IJST, Transactions of Electrical Engineering, Vol. 39, No. E1, pp 55-66
Printed in The Islamic Republic of Iran, 2015

VARIABLE STRUCTURE FINITE TIME GUIDANCE LAW WITH AUTOPILOT LAG*

M. GOLESTANI, I. MOHAMMADZAMAN** AND A. R. VALI

Dept. of Electrical Engineering, Malek-Ashtar University of Technology, Tehran, I. R. of Iran
Email: mohammadzaman@mut.ac.ir

Abstract– In this paper, the problem of finite time stabilization for guidance system is investigated and a novel nonlinear guidance law against maneuvering targets is proposed based on the principles of parallel navigation. The proposed law is developed using two variable structure control techniques. By applying finite time integral sliding mode and combining it with terminal sliding mode, a new guidance law with finite time convergence is designed. It is demonstrated that the proposed law is able to drive the line-of-sight (LOS) angular rate to the origin in finite time, before the final time of guidance process. Due to their crucial importance, the autopilot dynamics are taken into account and finite time stability of the guidance system is guaranteed in spite of the autopilot dynamics. Furthermore, in practice, it is desirable that the target acceleration be regarded as an unknown bounded disturbance. Since the proposed law is robust against target maneuvers, the exact measurement or estimation of the target acceleration is not required. Three-dimensional simulation results verify the robustness and usefulness of the proposed technique.

Keywords– Finite time guidance law, autopilot dynamics, variable structure control, proportional navigation

1. INTRODUCTION

Proportional navigation (PN) is known as the most popular approach to design guidance law due to its simplicity and efficiency; so, it has drawn the attention of many researchers [1, 2].

Sliding mode control is one the most efficient methods to deal with model uncertainties and disturbances in control systems [3, 4]. During recent years, the sliding mode approach has also been used to design guidance law. In [5], a guidance law has been proposed based on first-order sliding mode so that it is robust against target maneuvers and it doesn't need the exact measurement of the target maneuvers. By considering the dynamics of interceptor's autopilot, a sliding mode-based guidance law with angle of attack constraint has been presented [6]. According to the principles of partial stability, a nonlinear guidance law against maneuvering targets has been designed [7]. This approach is based on the classification of the state variables within the guidance system dynamics with respect to their required stabilization properties.

In recent years, the finite time stability for feedback control systems has become an active research area [8-11]. Using finite time stability approach, a guidance law has been proposed in [12]. The proposed law is able to guide the LOS angular rate to zero or a small vicinity of zero when the target maneuver is neglected. By introducing a new approach of finite time stability, a guidance law with finite time convergence has been presented based on Lyapunov scalar differential inequality [13], so that it is as complex as a first-order sliding mode guidance law. In [14, 15], two finite time convergent guidance laws have been proposed based on terminal sliding mode. These laws ensure that the LOS angular rate and the

*Received by the editors October 29, 2013; Accepted April 14, 2015.
**Corresponding author

LOS angular converge to zero and a desired impact angle respectively. However, they suffer from singularity. Non-singular terminal sliding mode approach has been used in order to overcome the singularity problem [16, 17]. The time taken to reach the equilibrium point from any initial state is guaranteed to be finite. To estimate the acceleration of the maneuvering target, a linear extended state observer is constructed [18]. The authors in [19, 20] presented two adaptive nonsingular terminal sliding mode-based guidance laws which do not require knowledge of the upper bound of the system uncertainties.

Although the above guidance laws possess finite time convergence property, they were designed for ideal dynamics of interceptor. From a practical point of view, the interceptor dynamics may severely affect the miss distance. When actual dynamics are considered, at the vicinity of the interception, the LOS angular rate diverges and, correspondingly, the required interceptor maneuver accelerates. As a result, the guidance loop tends to instability. By considering the dynamics of the interceptor's autopilot as a first-order lag, guidance laws with finite time convergence have been designed in [21-23].

Integral sliding mode can be described by adding an integrator in the sliding surface. A significant advantage of integral sliding mode is the improvement of the problem of reaching phase. In reaching phase, state variables have not yet reached the sliding surface, so the system is sensitive to any uncertainties or disturbances [24]. The issue of improving reaching phase has drawn an increasing attention in system and control theory; see, for example, [25]. The integral sliding mode control must maintain the system's trajectories on the integral sliding mode till trajectories converge to zero in spite of any disturbances or uncertainties. This approach has also been used to design guidance law. Using trajectory linearization, an integral sliding mode-based guidance law has been designed in [26].

