A METHOD OF MANEUVER IDENTIFICATION AND TRAJECTORY PREDICTION FOR AGILE TARGET

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Abstract

For the existing target seeker of the air-to-air missile, it has time delay when obtaining the precise target information under noise and disturbance. Meanwhile, the evading ability of a new generation of targets is increasing rapidly, which will result in greater miss distance without compensation, therefore effective methods for target state prediction are needed. To satisfy the development of the new generation air-to-air missile, a new type of prediction method is designed against the common maneuver model of the agile targets avoiding air-to-air missiles.

Firstly, starting from the target, several types of the maneuvers of agile target avoiding missiles such as circle, barrel, are investigated, the maneuvering trajectory is modeled offline, and an extensible target maneuver model library is established.

Then, an adaptive noise filter is designed to denoise the measurement noise. Meanwhile, this article has carried on the statistics and the analysis to the library of target maneuver model, three of the most common functions are identified as fitting functions, and the fitting order is optimized. The sampler, identification process, predictor and adaptive Kalman filter are designed according to the target maneuver characteristics, which constitute the maneuver identification predictor.

Finally, the target maneuver is predicted based on the results of online identification, and the time delay is compensated and corrected. Thus, the precision attack of the agile air target is realized. The simulation demos are excuted based on the classic chase model of missile and target in three dimension, the results show that the proposed method has high prediction accuracy and hit accuracy for different types of target maneuver.

Keywords: target maneuver; offline modeling； online identification； measurement noise； adaptive filtering

1. General Introduction

During the last several years, large quantity of method have been designed to predict the motion of target. The target model is the base of the target estimation method. The modelling method which is used in most literatures describes the maneuvering acceleration of a target as a time-dependent stochastic process, such as constant velocity (CV), constant acceleration (CA), coordinate turn (CT) and current statistical (CS). CS model is a kind of practical model which is most commonly used at present. The CS model considers that when the target is maneuvering with an acceleration, the acceleration value of the next moment is limited, and only in the field of the current acceleration, the predicted value of the "current" acceleration of the maneuvering target is the mean value [1]. The above methods only predict the maneuvering of the target statistically. However, a specific model has not been built.

When it comes to the guidance laws, ranging from proportional navigation (PN) to robust control algorithms. The PN guidance law and its variations have been widely used due to the advantages such as simple form and easy implementation [2, 3]. The PN guidance law can achieve high precision against nonmaneuvering targets. For maneuvering targets, if the target acceleration information can be estimated accurately, the augmented proportional navigation and the predictive guidance law are proposed to improve guidance precision [4, 5]. On the contrary, in practice, the target acceleration is difficult to be estimated precisely. In order to solve this problem, some robust control algorithms have been used to design guidance laws, such as the H∞ guidance (H∞ G) law [6], the Lyapunov nonlinear guidance law [7].

In this paper, a new method which is based on the maneuver type identification is proposed to predict the trajectory of target. A typical maneuvering model library is constructed for identification.

2. Maneuver Description and Model Establishment

In the air combat, the target can take action to avoid incoming missiles. With the development of fighter aerodynamic design and engine performance, the existing air-to-air missile guidance law is difficult to attack the high maneuvering target effectively. The specific maneuvering characteristics of the high maneuvering target need to be modeled in detail and the corresponding guidance law is required. In this section, some typical aircraft avoidance actions are analyzed and their kinematic models are established according to the characteristics of the target typical maneuver.

In order to facilitate the description of the target maneuvering action, the geographic coordinate system (OXYZ) is used as the reference coordinate system. The coordinate origin is the projection point of the missile launch point on the local horizontal plane. The OX axis points to the east in the tangent direction of the weft of the origin, OZ axis alongs the origin of the line where the tangent direction points to the north, OY axis points to the sky according to the right hand rule. Where the maneuvering model is the X-axis forward direction.

2.1 Accelerating Maneuver

Accelerating maneuver is the basic maneuver to avoid missile. After finding missiles, pilots will increase throttle to get higher velocity and prepare for subsequent large overloads. In the BVR, the target can also take an acceleration to escape the effective range of missiles. Accelerating maneuver is shown in Figure 1.

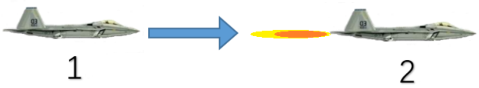

Figure 1 – Accelerating maneuver

Accelerating maneuver takes acceleration along the X-axis, without velocity and acceleration on the other axes. The kinetic model of the maneuver model is described as follows:

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2}=a_1,\quad \frac{\mathrm{d}^2y}{\mathrm{d}t^2}=0,\quad \frac{\mathrm{d}^2z}{\mathrm{d}t^2}=0 \tag{1}$$

The corresponding target velocity equation is

$$\frac{\mathrm{d}x}{\mathrm{d}t}=a_1t+v_{1x},\quad \frac{\mathrm{d}y}{\mathrm{d}t}=0,\quad \frac{\mathrm{d}z}{\mathrm{d}t}=0 \tag{2}$$

The maneuvering trajectory can be described as

$$x=0.5a_1t^2+v_{1x}t+x_0,\quad y=y_0,\quad z=z_0 \tag{3}$$

where (x_0,y_0,z_0) is the initial target position, v_{1x} is the initial velocity of target, t is time.

2.2 Circle/Loop Maneuver

Circle is a kind of common planar maneuver, and the flight trajectory is nearly circular in the maneuvering plane. If the maneuvering plane is parallel to the local horizontal plane, it is called circling maneuver, when the maneuvering plane is perpendicular to the local level, it is called loop. Circle/loop maneuver is shown in Figure 2.

