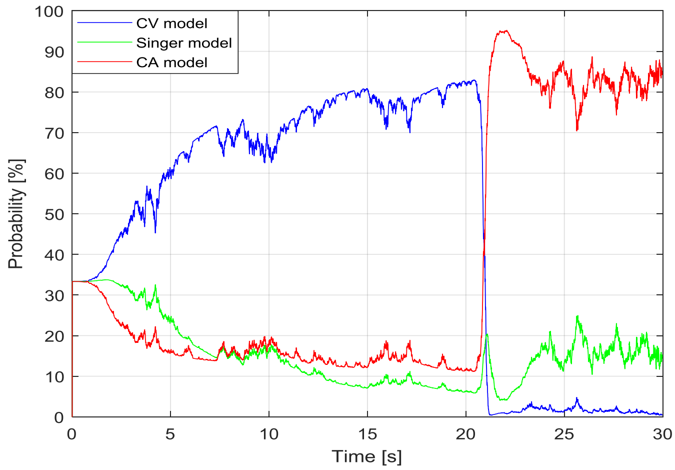

Fig. 4. The graph shows the correct probabilities of the model.

This trend continue to maintain in the remaining maneuverable time of the target. This evaluation result of the algorithm reflects quite correctly with the actual maneuvering of the target.

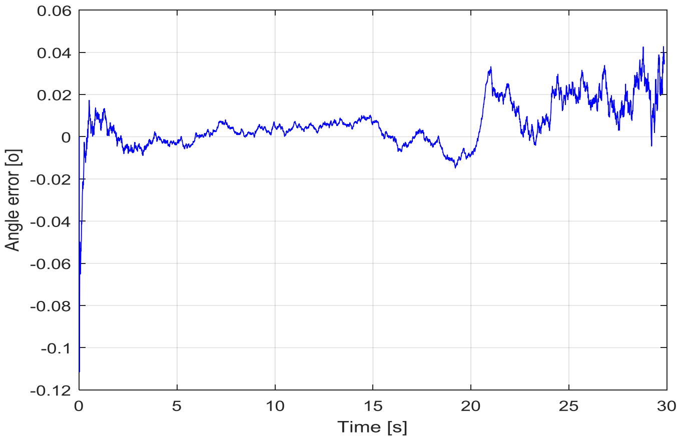

Fig. 5. Evaluation error of the line of sight angle

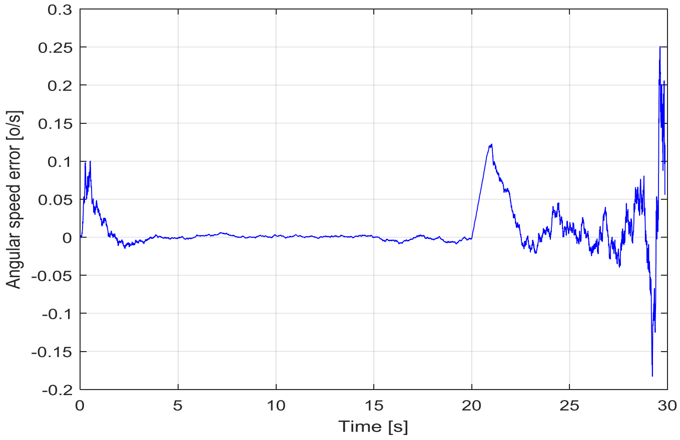

Fig. 6. Evaluation error of the line of sight angle speed

The simulation results show that, in all 3 states: the line of sight angle, the line of sight angle speed and the normal acceleration of the target, the IMM evaluation algorithm gives a greater error at the time the target starts to maneuver (model change time). But right after that, the clinging error is smaller. Compare the quality of the IMM filter algorithm with the optimal filter algorithm after 100 Monte-Carlo runs:

