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A Fuzzy Optimal Sliding-Mode Guidance for Intercepting Problem

Zhiwei Hou * **Mao Su** ** **Yongji Wang** *** **Lei Liu** ****

School of Automation, Key Laboratory of Ministry of Education for Image Processing and Intelligent Control, Huazhong University of Science and Technology, Wuhan, China

* *e-mail: houzw@hust.edu.cn*
** *e-mail: sumao1988@hust.edu.cn*
*** *e-mail: wangyjch@hust.edu.cn*
**** *e-mail: liulei@hust.edu.cn*

Abstract: In this paper, a novel terminal guidance law is proposed to solve the problem of exo-atmospheric interception. It is designed based on the proportional navigation (PN) and the classical optimal sliding-mode guidance (OSMG). It overcomes the shortcoming of these two traditional guidance laws and inherits their merits. Particularly, in the scenario of exo-atmospheric interception, when the maneuvering information of the targets are *unavailable*, the proposed guidance law has superior performance than the traditional guidance law. Briefly, to enhance the interceptive performance, we introduce the optimal control and sliding-mode control methods to the guidance law for maneuvering target's interception. On the other hand, the traditional proportional navigation law is introduced to intercept the target with a constant speed. After that, a fuzzy switching function is provided to harmonize both situations above, according to the real-time estimation of maneuver. To guarantee the stability of the law, a Lyapunov based condition is obtained. Finally, different from the two-dimensional simulation in most of the literatures of terminal guidance law researches, we illustrate our method in the nonlinear discrete three-dimensional simulation environment by the Runge-Kutta method. Compared with the pure OSMG and PN, the proposed law performs better.

Keywords: Terminal guidance, Optimal control, Sliding-mode control, Fuzzy control, Lyapunov stability.

1. INTRODUCTION

Guidance law is indispensable at the interception of a target by missile. Dynamic processes of the interception are determined by corresponding guidance laws, and so to the interception effectiveness. Hence, to design a missile is greatly depending on the design of guidance law.

The most widely used guidance law is traditional proportional navigation (PN). Ideally, if there are no maneuvering acceleration of target and no acceleration constraints of missile, and ideal dynamics are assumed, PN results in zero miss distance. However, a large number of simulation results showed that when intercepting a maneuvering target, PN was likely to make a lot of miss distance, see Andrieu et al. (2006). Furthermore, in this case, the overload of missile and the line-of-sight (LOS) rate between the missile and the target have poor characteristics.

Optimal control methodology was used in guidance law design, see Friedrichs et al. (2012) and Reisner et al. (2011). In Hu et al. (2010), a linear optimal guidance law was designed based on a quadratic objective function. Compared with the traditional proportional guidance, it reduces the need of missile overload. The disadvantage is that poor performance when intercepting maneuvering targets.

In Lu et al. (2006), a nonlinear optimal guidance law was designed to get smaller miss distance and better ballistic characteristics. However, it is highly complex and has poor practicability.

Nonlinear control method, such as sliding-mode control, was also used in guidance law design. See Shima et al. (2012) and Harl and Balakrishnan (2009). In Luo et al. (2012) and Gu et al. (2008), on the basis of the linear optimal guidance law, optimal sliding-mode guidance law (OSMG) was designed. In Zhou et al. (1999), an adaptive sliding-mode guidance (ASMG) was designed. The variable structure control theory was used to enhance robustness. When intercepting maneuvering targets using OSMG or ASMG, a certain degree of miss distance is reduced. However, OSMG and ASMG have the same disadvantage. Both of them have a big sliding mode item which guarantees the stability but causes the chattering problem near the switch surface. It makes missile hard to capture the target through the sensor as well as increase the switching frequency of orbit-control engine.

In order to estimate the target maneuvering, a number of estimation algorithms had been studied. See Yang et al. (2005), Qin et al. (2007) and Guo et al. (2008). In Sun et al. (2008), a method of estimating target maneuvering was proposed and the author separated the estimate of target maneuvering from the sliding mode item. What remained in the sliding mode item was a very small positive number. In this way, ASMG or OSMG can not only make the system quickly enter into the sliding mode surface but also effectively weaken chattering near the switch surface. But when intercepting constant speed targets, it makes more miss distance than PN does. Not surprisingly, on one hand, with appropriate effective navigation constant, PN can be proven to be a perfect guidance law only considering miss distance, on the other hand, the method of estimating target maneuvering can not be absolutely accurate.