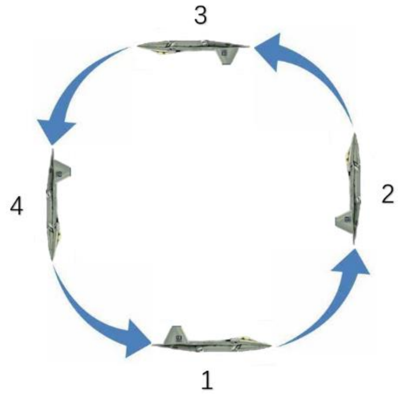

Figure 2 – Circle/loop maneuver.

The circle maneuver is a plane maneuver in the XOZ plane, there is no velocity and acceleration in the Y-axis. Loop maneuver is equivalent to change the plane to XOY. If trajectory is a circle, the maneuver can be described by equation

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2}=a_2\sin\left(\omega t+\omega_0\right),\quad \frac{\mathrm{d}^2y}{\mathrm{d}t^2}=0,\quad \frac{\mathrm{d}^2z}{\mathrm{d}t^2}=a_2\cos\left(\omega t+\omega_0\right) \tag{4}$$

In general, the velocity along X and Z axises is 0, the corresponding target velocity expression is

$$\frac{\mathrm{d}x}{\mathrm{d}t}=-\frac{a_2}{\omega}\cos\left(\omega t+\omega_0\right),\quad \frac{\mathrm{d}y}{\mathrm{d}t}=0,\quad \frac{\mathrm{d}z}{\mathrm{d}t}=\frac{a_2}{\omega}\sin\left(\omega t+\omega_0\right) \tag{5}$$

In circle maneuvering, v_{2x} , v_{2z} is 0, the maneuvering trajectory can be described as

$$x=x_0-\frac{a_2}{\omega^2}\sin(\omega t+\omega_0)\quad,\quad y=y_0,\quad z=z_0-\frac{a_2}{\omega^2}\cos(\omega t+\omega_0) \tag{6}$$

2.3 Immelman Turn/Split S

The initial state of Immelman turn can be considered as horizontal flight, however, the plane will change to inverse direction after a half cycle of the loop maneuver has been completed. In addition, the plane will roll to change its direction in order to achieve a semi cycle to level flight.

Split S engage roll for a semi cycle to inverted fly, then take a semi loop maneuver to level flight. The two maneuvering directions are reversed and can be equivalent to a half of loop maneuvering. Immelman Turn/ Split S maneuver is shown in Figure 3.

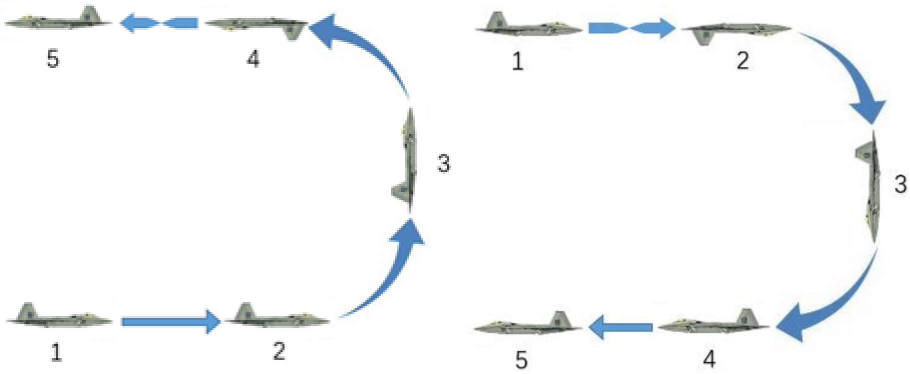

Figure 3 – Immelman turn/ split s.

2.4 Snake Maneuver

Snake maneuver not only maintain considerable forward velocity, but also produce a certain lateral acceleration, its cycle and amplitude have a larger adjustment space, the trajectory of snake maneuver "S" shape. Snake-like maneuvering is shown in Figure 4.

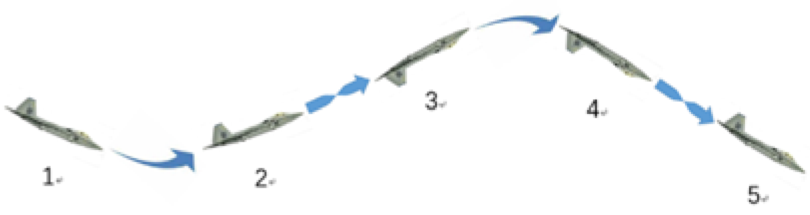

Figure 4 – Snake maneuver.

Snake maneuver is in the XOZ plane, aircraft keeps a constant velocity along X-axis. Meanwhile, the velocity on Z-axis changes in sinusoid wave, there is no velocity or acceleration in the Y-axis. The acceleration can be described by

$$\frac{d^2x}{dt^2}=0,\quad \frac{d^2y}{dt^2}=0,\quad \frac{d^2z}{dt^2}=a_3\sin(\omega t+\omega_0) \tag{7}$$

In general, the initial velocity in the X-axis is v_{3x}, the offset velocity in the Z-axis is 0, and the corresponding target velocity expression

$$\frac{dx}{dt}=v_{3x},\quad \frac{dy}{dt}=0,\quad \frac{dz}{dt}=-\frac{a_3}{\omega}\cos\left(\omega t+\omega_0\right) \tag{8}$$

Its trajectory can be described as

$$x=x_0+v_{3x}t,\quad y=y_0,\quad z=z_0-\frac{a_3}{\omega^2}\sin\left(\omega t+\omega_0\right) \tag{9}$$

2.5 Barrel roll

Barrel roll maneuver is one of the most effective missile defense maneuvers, with trajectory like a helix that can move forward while maintaining high lateral acceleration. The lateral overload direction of barrel roll maneuver changes rapidly, which can make full use of the shortcomings of the missile guidance system with delay, to make the guidance system of the missile change the instruction repeatedly. When the instruction changing frequency exceeds the system bandwidth, the rudder unable to track the acceleration instruction of the guidance system in time, and the dynamic error is increasing, which increases the error and leads to the missile miss. Barrel roll maneuver is shown in Figure 5.