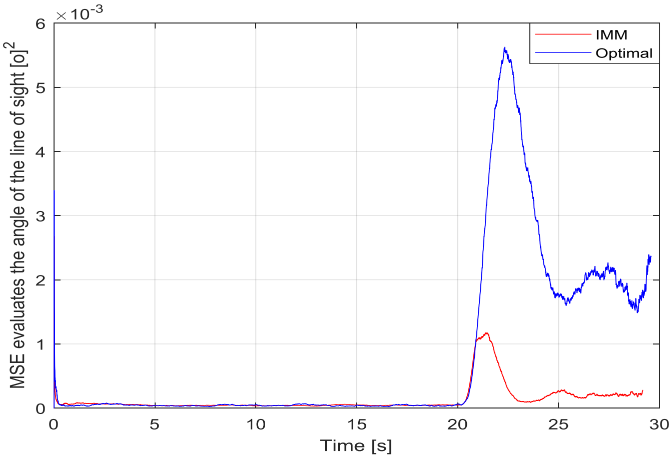

Fig. 7. Compare the MSE to evaluate the angle of the line of sight

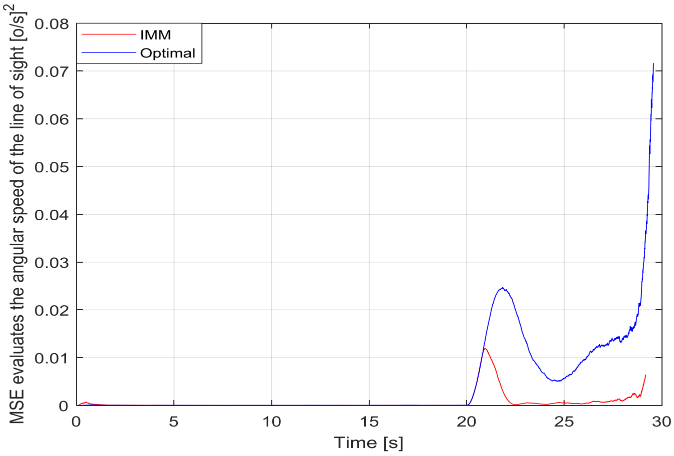

Fig. 8. Compare the MSE to evaluate the angular speed of the line of sight.

Before the maneuvering target time (20s), the evaluation quality of the two algorithms was equivalent (the evaluation error of the optimal filtering algorithm was trivial smaller). But after 20 seconds, there is a difference in evaluation quality.

In the case, the maneuvering target according to Singer model

- The target normal acceleration is generated from the following kinematic model:

$$j_t(k) = (1 - T.\alpha_{j_t})j_t(k-1) + T.u \tag{11}$$

Where: $\alpha_{j_t} = 1\ (1/s)$, T - discrete integral cycle.

u - control signal or maneuver command.

$$u = \begin{cases} 0 & when \quad t < 5\,s \\ 40.\alpha_{j_t}\ (m/s^2) & when \quad t < 15\,s \\ 0 & when \quad t \geq 15\,s \end{cases} \tag{12}$$

With this model, initially, the target evenly straight movement. After 5 seconds, the target begins to maneuver in a Singer model with a command acceleration is $40(m/s^2)$. After 15 seconds, the target reverted to its non-maneuver style.

Thus, this motion model has uncertainty in maneuvering moment, maneuvering time and maneuvering intensity.

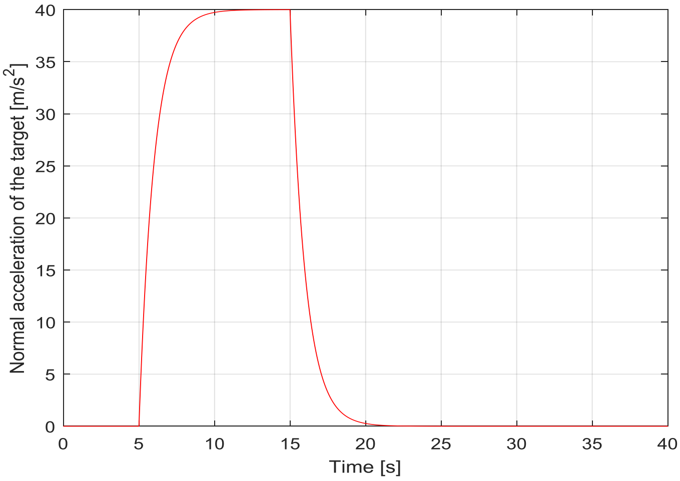

Fig. 9. Normal acceleration of the target.