PN doesn't perform on a sufficient basis at the interception of maneuvering targets. ASMG and OSMG are able to intercept maneuvering targets but may bring in more miss distance if compared with PN when intercepting targets at constant speed. In a real intercepting scenario, the information of target maneuvering is unknown to the missile and the target might even only maneuver for some time during the intercepting process. So, it is necessary to design a new guidance law in the absence of the maneuvering information of targets. In this paper, a new guidance law with strong robustness to target maneuver is derived by combining PN and OSMG together through a fuzzy switching function and the real-time estimation of target maneuvering. The stability of the new guidance law is analyzed by a Lyapunov function and the stability condition is obtained. The simulation results from different target maneuver conditions reveal that the new guidance law has superior performance than that of PN and OSMG.

The main contributions of this paper are:

(1) Designing a new guidance law of which the fault of PN and OSMG have can be conquered meanwhile their merits are inherited as well. Especially, this new guidance law has superior performance when intercepting the *unknown* maneuvering information targets.
(2) Using a method of estimating target maneuvering to weaken chattering of missile and ensure the stability of it.
(3) Obtaining the stability condition of the new guidance law.

2. MISSILE-TARGET RELATIVE MOTION MODEL

An exo-atmospheric interception problem is handled in this paper and here is no aerodynamic forces. So we assume that in the process of intercepting, a missile with separated guidance and control dynamics is considered. And missile rolls stably such that the guidance problem can be treated as planar in two perpendicular channels. We first present the full nonlinear planar relative motion model of missile and target, which will serve for the simulation and analysis of the guidance laws presented in the sequel. Then, a linearized motion model will be obtained, which will be used in guidance laws designing.

2.1 Nonlinear Motion Model

In order to simplify the problem, we establish a planar relative motion equation of missile and target at first. In Fig. 1, a schematic view of the planar endgame geometry

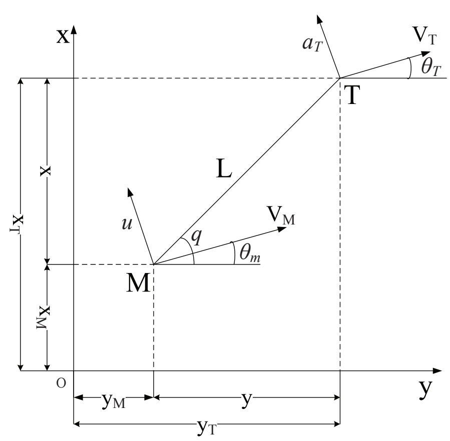

Fig. 1. Planar engagement geometry.

is shown, where $x - o - y$ is a fixed inertial reference frame. M and T are the shorthand of missile and target, respectively. We denote the variables associated with them by subscripts M and T, respectively. The speed is denoted by V and flight path angle is denoted by θ. The target-missile LOS angle is q, and L is the range between M and T. Then, we project the range L onto the x and y axis and get the projection vector $[x_1, y_1]$, and relatively the speed projection on the x and y axis is $[x_2, y_2]$. $[x_3, y_3]$ is the acceleration projection on the x and y axis. The lateral acceleration of missile and target are denoted by u and a_T, respectively. The nonlinear motion equation of missile and target can be established as follows.

$$\begin{cases} x_1 = x = x_T - x_M, \\ x_2 = \dot{x} = \dot{x}_T - \dot{x}_M = V_T \sin\theta_T - V_M \sin\theta_M, \\ x_3 = a_T \cos\theta_T + u\cos\theta_M, \\ y_1 = y = y_T - y_M, \\ y_2 = \dot{y} = \dot{y}_T - \dot{y}_M = V_T \cos\theta_T - V_M \cos\theta_M, \\ y_3 = a_T \sin\theta_T + u\sin\theta_M. \end{cases} \tag{1}$$