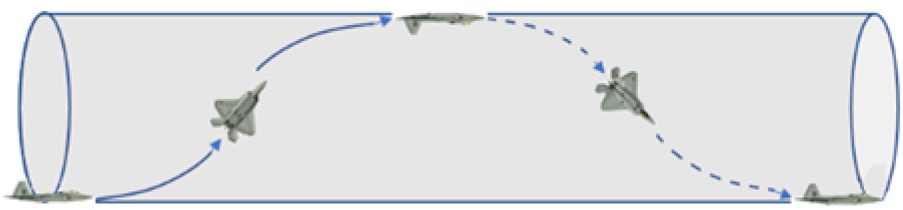

Figure 5 – Barrel roll.

The barrel roll maneuver can be separated into a straight line along the X-axis and a circular motion in the YOZ plane, and further split of the Y-axis and Z-axis can get two sine trajectories. The acceleration can be described by the following

$$\frac{d^2x}{dt^2}=0,\quad \frac{d^2y}{dt^2}=a_4\sin\left(\omega t+\omega_0\right),\quad \frac{d^2z}{dt^2}=a_4\cos\left(\omega t+\omega_0\right) \tag{10}$$

In general, the initial velocity in the X-axis is v_{4x} , the offset velocity in the Z-axis is 0, there is a corresponding target velocity expression

$$\frac{\mathrm{d}x}{\mathrm{d}t} = v_{4x}\,,\quad \frac{\mathrm{d}y}{\mathrm{d}t} = -\frac{a_4}{\omega}\cos\left(\omega t + \omega_0\right),\quad \frac{\mathrm{d}z}{\mathrm{d}t} = \frac{a_4}{\omega}\sin\left(\omega t + \omega_0\right) \tag{11}$$

Its trajectory can be described as

$$x = x_0 + v_{4x}t\,,\quad y = y_0 - \frac{a_4}{\omega^2}\sin\left(\omega t + \omega_0\right),\quad z = z_0 - \frac{a_4}{\omega^2}\cos\left(\omega t + \omega_0\right) \tag{12}$$

3. Target Maneuver Identification and Trajectory Prediction

3.1 Function Types Statistic

To build the target maneuver predictor, a table should be established to count the different function types of the above-mentioned maneuvers.

Maneuver types	X-axis	Y-axis	Z-axis
Accelerating	quadratic	linear	linear
Circle/Loop	trigonometric	linear	trigonometric
Immelman turn/Split S	trigonometric	trigonometric	linear
Snake	linear	linear	trigonometric
Barrel roll	linear	trigonometric	trigonometric

Table1 - Function types of classic maneuver.

Three types of functions can be used for fitting the target trajectories by least square method online: linear function, quadratic function and trigonometric function.

Linear function:

$$f(t) = A_1 t + A_2 \tag{13}$$

Quadratic function:

$$f(t) = B_1 t^2 + B_2 t + B_3 \tag{14}$$

Trigonometric function:

$$f(t) = C_1 \sin(C_2 t + C_3) + C_4 \tag{15}$$

Nonetheless, there is a significant disadvantage in the trigonometric function. When the target performs a uniform linear motion or a small acceleration, it may cause a large prediction error. As shown in the figure below: When the target moves at a constant velocity along a line parallel to the Z axis, the velocities in X and Y axises are zero. Since the sampling time is equidistant, each sampling point is equally spaced. When fitting with a trigonometric function, the theoretical amplitude should be zero. On account of the amplitude is not limited, there is a case where the amplitude is a non-zero finite value. When predicting with this parameter, the predicted points obtained will have a large deviation to the actual points.

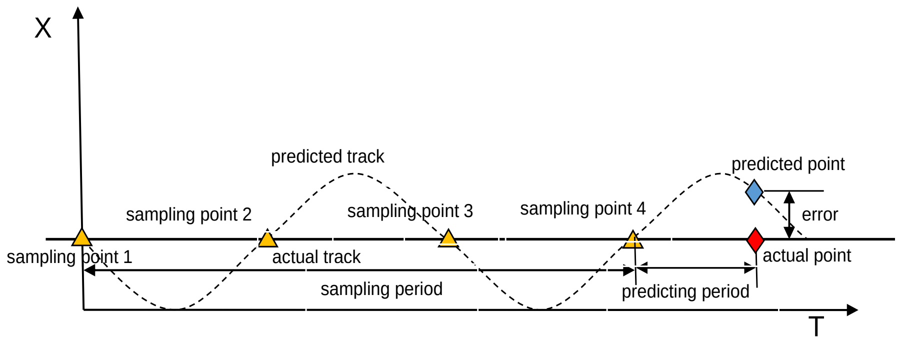

Figure 6 – Error of trigonometric function model.

In this case, using the trigonometric function method for prediction, the data of the sampling point can be placed on the fitted function to ensure a lower residual value, but the accuracy of the prediction result is obviously not as good as the linear function fitting. To summarize, the fitting function types should be arranged in the following order: linear function, quadratic function, trigonometric function.

As a result of the delay of the seeking system, the missile can only get delayed target data. The target maneuver predictor will identify the trajectory of it according to the received location data list and send the result of identification and prediction target location to the guiding system. The structure of target maneuver identification predictor is shown in Figure 7.

