Real-Time Effectiveness Evaluation of Air-to-Air Missile Based on Interaction Multiple Model Prediction

Donghui Mao, Yangwang Fang, Chao Zhang, Peifei Yang

Abstract— **The real-time effectiveness evaluation of aerial combat is especially emphasized in modern Network Centric Warfare (NCW). But it is difficult to evaluate the real-time effectiveness of long-distance air-to-air missile because of the bad estimation of target state, exactly when missile come into a guided-blind-zone. In order to avoid the considerable error caused by extrapolate method, a target plane state estimation method based on interacting multiple model prediction is analyzed. First, the main attack-avoidance maneuver models of target plane are researched. Then the number of fragments hitting the target of one single missile is calculated combined with surface panel method. The results of the paper have promising applications in real-time effectiveness evaluation of air-to-air missile.**

***Index Terms*—real-time effectiveness evaluation; interacting multiple model prediction; air-to-air missile**

I. INTRODUCTION

OBTAINING real-time damage effect of beyond visual range (BVR) air-to-air missile is an important way to improve the situational awareness of multi-aircraft cooperative formation in NCW, which is very necessary in effective-based combat. Thanks to advanced data-link[1-3] technology, the USA Air Force(UAF) keeps ahead in evaluating the BVR air-to-air missile real-time kill effectiveness. The AIM-120 missile equipped with intercommunication data link possesses the ability of sharing battlefield awareness and information, and the downloaded-link sends information of missile working-state, dimensional state, seeker interception, self-homing switch and kill probability. While in domestic district, the absence of effective intercommunicate method makes it hard to assess the real-time effectiveness of BVR missile. That does in turn weaken the quality of collaborative work.

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Manuscript received May 12, 2015; revised May 15, 2015.

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II. PROBLEM STATEMENT

With the aggrandizement of battle radius, most of the air combats take place in BVR airspace. The missile is guided to approach the target by the guidance system after launch. Then the fuse starts to work and will detonate the warhead when the conditions are satisfied in order to damage the target.

In this paper, we will focus on the method of using the information downloaded from the missile to analyze the missile's kill effectiveness real-timely. This is useful for the pilot to know the real-time damage effect. To simplify the problem , some assumptions are given as follow: ① The guidance system can't get the information of target position and velocity when the distance between missile and target is less than M (in the Blind Area of Guidance System, BAOGS). It can only guide the missile with the information of last frame. ② When the distance is *Y*, the fuse start working and can only measure the distance information. ③ After the fuse's explosion, the information of missile and target will not be obtained. ④ The information downloaded from the data link is real-time. ⑤ The state of the target is unchangeable after the explosion of the warhead.

III. TARGET STATE ESTIMATION [4]

1 Entering BAOGS

Assuming that the missile is entering the BAOGS at time k, the interacting multiple model (IMM) algorithm with m models is used to detect and track the target at time $t \le k$. Let p_i denote the probability of model m_i at time $t=k$ and define p_{ij} as the probability transferring from model m_i to model m_j.

The states and measurement can be described as follows:

$$\mathbf{X}(k'+1) = \mathbf{F}^{(i)}\mathbf{X}(k') + \mathbf{\Gamma}\mathbf{n}(k') \quad (1)$$

$$\mathbf{Z}(k') = f(\mathbf{X}(k')) + \mathbf{n}(k') \quad (2)$$

where $k'<k$, $f(\bullet)$ includes target measuring information of angle and distance.

After the missile entered the BAOGS, the measuring formula (2) doesn't update, and the extrapolation can be described:

$$\mathbf{X}(k+1)=\mathbf{F}^{(i)}\mathbf{X}(k)+\mathbf{\Gamma}\mathbf{n}(k) \qquad (3)$$

where $F^{(i)}$ represents the transfer matrix of model m_i.