At the same time, q can be obtained as (2)

$$q = \arctan\frac{x}{y}. \tag{2}$$

2.2 Linearized Motion Model

We let the x axis to be aligned with the initial LOS and assume that linearization of the endgame geometry can be performed around the initial LOS so that q, θ_M and θ_T are small enough, that is to say

$$\begin{cases} \cos\theta_T \approx 1, \\ \sin\theta_T \approx \theta_T, \\ \cos\theta_M \approx 1, \\ \sin\theta_M \approx \theta_M. \end{cases} \tag{3}$$

Meanwhile

$$q \approx \frac{x}{y}. \tag{4}$$

In the linearized motion model, we do not care about y_1, y_2 and y_3. We consider only errors projection on the x. So we choose x_1 and x_2 as the states of the system. The linearized planar relative motion can be expressed as (5).

$$\dot{X} = AX + Bu + Da_T. \tag{5}$$

where

$$X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, D = \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \quad (6)$$

3. FUZZY OPTIMAL SLIDING-MODE GUIDANCE & STABILITY

In this section, we use optimal control methodology to design optimal guidance law. At the same time sliding-mode control methodology has been used to design OSMG as well. Based on classical PN and OSMG, we then apply a fuzzy switching function and a method of estimating target maneuvering to design a new guidance law, namely fuzzy optimal sliding-mode guidance law (FOSMG). At last, we analyze the stability of the FOSMG by using Lyapunov method and obtain its stability condition.

3.1 Fuzzy Optimal Sliding-Mode Guidance

1) Optimal Guidance

Assuming that the lateral acceleration of target is zero ($a_T = 0$), equation (5) can now be simplified as (7).

$$\dot{X} = AX + Bu. \quad (7)$$

The quadratic performance index function is chosen as (8). The initial and final time are denoted by t_0 and t_f, respectively.

$$J = \frac{1}{2}X^T(t_f)CX(t_f) + \frac{1}{2}\int_{t_0}^{t_f}(X^TQX + u^TRu)dt. \quad (8)$$

where

$$C = \begin{bmatrix} c_1 & 0 \\ 0 & c_2 \end{bmatrix}, Q = [0]_{2\times 2}. \quad (9)$$

c_1 is the terminal miss-distance weight coefficient and c_2 is that of terminal velocity. The missile overload weight coefficient is denoted by R. Because terminal velocity has no effect on miss-distance, in this paper, we ignore it. That is to say, we make $c_2 = 0$. Then, using minimum principle, we define the Hamiltonian function as (10).

$$H = \frac{1}{2}u^TRu + \lambda^T(AX + Bu) = \frac{1}{2}Ru^2 + \lambda_1 x_2 + \lambda_2 u. \quad (10)$$

Where λ is the undetermined coefficient of the function.

$$\lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix}. \quad (11)$$

By solving this optimal control problem, we obtain the optimal control strategy $u_{og}(t)$ in (12) to minimize the quadratic performance index function (8).

$$u_{og}(t) = -\frac{3(t_f - t)x_1(t) + 3(t_f - t)^2 x_2(t)}{\frac{3R}{c_1} + (t_f - t)^3}. \quad (12)$$

By taking the derivative of (4) with respect to time, the LOS rate can be expressed as the following function.

$$\dot{q} = \frac{x_1 + (t_f - t)\dot{x}_1}{V_c(t_f - t)^2} = \frac{1}{V_c}\left[\frac{x_1}{(t_f - t)^2} + \frac{x_2}{t_f - t}\right]. \quad (13)$$

Where V_c is the closing speed between missile and target. Substituting (13) into (12), we obtain

$$u_{og}(t) = -\frac{3V_c(t_f - t)^3}{\frac{3R}{c_1} + (t_f - t)^3}\dot{q}. \quad (14)$$

Equation (14) is the analytical expression of the optimal guidance law.