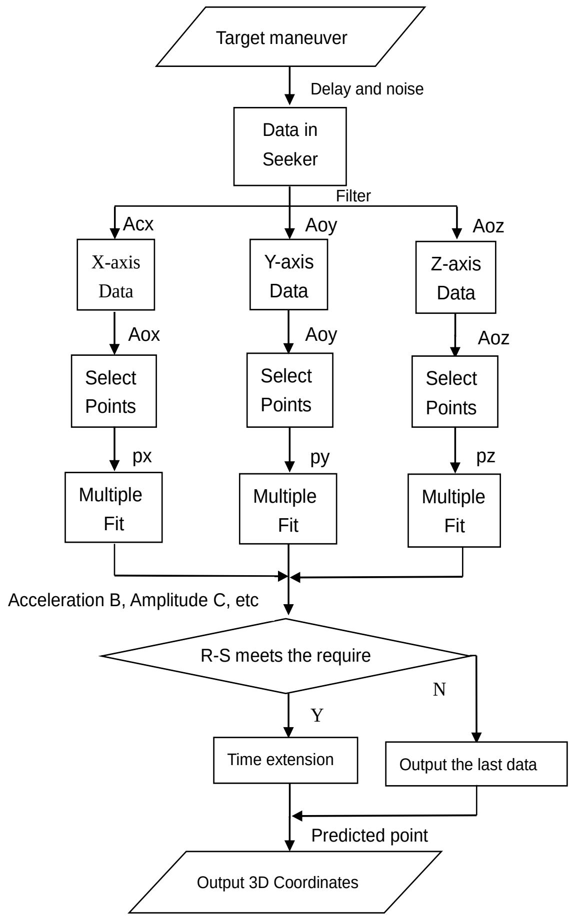

Figure 7 – Flow chart of identification and prediction.

Step 1: The target is detected by the seeker firstly. The target location will be transferred into global coordinate and organized into a time-varying list. In the terminal guidance, the target is locked and be tracked steadily by the seeker.

Step 2: Decoupling the data into three axises. Hence there are three data lists for three individual axises.

Step 3: 15 valid time points are selected in the sequence of T-1.4 , T-1.3……T with 0.1s interval in each list, where T is the latest time.

Step 4: Fitting and identifying the valid data according to the maneuver model library. The maneuver model library utilized in this research is capable of linear, quadratic, trigonometric fitting, through least squares techniques to solve the R-Square. The calculation of R-Square is shown below

$$R-square=\frac{SSR}{SST}=1-\frac{SSE}{SST} \tag{16}$$

Where

$$SSR=\sum_{i=1}^{n}\left(\hat{y}_i-\bar{y}_i\right)^2 \tag{17}$$

$$SST=\sum_{i=1}^{n}\left(y_i-\bar{y}_i\right)^2 \tag{18}$$

$$SST=SSE+SSR \tag{19}$$

Where SSR is the sum of squares of the difference between the prediction data and the original data. SST is the variance of the original data. SSE is the sum of squares of residual error.

Whether the fitting completed or not is depends on the value of R-Square. The standard of R-Square is 0.994 for linear and quadratic function, 0.98 for trigonometric function. After the fitting, the fitting style and factors will be output. If all the fitting function types are judged failure, then the identification are output to be fail.

Step 5: If the identification succeeds, the identified function is extended according to the function type and parameter of the identification, the extension time is equal to the delay of the seeker. In this way, the delay of the target data can be completely compensated by the predictor. If the identification fails, the prediction is invalid, no time extension is executed, and output the most recent data point only. The illustration of prediction method is shown in Figure 8

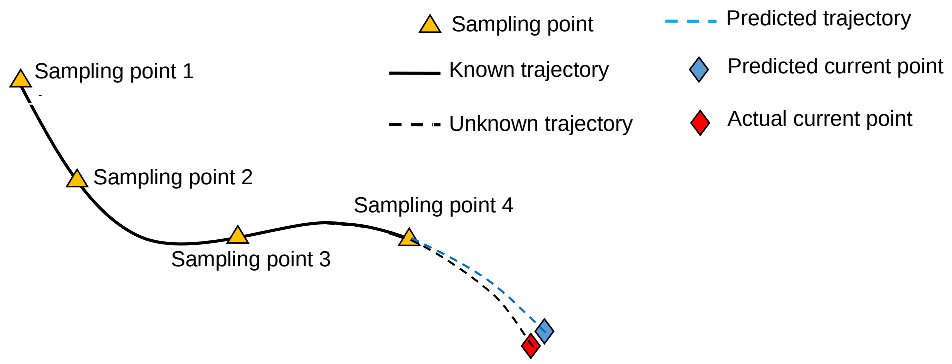

Figure 8 – Illustration of prediction method.

3.2 Filter

Suppose the position vector of the target is given below

$$\boldsymbol{X}=\begin{bmatrix}x & y & z\end{bmatrix} \tag{20}$$

According to the Kalman filter, the discreted state equation of the target is

$$X(k+1)=\boldsymbol{F}(k)X(k)+Q(k) \tag{21}$$

$Q(k)$ is white Caussian distributed with zero mean, $\boldsymbol{F}(k)$ is state transition matrix. Since the discrete interval is short, the motion state of the target is unknown, and the target position at the next moment is unchanged by default

$$\boldsymbol{F} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{22}$$

Assume that the measurement equation of the maneuvering target is

$$Z(k) = \boldsymbol{H}(k)X(k) + R(k) \tag{23}$$

$\boldsymbol{H}(k)$ is the measurement matrix, $R(k)$ is Gaussian white noise during measurement, the single step estimated value of the state is

$$\hat{X}(k+1|k) = \boldsymbol{F}(k)\hat{X}(k|k) \tag{24}$$

The measurement of estimated state is

$$\hat{Z}(k+1|k) = \boldsymbol{H}(k+1)\hat{X}(k+1|k) \tag{25}$$

The single-step prediction of covariance is

$$P(k+1|k) = \boldsymbol{F}(k)P(k|k)F^{'}(k) + Q(k) \tag{26}$$

The Kalman gain is

$$K(k+1) = P(k+1|k)H^{'}(k+1)/[H(k+1)P(k+1|k)H^{'}(k+1) + R(k+1)] \tag{27}$$

$$\hat{X}(k+1|k+1) = \hat{X}(k+1|k) + K(k+1)[Z(k+1) - \hat{Z}(k+1|k)] \tag{28}$$

where $\hat{X}(k+1|k+1)$ is the optimal estimated value of target state in $k+1$. The updated covariance is

$$P(k+1|k+1) = [1 - K(k+1)H(k+1)]P(k+1|k) \tag{29}$$

where $P(k+1|k+1)$ covariance of target state in $k+1$, taken as the initial value of the next iteration with $\hat{X}(k+1|k+1)$ together.