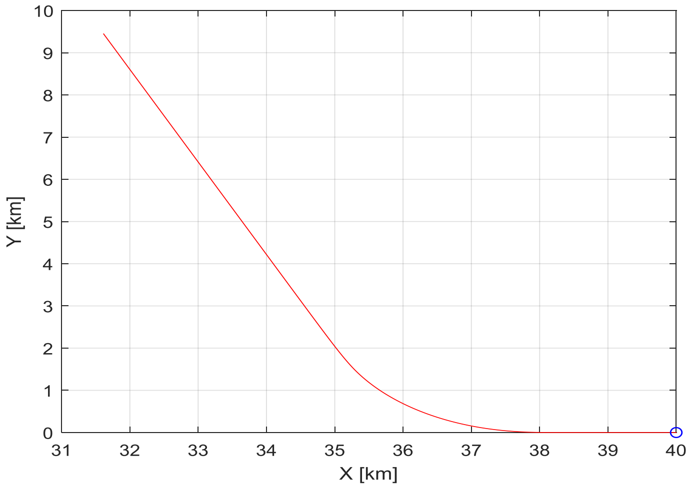

Fig. 10. Singer style maneuvering target trajectory.

The simulation results of the target angle coordinate system for the maneuvering target case according to Singer model are as follows:

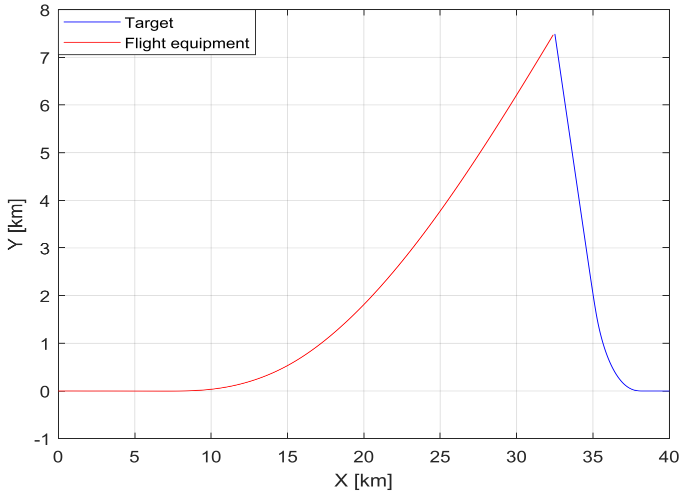

Fig. 11. Missile - Target trajectory.

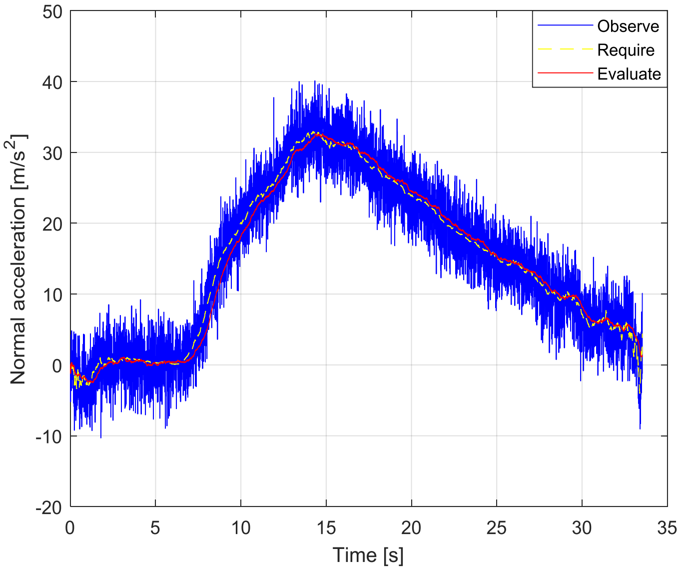

Fig. 12. Normal acceleration of the missile.

When the target starts to maneuver, the normal acceleration requires an increase and when the target changes to the non-maneuver model, the required normalized acceleration of missile tends to decrease to *0*.