2) OSMG

Then on this basis we apply sliding-mode control method to derive OSMG. In the process of interception, the missile will intercept the target successfully if the LOS rate, $\dot{q}$, approaches to zero. Hence based on the principle of quasi parallel approaching method, the switch function is chosen as follow.

$$s = \dot{q} = K_1(t)X = \begin{bmatrix} \frac{1}{V_c(t_f - t)^2} & \frac{1}{V_c(t_f - t)} \end{bmatrix} X. \quad (15)$$

From the relationship of (7) and (12), we obtain the optimal motion outside of the sliding mode surface as the following function.

$$\dot{s} = N(t)s. \quad (16)$$

Where

$$N(t) = \frac{2[\frac{3R}{c_1} + (t_f - t)^3] - 3(t_f - t)^3}{(t_f - t)[\frac{3R}{c_1} + (t_f - t)^3]}. \quad (17)$$

In order to make the missile chatter less in the sliding motion and ensure that all trajectories starting from any point reach to sliding surface in finite time, we apply the reaching law as follow.

$$\dot{s} = -K(t)s - E(t)\mathrm{sgn}s. \quad (18)$$

Where

$$K(t) = -N(t). \quad (19)$$

$$E(t) = \frac{\varepsilon}{V_c(t_f - t)}, \varepsilon = const > 0. \quad (20)$$

From the relationship of (7)(13)(15), and (18), substituting the sign function sgn$\dot{q}$ by a continuous function as (21) showing, using the method proposed in Sun et al. (2008) to weaken the chattering phenomenon, we obtain the analytical expressions of OSMG as (22).

$$\mathrm{sgn}(\dot{q}) \approx \varepsilon\frac{\dot{q}}{|\dot{q}| + \sigma}. \quad (21)$$

$$u_{osmg}(t) = -\frac{3V_c(t_f - t)^3}{\frac{3R}{c_1} + (t_f - t)^3}\dot{q} - \varepsilon\frac{\dot{q}}{|\dot{q}| + \sigma} - \omega(t - \tau). \quad (22)$$

Where ε is a positive real number and σ is a small positive real number satisfying σ approaches to 0. $\omega(t - \tau)$ is the estimation of target maneuvering, proposed in Sun et al. (2008), as (23) showing which will be used in FOSMG designing as well. Details on the value of ε will be discussed in later subsection.

$$\begin{aligned} \omega(t - \tau) = {} & L(t - \tau)\ddot{q}(t - \tau) \\ & -2V_c(t - \tau)\dot{q}(t - \tau) - u(t - \tau). \end{aligned} \quad (23)$$

Where τ is a time constant and $\omega(t-\tau)$, which is obtained from the dynamic relationships in the process of interception, represents the estimation of target maneuvering at $t - \tau$. When τ is small enough, $\omega(t - \tau)$ is approximately equal to the current target maneuvering.

3) FOSMG

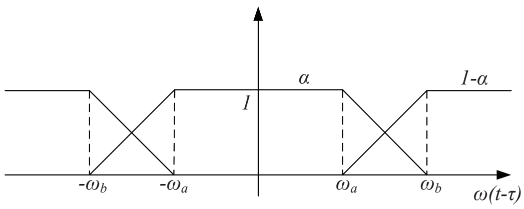

Fig. 2. Fuzzy Switching Function

In Zhang and Man et al. (2000), a new fuzzy sliding mode control scheme was proposed and a fuzzy switching function was introduced to change the sliding mode surfaces smoothly, see Fig. 2. In this paper, we use the same fuzzy switching function $\alpha(\omega)$ to change PN and OSMG smoothly when the estimation of target maneuvering changes. A new guidance law, FOSMG, is shown as the following function.

$$u^*(t) = \alpha u_{pn}(t) + (1-\alpha)u_{osmg}(t) - \alpha\omega(t-\tau). \tag{24}$$

Where u_{pn} is the traditional proportional navigation as (25).

$$u_{pn}(t) = -3V_c\dot{q}. \tag{25}$$

The fuzzy switching function $\alpha(\omega)$ works according to the following rules:

(1) When the absolute value of $\omega(t-\tau)$ is smaller than ω_a, $\alpha = 1$;
(2) When the absolute value of $\omega(t-\tau)$ is bigger than ω_b, $\alpha = 0$;
(3) When $\omega_a < |\omega(t-\tau)| < \omega_b$,

$$\alpha = \frac{\omega_b - |\omega(t-\tau)|}{\omega_b - \omega_a} < 1. \tag{26}$$

Pay attention to (24), the reasons for subtracting $\alpha\omega(t-\tau)$ is that this kind of design plays a very important role in stability analysis.