3.3 Adaptive Kalman Filter with Fading Factor

The current filtered value of the classic Kalman filter brings all previous data into calculation. These data will gradually accumulate by the time, causing the new measurement value to gradually reduce the ability to correct the optimal estimated value. Especially when the target changes the maneuver state, the classic Kalman filter causes a large time delay and error accumulation. Then, adaptive Kalman filter is used to improve the weight of new measurement data during filtering and avoid excessive accumulation of previous data.

New covariance prediction formula is

$$P(k+1|k) = \lambda_k \boldsymbol{F}(k)P(k|k)F^{'}(k) + Q(k) \tag{30}$$

where λ_k is fading factor, $\lambda_k \geqslant 1$, which increases the gain of the Kalman filter, increasing the weight of the measurement data when calculating the state estimate. The value of λ_k depends on the estimation method. A new method of calculating fading factors based on innovation covariance is presented by the following[8]

$$V(k+1) = Z(k+1) - \hat{Z}(k+1|k) \tag{31}$$

$$\bar{S}(k+1) = \begin{cases} \dfrac{\lambda_k V(k+1)V(k+1)^{\mathrm{T}}}{1+\lambda_k}, k \geq 1 \\ 0.5V(0)V(0)^{\mathrm{T}}, k = 0 \end{cases} \tag{32}$$

$$S(k+1) = H(k+1)P(k+1|k)H^{'}(k+1) + R(k+1) \tag{33}$$

$$\lambda_{k+1} = \max\left\{1, \frac{\mathrm{trace}(\bar{S}_{k+1})}{\mathrm{trace}(S_{k+1})}\right\} \tag{34}$$

where $V(k+1)$ is innovation, $\bar{S}(k+1)$ is innovation covariance calculated according to actual measured data, $S(k+1)$ is innovation covariance calculated according to the filter function. $\mathrm{trace}(\bar{S}_{k+1})$ and $\mathrm{trace}(S_{k+1})$ are the traces of $\bar{S}_{k+1}$ and S_{k+1} respectively.

4. SIMULATION

In this chapter, the performance of the new method of identification and prediction has been tested by simulations. The target is an agile UAV. According to the typical air combat situation, at the beginning the target maintains constant straight flight, a few seconds after the missile launch, the target detect the arrival of the missile, then immediately begin to maneuver. The three examples in this chapter correspond to three typical evasive maneuvers, and the initial states are as follows:

The initial point of missile

$$x_{m0} = 0m$$

$$y_{m0} = 1000m$$

$$z_{m0} = 0m$$

The initial point of target

$$x_{t0} = 5000m$$

$$y_{t0} = 4000m$$

$$z_{t0} = 3000m$$

The delay of seeker is 0.5s. During the first 2s of the simulation, the missile stays on the carrier. During 2~2.5s, the missile flies out along the launcher, the elevation and azimuth of the launch is 30 degrees, and after the launch, keep straight flight. After 2.5s, the flight trajectory is changed according to the command of the control system. The proportional coefficient is 4. After the simulation is started, the target is flying according to the intended trajectory. The velocity of missile is 300m/s, the velocity of target is 100m/s. Every example runs in classic proportional navigation (PN) and proportional navigation with linear prediction only for comparison. The predicted points in different methods are shown in the following figure

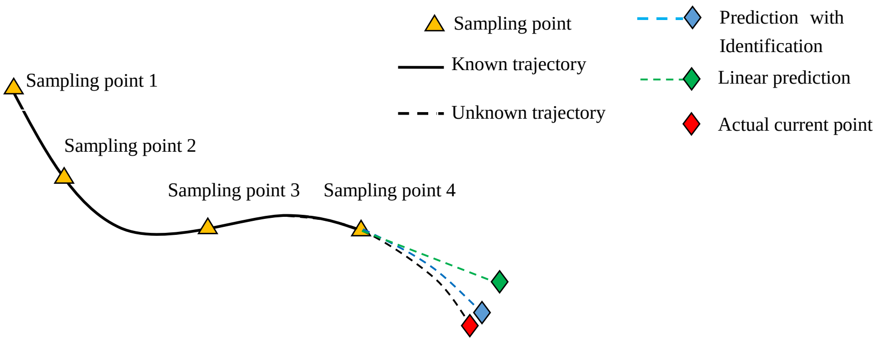

Figure 9 – Prediction in three methods for simulation.

4.1 Missile-target Kinematic Model

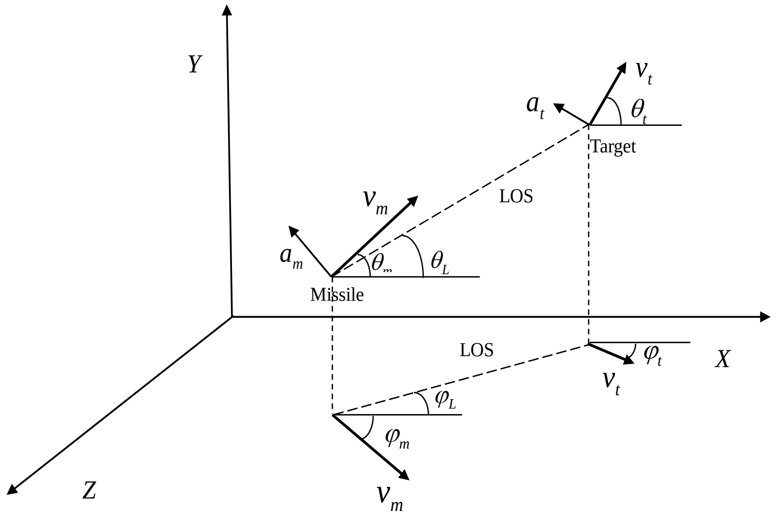

Figure 10 – 3D model of missile and target.