Suppose that transform of models is Markov, the initial condition of filter matching model $m^{(j)}$ can be obtained based on the assumption $\hat{\mathbf{X}}^{(i)}_{k-1|k-1}$ and covariance $\mathbf{P}^{(i)}_{k-1|k-1}$ of model i.

$$\hat{\mathbf{X}}^{(j)}_{k-1|k-1}=\sum_{i=1}^{r}\hat{\mathbf{X}}^{(i)}_{k-1|k-1}\cdot\mu^{(j/i)}_{k-1|k-1} \qquad (4)$$

$$\hat{\mathbf{P}}^{(j)}_{k-1|k-1}=\sum_{i=1}^{r}[\mathbf{P}^{(i)}_{k-1|k-1}+(\hat{\mathbf{X}}^{(i)}_{k-1|k-1}-\hat{\mathbf{X}}^{(j)}_{k-1|k-1}) \cdot(\hat{\mathbf{X}}^{(i)}_{k-1|k-1}-\hat{\mathbf{X}}^{(j)}_{k-1|k-1})^T]\cdot\mu^{(i/j)}_{k-1|k-1} \qquad (5)$$

where, i,j=1,2,⋯, r $\bar{c}_i=\sum_{j=1}^{r}\pi_{ij}\mu^{(j)}_{k-1}$ is the regularization constant, $\mu^{(j)}_{k-1}$ is the probability of model m_j, π_{ij} is the transition probability from model m_i to m_j [5]。At this moment, there is no detection to offer measurement data. Only one-step prediction of $i=1,\cdots,r$ model's $\hat{\mathbf{X}}^{(i)}_{k-1|k-1}$ and $\hat{\mathbf{P}}^{(i)}_{k-1|k-1}$ can be forecasted as:

$$\mathbf{X}^{(i)}(k\,|\,k-1)=F\mathbf{X}^{(i)}(k-1\,|\,k-1) \qquad (6)$$

$$\mathbf{P}^{(i)}(k\,|\,k-1)=\mathbf{F}\mathbf{P}^{(i)}(k-1\,|\,k-1)\mathbf{F}^T \qquad (7)$$

In common IMM algorithm[6-11], the probability of models is updated according to the measurement and one-step prediction. But in this problem, the radar seeker can't measure the target which makes it impossible to update the probability of the model. So the probability remains the same as:

$$\mu^{(i)}_k=\mu^{(i)}_{k-1}\quad t=1,2,\cdots,r, \qquad (8)$$

The one-step prediction is:

$$\hat{\mathbf{X}}_{k|k-1}=\sum_{i=1}^{r}\mathbf{X}^{(i)}_{k|k-1}\mu^{(i)}_k \qquad (9)$$

$$\mathbf{P}_{k|k-1}=\sum_{i=1}^{r}[\mathbf{P}^{(i)}_{k|k-1}+(\hat{\mathbf{X}}_{k|k-1}-\hat{\mathbf{X}}^{(i)}_{k|k-1})\cdot(\hat{\mathbf{X}}_{k|k-1}-\mathbf{X}^{(i)}_{k|k-1})^T]\mu^{(i)}_k \qquad (10)$$

Let $\hat{\mathbf{X}}_{k|k}=\hat{\mathbf{X}}_{k|k-1}$, $\mathbf{P}_{k|k}=\mathbf{P}_{k|k-1}$ to achieve the probability updating of the IMM without measurement.

2 After Fuse Starts to Work

When the condition of fuse working is satisfied (the distance is less than Y), the fuse starts to work and the distance can be measured by fuse. Temporality the estimation of the target state can be corrected by the measured distance. The problem can be described as follows:

The state equation and the measurement equation:

$$\mathbf{X}(k+1)=\mathbf{F}^{(i)}\mathbf{X}(k)+\mathbf{\Gamma}\mathbf{u}(k) \qquad (11)$$

$$\mathbf{Z}(k)=f(\mathbf{X}(k))+\mathbf{n}(k) \qquad (12)$$

where the $f(\bullet)$, which is different from ordinary tracking problems, only includes the distance measurement.

When $r<Y$, the target velocity state is estimated by common IMM. If the target is tracked by single model rather than IMM before it goes into BAOGS, it is difficult to obtain the probability of each model when using IMM to predict the target state entering into BAOGS. By analyzing the target maneuver models and corresponding probability, the error caused by model unmatched can be reduced when using IMM algorithm.

The target maneuver models include: white-noise constant acceleration (CA) model, constant turn (CT) model with known turn rate, CT model with afterburner, variable turn (VT) model, climbing model, evadable turning model and furthest acceleration model. There are two preconditions in our problem: 1. The target is faced with missile attack; 2. The distance between target and missile is close (about 300m). Under these conditions, only CT model with afterburner, evadable turning model and furthest acceleration model can be chosen for IMM algorithm. At the last moment, the most commonly used model is CT model with afterburner, so we select it to predict the target state.