3.2 Stability Analysis

In this subsection, we use Lyapunov method to analyze the stability of FOSMG. In the process of interception, the missile will intercept the target successfully if the LOS rate, $\dot{q}$, approaches to zero. Therefore, we choose $\dot{q}$ to be the state of the system to analyze the stability, which is the linear combination of x_1 and x_1 as shown in equation (13).

By dynamic relationships in the process of interception, we can obtain the following equation (27).

$$\ddot{q} = \frac{2}{t_f - t}\dot{q} + \frac{1}{V_c(t_f-t)}u + \frac{1}{V_c(t_f-t)}\omega. \tag{27}$$

Where u and ω represent the lateral acceleration of missile and target, respectively.

Lyapunov function is chosen as follow.

$$V = \frac{\dot{q}^2}{2}. \tag{28}$$

Using the relationship of (24)(27), and (28), assuming that τ is small enough and $\omega(t-\tau) \approx \omega(t)$, we obtain

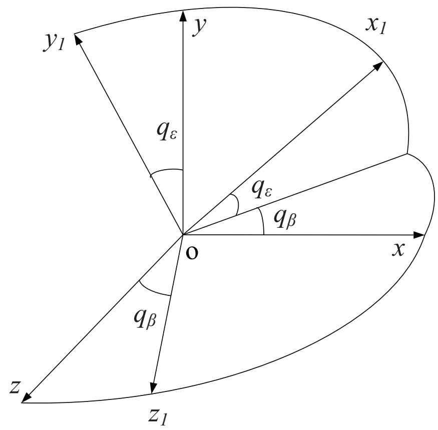

Fig. 3. Coordinates transform.

$$\begin{aligned}\dot{V} = \frac{\dot{q}^2}{t_f - t}[2 - &\frac{3(1-\alpha)(t_f-t)^3}{\frac{3R}{c_1} + (t_f-t)^3} \\ &-\frac{(1-\alpha)\varepsilon\mathrm{sgn}\dot{q}}{V_c\dot{q}} - 3\alpha].\end{aligned} \tag{29}$$

We introduce a new variable called $\hat{\dot{V}}$ here.

$$\hat{\dot{V}} = \frac{\dot{q}^2}{t_f - t}[2 - \frac{(1-\alpha)\varepsilon\mathrm{sgn}\dot{q}}{V_c\dot{q}} - 2\alpha]. \tag{30}$$

It is evidently clear that $\dot{V} < \hat{\dot{V}}$.

If we choose

$$\varepsilon > 2V_{cmax}\dot{q}_{max}, \tag{31}$$

it can be obtained that $\dot{V} < \hat{\dot{V}} < 0$, and $\dot{q}$ is stable. Inequation (31) is the stability condition of FOSMG, where V_{cmax} and $\dot{q}_{max}$ represent the largest closing speed and LOS rate during the guidance, respectively.

From (31) we can see that, the stability condition is unrelated to α. That is to say, the fuzzy switching function parameters, ω_a and ω_a, can be chosen freely.

4. SIMULATION RESULTS

To look at the performance of FOSMG, we use a sample exo-atmospheric interception simulation. Assuming that the missile guidance and control dynamics are separated and no coupling is considered in the process of exo-atmospheric interception, the guidance problem can be treated independently in the three-dimensional coordinate system which is denoted by $o - x_1 - y_1 - z_1$. In both perpendicular planes, LOS are denoted by q_ε and q_β, respectively. As shown in Fig. 3, $o-x-y-z$ is the inertial coordinate system and $o - x_1 - y_1 - z_1$ denotes the sight coordinate system.