The three-dimensional pursuit-evasion geometry is described in the spherical LOS coordinates. By virtue of principles of kinematics, the relative motion can be expressed by the following nonlinear differential equations.

$$\begin{cases} \dot{r} = v_{\mathrm{t}} \cos\theta_{\mathrm{t}} \cos\varphi_{\mathrm{t}} - v_{\mathrm{m}} \cos\theta_{\mathrm{m}} \cos\varphi_{\mathrm{m}} \\ \dot{\theta}_L = \dfrac{v_{\mathrm{t}} \sin\theta_{\mathrm{t}} - v_{\mathrm{m}} \sin\theta_{\mathrm{m}}}{r} \\ \dot{\varphi}_L = \dfrac{v_{\mathrm{t}} \cos\theta_{\mathrm{t}} \sin\dot{\varphi}_{\mathrm{t}} - v_{\mathrm{m}}\theta_{\mathrm{m}} \sin\varphi_{\mathrm{m}}}{r\cos\theta_{\mathrm{L}}} \\ \dot{\theta}_{\mathrm{m}} = \dfrac{a_{\mathrm{zm}}}{v_{\mathrm{m}}} - \dot{\varphi}_L \sin\theta_L \sin\varphi_{\mathrm{m}} - \dot{\theta}_L \cos\varphi_{\mathrm{m}} \\ \dot{\varphi}_{\mathrm{m}} = \dfrac{a_{\mathrm{ym}}}{v_{\mathrm{m}} \cos\theta_{\mathrm{m}}} + \dot{\varphi}_L \sin\theta_L \tan\theta_{\mathrm{m}} \cos\varphi_{\mathrm{m}} - \dot{\theta}_L \tan\theta_{\mathrm{m}} \sin\varphi_{\mathrm{m}} - \dot{\varphi}_L \cos\theta_L \\ \dot{\theta}_{\mathrm{t}} = \dfrac{a_{\mathrm{zm}}}{v_t} - \dot{\varphi}_L \sin\theta_L \sin\varphi_{\mathrm{t}} - \dot{\theta}_L \cos\varphi_{\mathrm{t}} \\ \dot{\varphi}_{\mathrm{t}} = \dfrac{a_{\mathrm{yt}}}{v_{\mathrm{t}} \cos\theta_{\mathrm{t}}} + \dot{\varphi}_L \sin\theta_L \tan\theta_{\mathrm{t}} \cos\varphi_{\mathrm{t}} - \dot{\theta}_L \tan\theta_{\mathrm{t}} \sin\varphi_L - \dot{\varphi}_L \cos\theta_L \end{cases} \tag{35}$$

where r and $\dot{r}$ are radial relative distance and velocity between missile and target. v_t and v_m are velocity of target and missile. a_{zt} and a_{yt} are tangential and normal acceleration of target. a_{zm} and a_{ym} are tangential and normal acceleration of missile. θ_t and φ_t are elevation and azimuth of target. θ_m and φ_m are elevation and azimuth of missile. θ_L and φ_L are elevation and azimuth of line of sight(LOS).

4.2 Guidance Law

The proportional guidance is utilized as the guidance law of the missile navigation system. The pitch control and yaw control are independent with each other as following

$$\dot{\theta}_{\mathrm{m}} = K_{\mathrm{theta}} \dot{\theta}_{\mathrm{L}} \tag{36}$$

$$\dot{\varphi}_{\mathrm{m}} = K_{\mathrm{psai}} \dot{\varphi}_{\mathrm{L}} \tag{37}$$

where K_{theta} is proportional navigation coefficient in pitch control, K_{psai} is proportional navigation coefficient in yaw control. Gravity is taken into consideration. The guidance loop of missile is shown as following

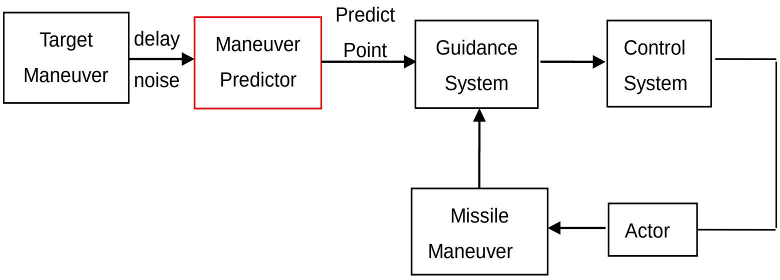

Figure 11 – Guidance loop of missile.

4.3 Case 1: Circle Maneuver

Between t=0s and t=12s, the path of the target is a straight line. Its initial elevation and heading are -5.7deg and 185.7deg, respectively. When t=12s, the target begin to perform circle maneuver, the overload is 5.5g, the simulation results are shown in figure below. The vertical axis represents different identification results, in which number 2 represents the linear function, number 3 is quadratic function, number 4 is about trigonometric function and number 0 is regarded as identification failure. The measurements for every axis are added Gaussian white noise with variance of 3.