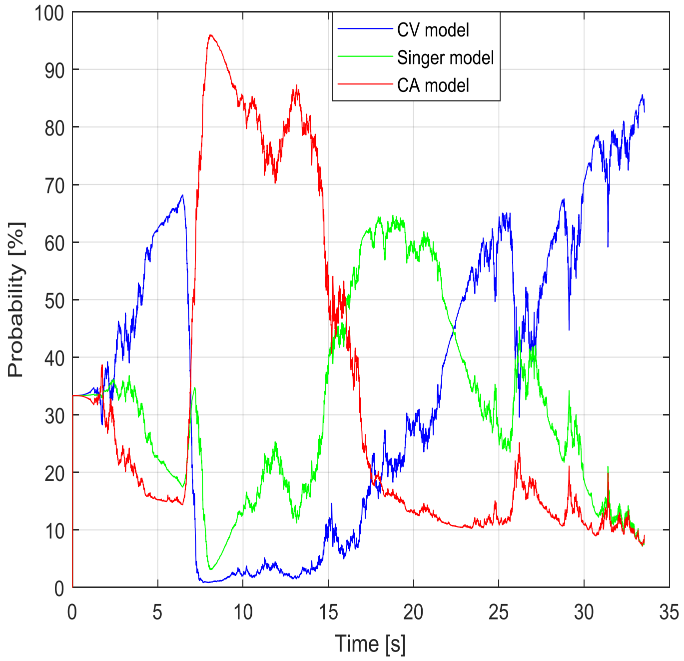

Fig. 13. Graphs update model probabilities.

Obviously, when the target of evenly straight movement in the first 5 seconds, the CV model dominates over the other 2 models. In the time of the maneuvering target (5 ÷ 15s), the CA and Singer models dominate again, in which the weight of the CA model is greater, because the target maneuvering command in this case is quite large $(40\, m/s^2)$ makes the CA model fit with more practical. And when the target ends maneuver time, the correct probability belongs to the CV model.

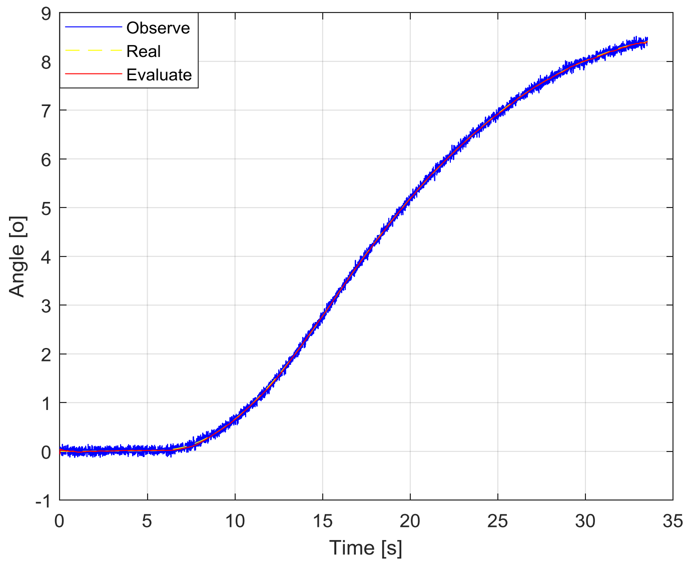

Fig. 14. Evaluate the angle of the line of sight.

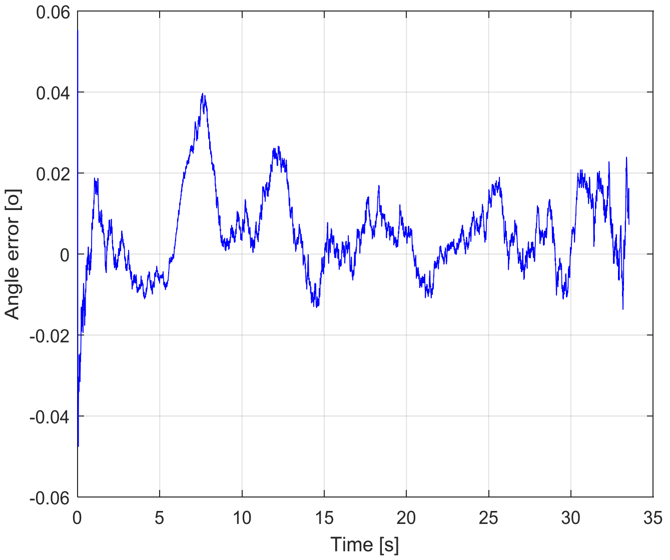

Fig. 15. Evaluation error the angle of the line of sight.