Through this method, the nonlinear discrete three dimensional simulation is used to illustrate the performance of FOSMG and compare it with that of PN and OSMG.

In the inertial coordinate system, initial kinematic parameters of both missile and target are shown in Table 1 and Table 2.

Table 1. Initial parameters of Missile

$X_m(m)$	$Y_m(m)$	$Z_m(m)$	$X_{mv}(m/s)$	$Y_{mv}(m/s)$	$Z_{mv}(m/s)$
64591	0	0	-677	1698	4365

Table 2. Initial parameters of Target

$X_t(m)$	$Y_t(m)$	$Z_t(m)$	$X_{tv}(m/s)$	$Y_{tv}(m/s)$	$Z_{tv}(m/s)$
0	30445	70976	5174	-1034	-1988

The acceleration of gravity(g) is 9.81m/s^2. The missile's maximum overload is $6g$ and the target's maximum overload is $4g$. We suppose that the lateral acceleration of target changes with time as a sine wave to imitate its maneuvering. The discrete simulation method in Sun et al. (2008) is used. This method is closer to engineering practice and considers the step of the detecting loop being larger than that of the control loop. In this paper, the step of the control loop is set to be 0.1ms and the step of the detecting loop is 1ms.

Table 3. Simulation parameters

OSMG	FOSMG
$R = 1$, $c_1 = 1$	$R = 1$, $c_1 = 1$
$\varepsilon = 10$,$\sigma = 0.0001$	$\varepsilon = 10$,$\sigma = 0.0001$, $\omega_a = 10$,$\omega_b = 20$

Table 4. Miss-distance of different guidance laws in different target maneuver conditions

Target	Miss-Distance(m)		
	PN	OSMG	FOSMG
No maneuvering	0.5254	0.8561	0.5290
Maneuvering	25.4609	0.2887	0.2285
0s-6s Maneuvering	0.7856	0.8095	0.7741
2s-6s Maneuvering	0.2171	0.3683	0.0975

By the Runge-Kutta simulation method, table 4 presents the miss distance of different guidance laws in different target maneuver conditions. Results show that FOSMG overcomes the shortcoming of OSMG, which makes slightly larger miss distance than PN when intercepting the constant speed targets without maneuvering. Furthermore, FOSMG appears better performance on the miss distance than that of PN and OSMG when the target only maneuvers for some time. Admittedly, the simulation results depend on many factors, such as the simulation step size, and so on.

Let the target maneuver from the time of 2 to 6 second. We can see from Fig. 4 to Fig. 6 that, when PN is used, the lateral acceleration of missile sustains till the end of guidance but OSMG and FOSMG jump to 0 instantly at the 6 second because they enter into the sliding mode surface quickly. It illustrates that the OSMG and the FOSMG will have better effective on energy saving.

From figures Fig. 7 to Fig. 9, we can see that compared with PN, OSMG and FOSMG effectively weaken the chattering phenomenon of missile. So it is easier for missile to capture the target through the sensor and the switching frequency of orbit-control engine is reduced.

5. CONCLUSION

A Fuzzy Optimal Sliding-Mode Guidance Law (FOSMG) is presented in this paper. It overcomes the shortcoming

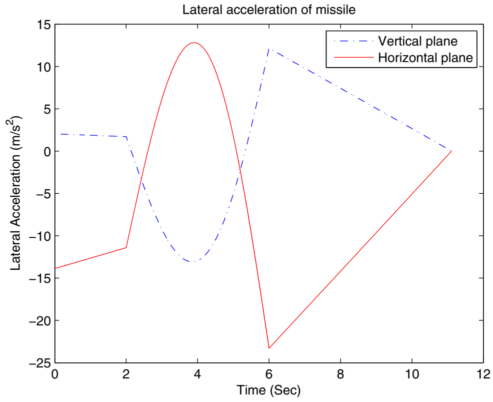

Fig. 4. PN lateral acceleration.