Therefore we set model m_1 and m_2 in the IMM algorithm, m_1 is CA model and m_2 is CT model. For details see reference [12,13]。

Suppose the state vector of m_1 is $X_1(k)=\left[x,y,z,v_x,v_y,v_z\right]^T$, the state-transition matrix is

$$F_1=\begin{bmatrix}1&&&&&\\&1&&&&\\&&1&&&\\&&&T&&\\&&&&T&\\&&&&&T\end{bmatrix}$$

in which T is the simulation step.

the state vector of m_2 is $X_2(k)=\left[x,y,z,v_x,v_y,v_z,a_x,a_y,a_z\right]^T$, the state-transition matrix is:

$$F_2=\begin{bmatrix}1&0&0&\frac{\sin\omega T}{\omega}&0&0&\frac{1-\cos\omega T}{\omega^2}&0&0\\0&1&0&0&\frac{\sin\omega T}{\omega}&0&0&\frac{1-\cos\omega T}{\omega^2}&0\\0&0&1&0&0&\frac{\sin\omega T}{\omega}&0&0&\frac{1-\cos\omega T}{\omega^2}\\0&0&0&\cos\omega T&0&0&\frac{\sin\omega T}{\omega}&0&0\\0&0&0&0&\cos\omega T&0&0&\frac{\sin\omega T}{\omega}&0\\0&0&0&0&0&\cos\omega T&0&0&\frac{\sin\omega T}{\omega}\\0&0&0&-\omega\sin\omega T&0&0&\cos\omega T&0&0\\0&0&0&0&-\omega\sin\omega T&0&0&\cos\omega T&0\\0&0&0&0&0&-\omega\sin\omega T&0&0&\cos\omega T\end{bmatrix}$$

IV. THE KILL PROBABILITY OF MISSILE

The kill probability of single missile can expressed as[14]:

$$P_K=\frac{R_K^2}{R_K^2+\frac{R_{0.5}^2}{1.386}}\cdot\exp\left[\frac{-R_T^2}{R_K^2+\frac{R_{0.5}^2}{1.386}}\right]\cdot\left[1-\exp\left(-N_v\cdot P_{ai}\right)\right]$$

(13)

where R_K is the lethal radius of warhead, $R_{0.5}$ is the circular probable error, R_T is the miss distance, N_v is the number of fragment hitting the damageable parts, P_{ai} is the kill probability of single fragment.

In engineering, P_{ai} is obtained by empirical formula:

$$p_{ai}=\begin{cases}0 & E_i\le 19.3\\ 1+2.65e^{-0.34E_i}-2.96e^{-0.14E_i} & E_i>19.3\end{cases} \quad (14)$$

$$E_i=2.18\times10^{-4}\frac{q_f^{1/3}V_{fdi}'^{2}}{h_{ci}} \quad (15)$$

$$V_{fdi}'=\sqrt{V_{fdi}^2+V_t^2+2\cdot V_t\cdot V_{fdi}\cdot\cos(\varsigma)} \quad (16)$$

$$V_{fdi}=V_{fd0}\cdot e^{-K\cdot r} \quad (17)$$

$$K=0.0082\cdot\rho(H)\cdot q_f^{-1/3} \quad (18)$$

$$V_{fd0}=\sqrt{V_{f0}^2+V_m^2-2V_{f0}\cdot V_m\cdot\cos\beta} \quad (19)$$

where, q_f is the fragment mass; V_{fdi} is the impact velocity of fragment, h_{ci} is the equivalent aluminum thickness of i_{th} compartment, V_{fd0} is the dynamic velocity of the fragment, r is the flying distance of fragment, K is the attenuation coefficient of fragment velocity, $\rho(H)$ is the atmospheric density at height H, V_{f0} is the static velocity of the fragment, V_m is the velocity of the missile, β is the intersection angle between V_{f0} and V_{f0}, ς is the intersection angle between target velocity V_t and fragment beam. V_t and V_{fdi} are decomposed along the earth coordinate system in order to simplify the calculation.