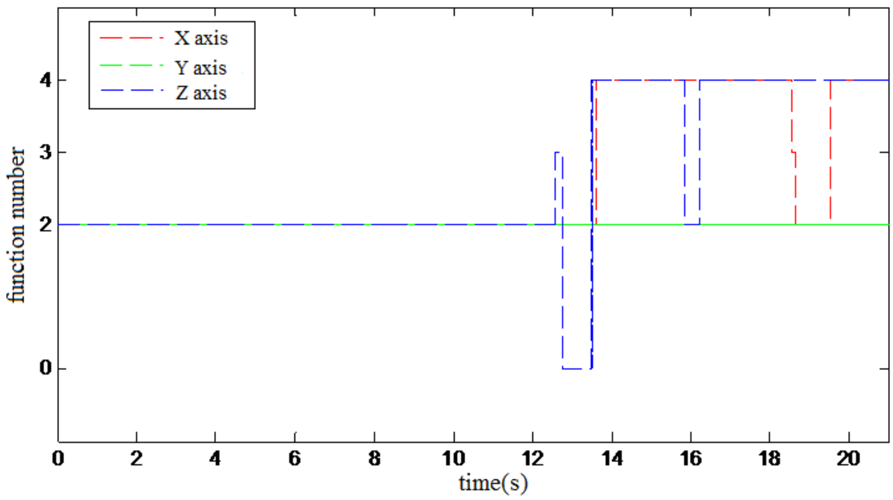

Figure 12 – Results of function fitting in case 1.

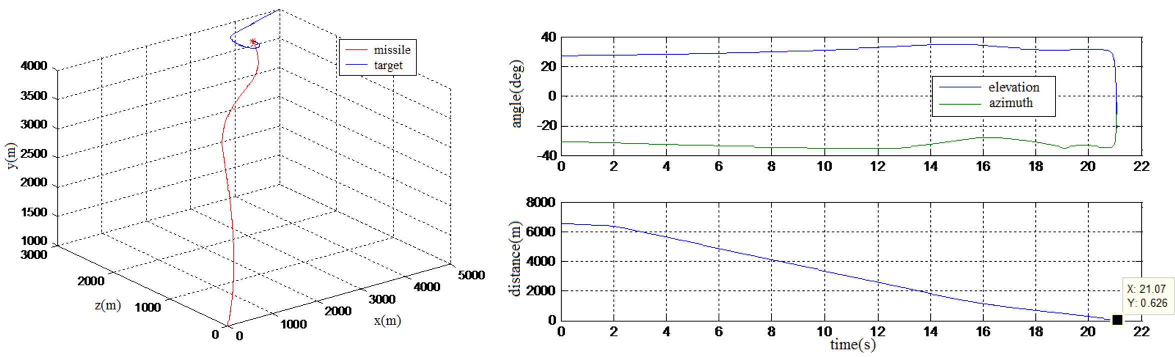

Figure 13 – 3D track and guidance information in case 1.

The miss distance of the three guidance laws are shown in the following table

Guidance Law	Miss Distance (m)
PN with maneuver prediction	0.626
PN with linear prediction	6.861
PN only	48.64

Table2 - Miss distances of three guidance laws in case 1.

4.4 Case 2: High-g Barrel Roll

Between t=0s and t=10s, the path of the target is a straight line. Its initial elevation and heading are -5.7deg and 185.7deg, respectively. When t=10s, the target begin to perform barrel roll, the overload is 19g, the simulation results are plotted in figure below.

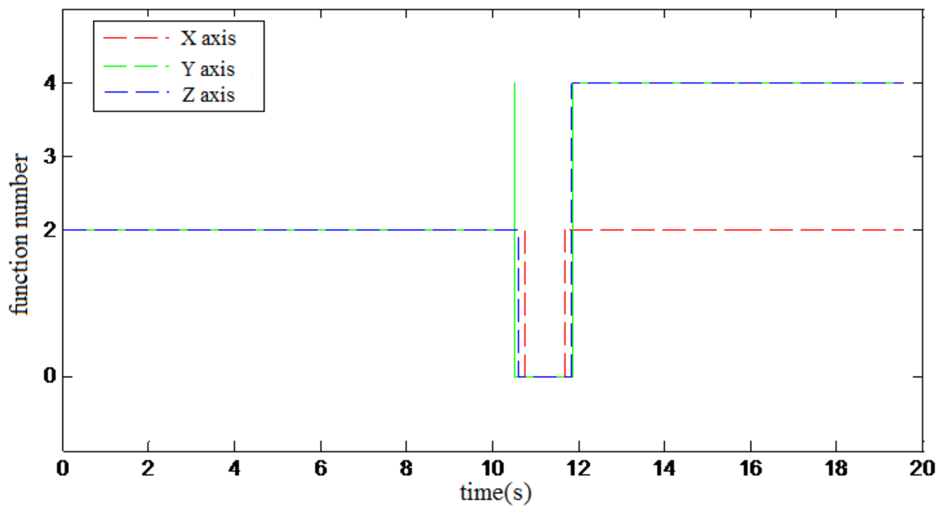

Figure 14 – Results of function fitting in case 2.

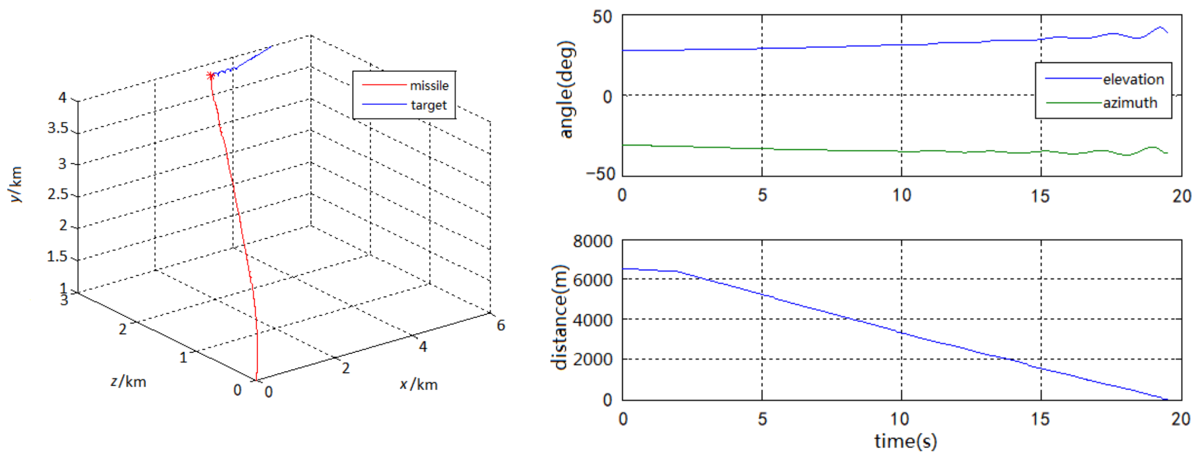

Figure 15 – 3D track and guidance information in case 2.