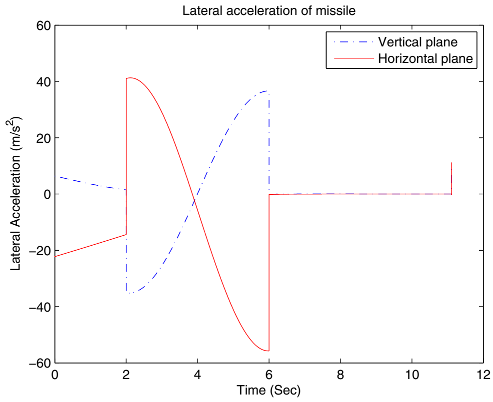

Fig. 5. OSMG lateral acceleration.

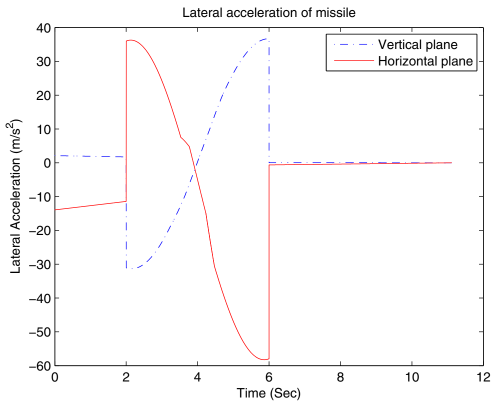

Fig. 6. FOSMG lateral acceleration.

of classical PN and OSMG but inherits their merits in different situations. Specially, FOSMG can get more satisfied miss distance than that of PN and OSMG when the target only maneuvers occasionally. It's noteworthy that, according to the analysis of Lyapunov stability, the stability condition of FOSMG is unrelated to the fuzzy switching function due to introduction of the real-time estimation of target maneuvering. That is to say, the parameters of FOSMG are independent to the target maneuvering and can be chosen freely. Therefore, the proposed guidance law has enough automatic adaptation ability for the maneuvering of target. It could be widely

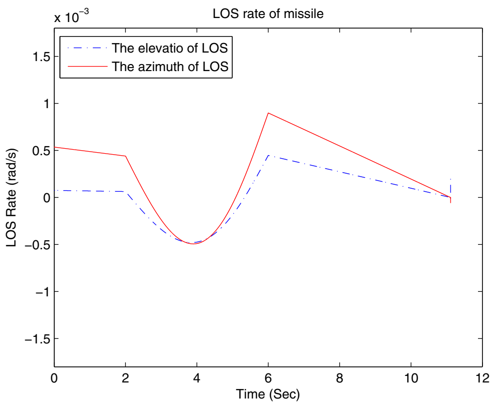

Fig. 7. PN LOS rate.

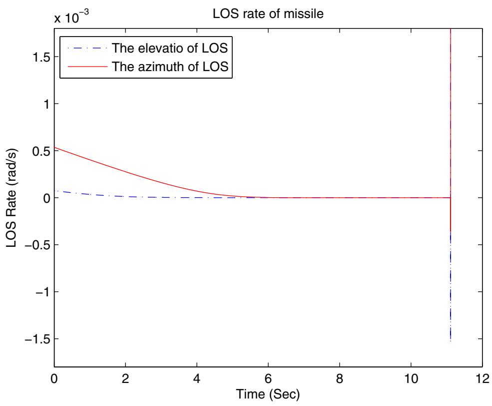

Fig. 8. OSMG LOS rate.

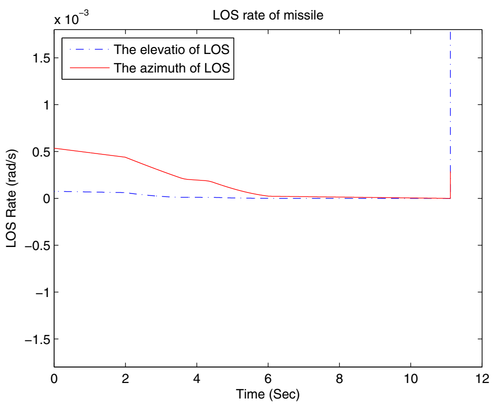

Fig. 9. FOSMG LOS rate.

implemented to the scenarios where the maneuvering information of targets is unavailable.

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