V. Effective Fragment Number

1 Fragment Beam Model

The fragment flies in response to gravity and air resistance. Because of the large velocity of the fragment and short intersection period, the gravity can be ignored when compared to the air resistance. So, the fragment is doing a variable decelerated rectilinear motion and the motion equations can be set up[15]. The fragment beam can be divided into infinitesimals which can be confirmed by scattering angle ϕ and azimuth angle θ (as shown in Figure 1). The motion of one single fragment beam in missile body coordinate system can be written as a set of coupled equations:

$$\begin{cases}x_m=l\cos\varphi\\ y_m=l\sin\varphi\cos\theta\\ z_m=l\sin\theta\sin\varphi\end{cases}.$$

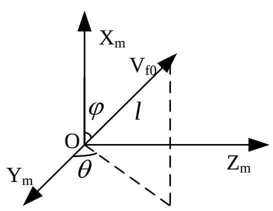

Figure1 Angles of Fragment Beam

where l, which depends on the fragment velocity and its attenuation coefficient, is the flying distance of fragment beam. If let $\varphi_i=\varphi_1+(i-\frac{1}{2})\Delta\varphi$, ($i=1\cdots n_1$), then $\Delta\varphi=\frac{\varphi_2-\varphi_1}{n_1}$, n_1 is the number of the divided angles, φ_1 is the dynamic scattering angle. Dividing θ into n_2 equal parts in the range of 360°, $n_1\times n_2$ fragment beams motion equations could be established.

Because the fragments follows Gaussian distributions in scattering zone, the probability density of single fragment dropped into ϕ_f is:

$$f(\phi_f)=\frac{5.4N_f}{\sqrt{2\pi}\Omega}\exp\left(-\frac{18(\phi_f-\phi)^2}{\Omega^2}\right) \quad (20)$$

If φ is small enough, the fragments in the angle obeys uniform distribution, and the angular density is:

$$f_\phi(\varphi)=f(\phi_f) \quad (21)$$

The 360° space in φ_i is divided into n_2 fragment beams, and the fragment number in each beams follows:

$$M(i,j)=\frac{1}{n_2}f_\phi(\varphi_i)=\Delta\varphi\frac{1}{n_2}\frac{5.4N_f}{\sqrt{2\pi}\Omega}\exp\left(-\frac{18(\varphi_i-\phi)^2}{\Omega^2}\right) \quad (22)$$

For fragment, if the static velocity is $\overline{V_{f0}}$, the dynamic velocity, as shown in Figure 2, is[16]: $\overline{V_{fd0}}=\overline{V_{f0}}+\overline{V_m}$

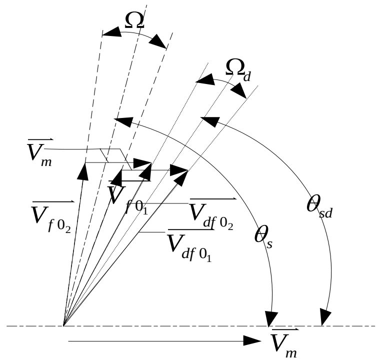

Figure 2 Static and *Dynamic Velocities of Fragment*

Rewritten it into scalar:

$$v_{di}=\sqrt{v_{0i}{}^2+v_m{}^2+2v_{i0}v_m\cos\theta_s} \quad (23)$$

Then the relative dynamic scattering angle (RDSA) of each fragment beam is:

$$\theta_{di}=arc\sin\left[\frac{v_{i0}\sin(\pi-\theta_s)}{v_{di}}\right] \quad (24)$$

In view of the equation $V_{fdi}=V_{fd0}\cdot e^{-K\cdot r}$, the relationship between distance and time of fragment motion can be obtained:

$$dr=V_{fd}\cdot dt=V_{fd0}\cdot e^{-K\cdot r}\cdot dt \quad (25)$$

2 Effective Fragment Number for Killing

The fragments could be supposed to blast at the same time while exploding[17-19], and the fragments have the same velocities and accelerations. Therefore the fragments can be considered in the head of each beam, and have the same motion states and features.

Considering the geometrical parameters of the target, the target surface model is established by plate-element method, as shown in Figure 3.