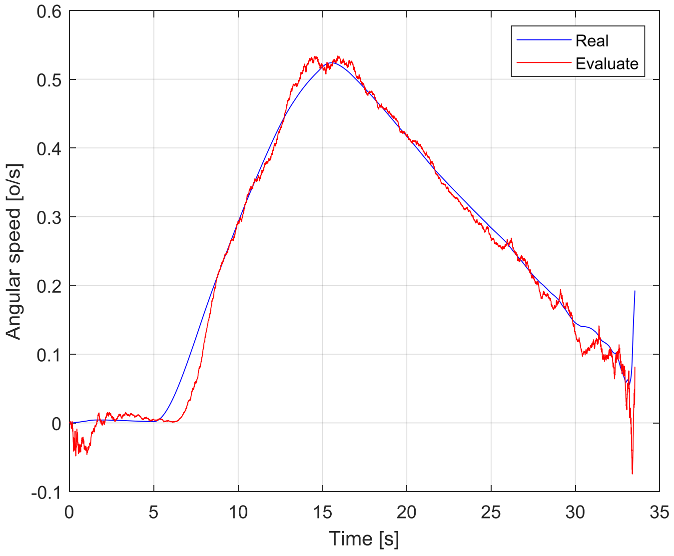

Fig. 16. Evaluate the angular speed of the line of sight

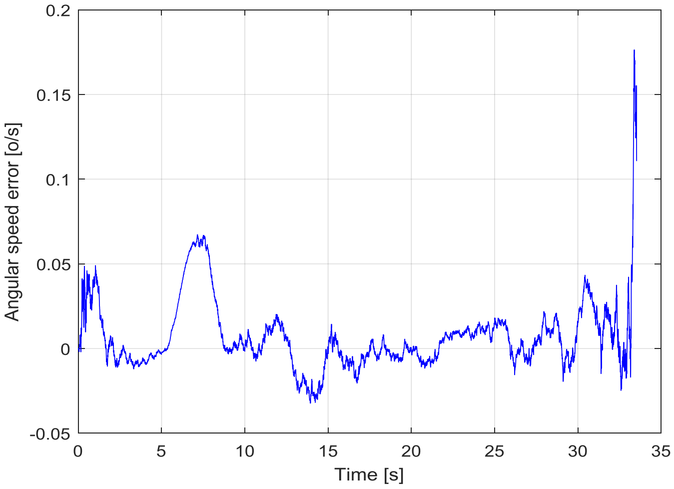

Fig. 17. Evaluation error the angular speed of the line of sight.

In this case, all 3 target phase coordinates have a larger evaluation error at the time of model transfer (from non-maneuver to maneuver and on the contrary), but then IMM filter algorithm gives smaller evaluation error.

Comparing the quality of the IMM filter algorithm with the optimal filtration algorithm after 100 runs of Monte-Carlo for the case of Singer style maneuvering target gives the following results:

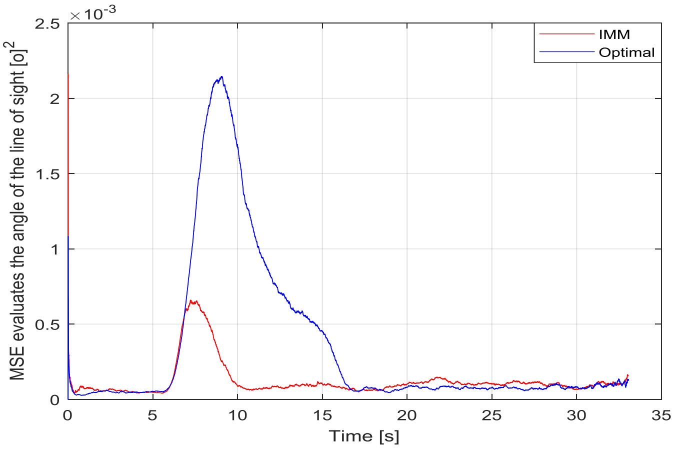

Fig. 18. Compare the MSE to evaluate the angle of the line of sight.