The miss distance of the three guidance laws are shown in the following table

Guidance Law	Miss Distance (m)
PN with maneuver prediction	0.639
PN with linear prediction	23.02

PN only	49.17

Table3 - Miss distances of three guidance laws in case 2.

4.5 Case 3: High-g Combined Maneuver

Between t=0s and t=6s, the path of the target is a straight line. Its initial elevation and heading are -5.7deg and 185.7deg, respectively. When t=6s, the target turn left to circle, the overload is 5.5g, and the cycle of loop is 12s, maintaining the descent velocity of 10m/s, when t=11.8s, the target begin to engage barrel roll, the overload is 19g, the simulation results are plotted in figure below.

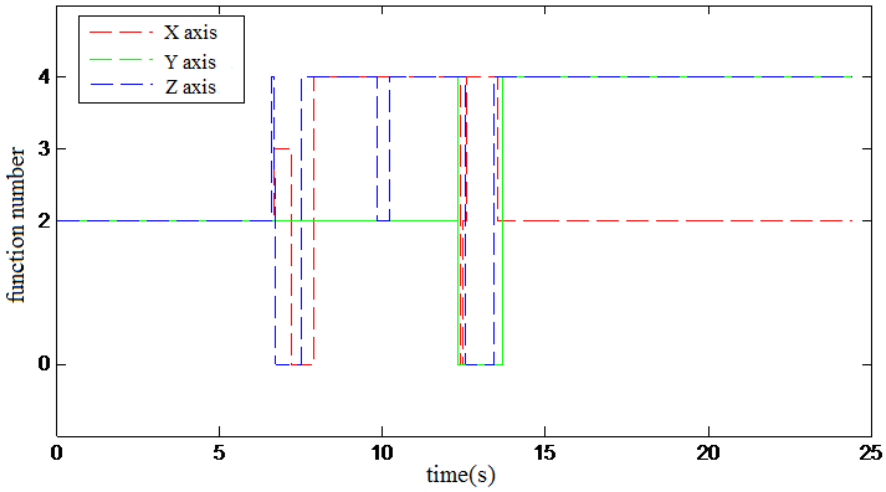

Figure 16 – Results of function fitting in case 3.

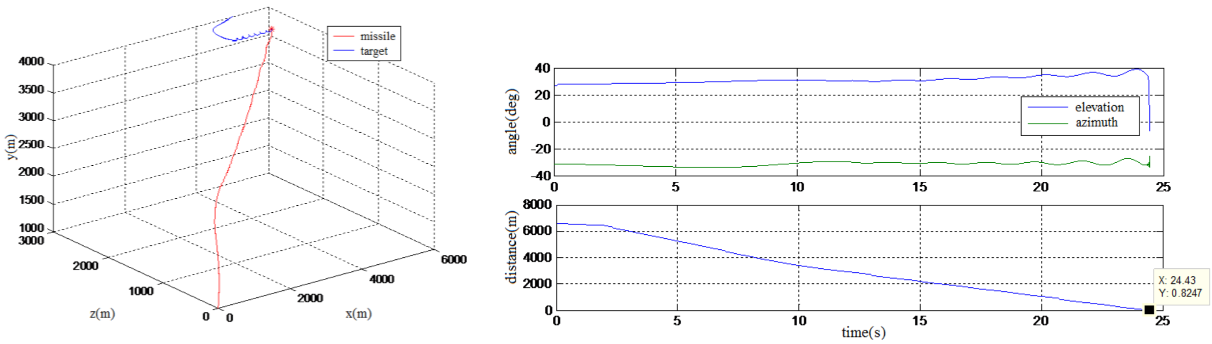

Figure 17 – 3D track and guidance information in case 3.

The miss distance of the three guidance laws are shown in the following table

Guidance Law	Miss Distance (m)
PN with maneuver prediction	0.825
PN with linear prediction	23.09
PN only	48.55

Table4 - Miss distances of three guidance laws in case 3.

The simulation results show that: for the typical maneuvering target, the guidance law with maneuver identification and prediction can make the miss distance under 1 meter, which meet the requirement of kinetic warhead, while the miss distances of simple proportional guidance laws are more than 5 meters, which is difficult to hit the target. The maneuvering identification predictor has high identification precision for the typical evasive maneuver against missile, which can compensate the observation delay of the target accurately. The guidance law with linear prediction assumes that the target is not maneuvered during the delay period, and the distance of delay is compensated according to the last observed information. The greater the target maneuver overload, the worse the compensation effect.

5. Conclusion

The typical maneuvers of agile aircraft to avoid the missile are analyzed and modeled, and the model library is established. At the same time, the target maneuver predictor is designed based on the fitting results with adaptive Kalman filter. After completed fitting and identification process, the simulation is proceeded based on the proportional navigation guidance. The maneuvering type can be identified accurately when the target is in the typical evasive maneuver, and the delay caused by the seeker can be compensated precisely, which solves the problem that if a single model which is not in the model library will have low fitting precision on low overload maneuver. The established target maneuvering model library is extensible, and new maneuver models can be added to the model library in the future. The simulation results shown that this method has advantages over other guidance laws.

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