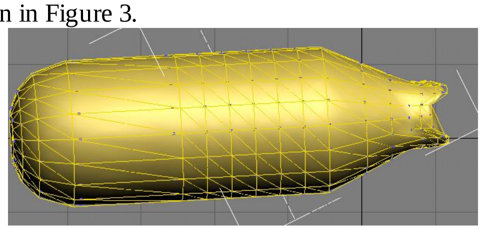

Figure 3 Plate-element Model of Target

ISBN: 978-988-14047-2-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

For each palte-element in Firuge 3, there are 3 vertexes which can determine the location and the normal vector each plate-element. As shown in Figure 4, ΔABC is a plate-element. The normal vector is determined as $\mathbf{n}' = \mathbf{l}_{AB} \times \mathbf{l}_{AC}$ by A,B and C.

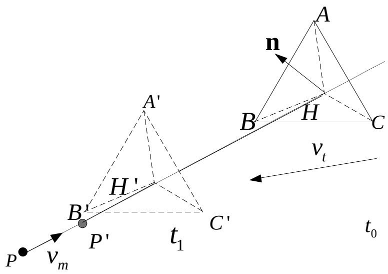

Figure 4 Rendezvousing Between Fragment And Plate-element

In the rendezvous shown in Figure 4，at the time t_0=0, the fragment is at point P, after t_1- t_0, the fragment goes from point P to point P', and plate-element goes from ABC to $A'B'C'$, here, the plane where plate-element lies in and the fragment beam cross at point H'. If at time t^*, P' and H' coincidence, there must be a intersection point between the fragment and the plane, and the coordinates of the point can be obtained according to the track of the fragment. If the point is in the plate-element, by means of triangle-area-method, the point is a hitting point of fragment. For details see [20].

VI. SIMULATION

1 Simulation without Measurement Data

The angular velocity of the target: suppose that M=300m, Y=100m, when 100≤r≤300 there are no measurements. We use IMM to predict the target states. Let the maneuvering model be CT model, and the initial state is $\begin{bmatrix}100 & 200 & 100 & -200 & 210 & 100 & 10 & 2 & 10\end{bmatrix}^T$. The maximum overload that the pilot can bear is 9g. The relationship of plane's angular velocity and maximum overload in 2 seconds are shown in Figure 5 and Figure 6.

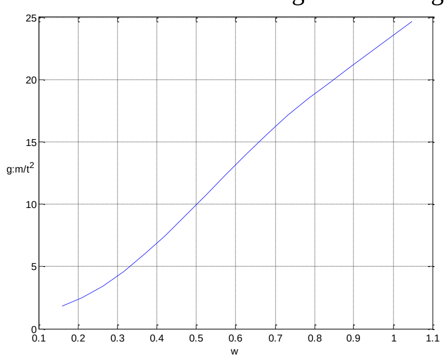

Figure 5 The Maximum overload and angular velocity (ω) in 2 seconds in CT model

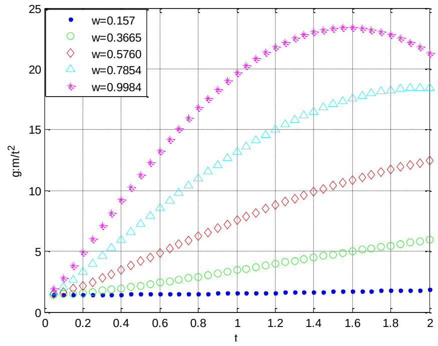

Figure 6 The Overload with Different ω in CT Model

We can see from the figure that when $\omega = 0.38 = \dfrac{\pi}{8.26}$, the maximum overload of the target is 8.98g, so in the simulation, the angular velocity is set as 0.38. .

Scenario 1:

The target is doing CT maneuver before Y>300m, and keeps it up. Using IMM to track the target, the probability of CA is 0.1 while the CT is 0.9, and the transition probability matrix is $\begin{bmatrix}0.98 & 0.02\\ 0.02 & 0.98\end{bmatrix}$. The initial state vector and covariance matrix are:

$$\mathbf{X}_1(0) = \begin{bmatrix}95 & 195 & 105 & -199 & 209 & 100\end{bmatrix}^T,$$

$$P_1(0) = diag\left(\begin{bmatrix}1 & 1 & 1 & 10 & 10 & 10\end{bmatrix}^T\right),$$

$$\mathbf{X}_2(0) = \begin{bmatrix}95 & 195 & 105 & -199 & 209 & 100 & 9.8 & 1.9 & 10.1\end{bmatrix}^T,$$

$$P_2(0) = diag\left(\begin{bmatrix}1 & 1 & 1 & 10 & 10 & 10 & 50 & 50 & 50\end{bmatrix}^T\right)。$$