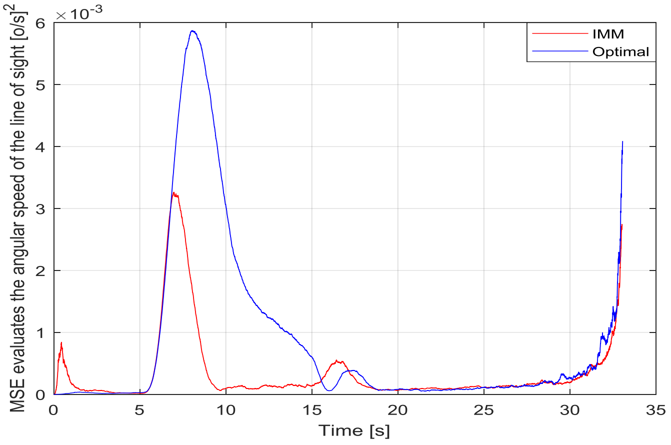

Fig. 19. Compare the MSE to evaluate the angular speed of the line of sight.

MSE simulation results show that, in the non-maneuver target stages (before 5 seconds and after 15 seconds), the evaluation quality of the line of sight angle coordinate filter when using the IMM filter algorithm is slightly worse when compared with the optimal filtering algorithm. However, at the maneuvering target stage (5 ÷15 seconds), the evaluation error of IMM algorithm is significantly smaller. Detail:

- At the moment the target starts to maneuver, for optimal filtering algorithm is $MSE(\varepsilon_d) \approx 2,2.10^{-3}\,(o)^2$, $MSE(\omega_d) \approx 6.10^{-3}\,(o/s)^2$, $MSE(j_t) \approx 1000\,(m/s^2)^2$; also for IMM filtering algorithm is $MSE(\varepsilon_d) \approx 0,6.10^{-3}\,(o)^2$, $MSE(\omega_d) \approx 3,2.10^{-3}\,(o/s)^2$, $MSE(j_t) \approx 850\,(m/s^2)^2$.
- At the stable tracking stage, for the optimal filtering algorithm is $MSE(\varepsilon_d) \approx 0,7.10^{-3}\,(o)^2$, $MSE(\omega_d) \approx 1,7.10^{-3}\,(o/s)^2$, $MSE(j_t) \approx 600\,(m/s^2)^2$; also for IMM filtering algorithm is $MSE(\varepsilon_d) \approx 0,1.10^{-3}\,(o)^2$, $MSE(\omega_d) \approx 0,15 \times 10^{-3}\,(o/s)^2$, $MSE(j_t) \approx 30\,(m/s^2)^2$.

IV. CONCLUSION

The article has synthesized the line of sight angle coordinates filter between the missile and the target using the interactive multi-model adaptive filter technique. The suboptimal target angle coordinate tracking system is constructed from individual filters and combined with an antenna control system to create a multi-loop target angle coordinate system. Obviously, the target's maneuvering directly influence to the evaluation filter the line of sight angle coordinate. So, in order to synthesize the target angle coordinate determination system with high accuracy in the maneuvering target conditions, just improve the line of sight angle coordinate evaluation filter, the other filters are kept.

The simulation results of the tracking multi-loop target angle coordinate system show that, when comparing the quality of the line of sight angle coordinate filter using the IMM filter algorithm based on the MSE criteria, the evaluation error is smaller than the optimal filtering algorithm under different maneuvering target conditions. Here, the change of the target maneuvering styles while in the process of the missile approaches the target, highlighting the advantages and reliability of the interactive multi-model evaluation algorithm. The advantage is that during the evaluation process, the algorithm will always update the closest approximate model to the actual motion of the target, resulting in a combination of state evolution from the component filters giving results more precisely the optimal filter has a fixed parameter. Of course, the more models that are taken into account when designing the line of sight angle coordinate filter, the higher the adaptability of the filter to target maneuverability, but we need to consider the cost of calculation and real time response of the electronic computer on board.

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