The predictive track and root mean square error (RMSE) are as follows:

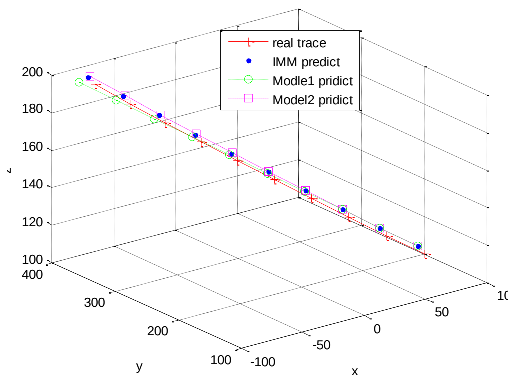

Figure 7 The Predictive Track Using IMM

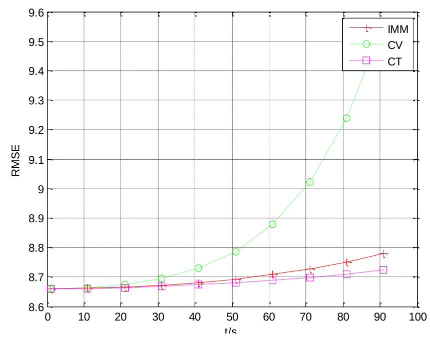

Figure 8 RMSE in IMM, CV and CT models

The figures show that the CT model gives the best result. And the CV model causes big error when the overload becomes large. The IMM algorithm can avoid the error.

ISBN: 978-988-14047-2-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Scenario 2:

The target does CV maneuver when Y>300m and changes to CT immediately when Y<300m. The probability of CA is 0.9 while the CT is 0.1, and $\omega = 0.38 = \dfrac{\pi}{8.26}$. The prediction is shown in Figure9.

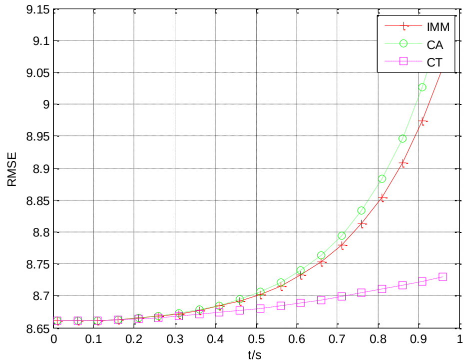

Figure 9 RMSE in IMM

From Figure 9, the models in and before BAOGS give reverse estimate results, and there is no measurement data to correct it, so the prediction is bad.

Scenario 3:

The target does CV maneuver before Y>300m and CT when Y<300m. The probability of CA is 0.1 while the CT is 0.9. The RMSE within maneuver time is shown in Figure 10.

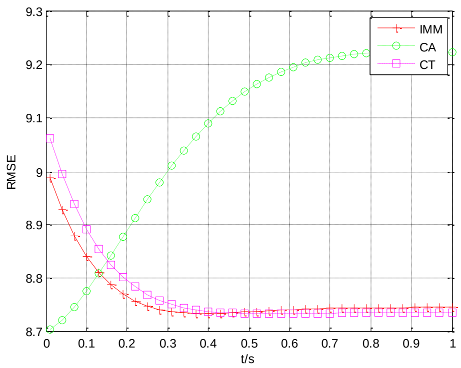

Figure 10 RMSE with Maneuver Time

From Figure 10, if the target does CT before entering into BAOGS, the earlier the model changes, the worse the result becomes. And if the target changes model after 0.4s, the infection is not obvious.

2 IMM Filtering with Distance Measured by Fuse

Narrate by preamble, the state and measurement are:

$$\mathbf{X}(k+1) = \mathbf{F}^{(i)}\mathbf{X}(k) + \mathbf{\Gamma u}(k)$$

$$\mathbf{Z}(k) = \sqrt{x^2(k) + y^2(k) + z^2(k)} + \mathbf{n}(k)$$

There is only distance in measurement.

Firstly, the filtering result is analyzed with only distance measurement, and the BAOGS is excluded.

Scenario 4:

The target does CV maneuver and then CT. The initial state of the target is $[100\ 200\ 100\ \text{-}200\ \text{-}210\ \text{-}100\ 10\ 2\ 10]^T$. The measurement of the fuse is a white Gaussian noise whose expectation is 0, and variance is 2. Using a two models IMM to track the target and we got Figure 11.

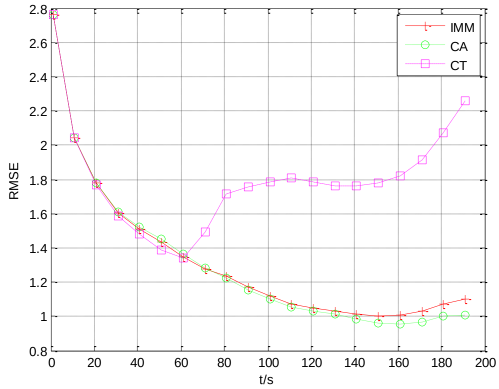

Figure 11 IMM Filtering with Only Distance

As shown in Figure 11, the tracking precision is better when using single model algorithm, but if the model doesn't match, the precision will depressed. Using IMM can effectively avoid the error caused by unmatched model.

3 The Influence on Killing Probability

Scenario 5:

There are 2500 fragments in the warhead, the static scattering angel is 15°, the static flying direction angle is 90°, the rendezvous velocity is 600m/s, the static initial velocity of fragment is 2000m/s, the fragment mass is 4g, the efficient killing radius is 7m, the vital part is a 2×3×5（unit：m）cuboid. Then the miss distance and the fragment number that hit the target is shown in Figure 12.

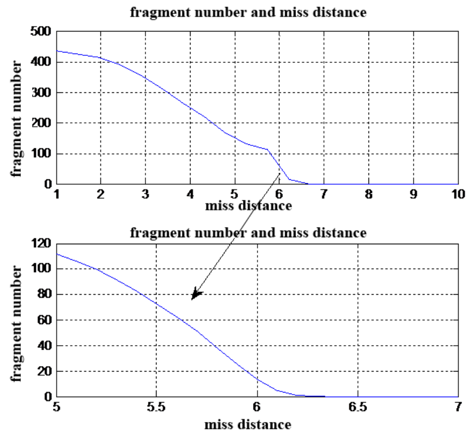

Figure 12 Fragment Number and Miss Distance

As shown in Figure 12, we can conclude that the veracity of miss distance prediction affects the hit number and then the kill probability. From Scenario 2 and Scenario 3, the earlier the target changes its maneuver, the more obvious the influence is in the 0.4s when the missile entering into its BAOGS. Since when the missile enters into its BAOGS is uncertain, the time target changes its maneuver is random. Suppose that the time obeys uniform distribution in a time interval. The variances of miss distance prediction and the true miss distance with maneuver changing time are drawn in Figure 13. From the figure we can see that the IMM algorithm is the most stable method.

ISBN: 978-988-14047-2-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

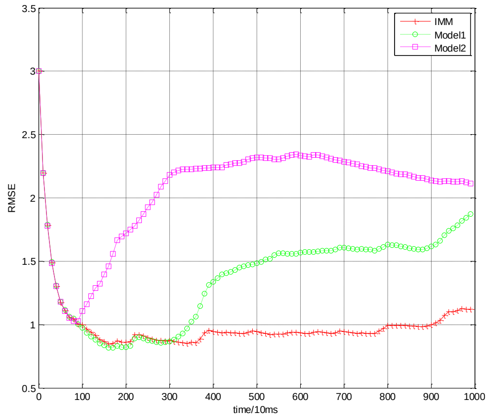

Figure 13 Variances of Different Method

VII. CONCLUDING REMARKS

In the problem of assessing the real-time effectiveness of air-to-air missile, the veracity of miss distance prediction affects the result directly. The IMM algorithm, after analyzing the change of information in the tail end of the attacking process and the rendezvous between the target and the missile, is given to predict the target track. The distance measured by fuse is used to avoid the influence caused by the unmatched model. The validity and stability are demonstrated by simulation. That enhances the reliability of prediction. But there are only CV model and CT model in IMM algorithm model set; further research is needed to solve the problem.

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