Motivated by the above discussions, this paper introduces a new nonlinear guidance law against maneuvering targets. Variable structure control method is used to design the proposed guidance law. First, an integral sliding mode manifold including terminal sliding mode manifold is introduced. Then, a guidance law with finite time convergence is designed that is able to guide the LOS angular rate to zero within a finite time. Furthermore, the dynamics of the interceptor's autopilot are considered as a first-order lag.

The rest of this paper is organized as follows. In the next section, system description and problem formulation are given and the main results of the paper are then included, where a guidance law with finite time convergence is developed by combining integral sliding mode and terminal sliding mode approaches. In section 3, the planer finite-time convergent guidance law is extended to three-dimensional model. The simulation results are presented in section 4. Finally, concluding remarks are given in section 5.

2. PLANAR FINITE TIME CONVERGENT GUIDANCE LAWS

a) Formulation of pursuit–target engagement

The geometry of planar interception is shown in Fig. 1. According to the principles of kinematics, the corresponding equations of motion between the target and the interceptor can be described by [13]:

$$\ddot{R} = \dot{\lambda}^2 R + a_{TR} - a_{MR} \tag{1}$$

$$\ddot{\lambda} = -\frac{2\dot{R}}{R}\dot{\lambda} + \frac{a_{T\lambda}}{R} - \frac{a_{M\lambda}}{R} \tag{2}$$

where R denotes relative distance between the target and the interceptor; $\dot{\lambda}$ represents the LOS angular rate; a_{TR} and a_{MR} denote the target and the interceptor acceleration along the LOS, respectively; and $a_{T\lambda}$ and $a_{M\lambda}$ represent the target and the interceptor acceleration normal to the LOS, respectively.

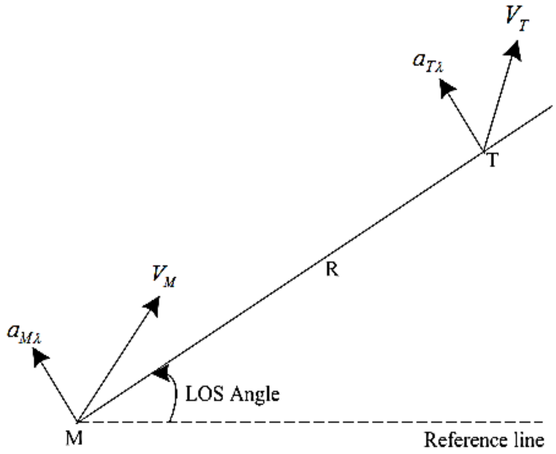

Fig. 1. Planar interception geometry

Furthermore, the autopilot dynamics can be considered as a first-order differential equation as follows:

$$\dot{a}_{M\lambda} = -\frac{1}{\tau} a_{M\lambda} + \frac{1}{\tau} u \tag{3}$$

where τ represents the autopilot's time constant, and u denotes the command to the autopilot.
Let $x_1 = \dot{\lambda}$ and $x_2 = \dot{x}_1 = \ddot{\lambda}$. Substituting them into Eq. (2) yields:

$$x_2 = -a_g x_1 - b_g a_{M\lambda} + b_g a_{T\lambda} \tag{4}$$

where

$$a_g = \frac{2\dot{R}}{R}, \quad b_g = \frac{1}{R} \tag{5}$$

It is clear from Eq. (4) that

$$a_{T\lambda} = a_{M\lambda} + \frac{1}{b_g}(a_g x_1 + x_2) \tag{6}$$

Differentiating Eq. (4) with respect to time and using Eq. (3) and (6) gives

$$\dot{x}_2 = A_1 x_1 + A_2 x_2 + bu - ba_{M\lambda} + f \tag{7}$$

where

$$\begin{aligned} A_1 &= -\dot{a}_g + \frac{\dot{b}_g}{b_g} a_g, \qquad A_2 = -a_g + \frac{\dot{b}_g}{b_g} \\ b &= -\frac{b_g}{\tau}, \qquad f = b_g \dot{a}_{T\lambda} \end{aligned} \tag{8}$$

Thus the state space can be described as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= A_1 x_1 + A_2 x_2 + bu - ba_{M\lambda} + f \end{aligned} \tag{9}$$

In Eq. (9), f is viewed as a bounded external disturbance, i.e. $\|f\| \le \Delta$, where $\Delta = const. > 0$.

According to parallel navigation notion, if LOS direction is kept unchanged with respect to inertial frame and relative range between the interceptor and the target is getting low $(\dot{R} < 0)$, collision will be certain [2]. In other words, the LOS rate must be zero.

b) Finite-time stability of nonlinear systems

In this section, a finite-time convergent guidance law is designed to guarantee that the LOS angular rate converges to zero in finite time. Before giving the design procedure, some results about finite-time stability of nonlinear system, which will be utilized in the following guidance law design, are introduced.

Definition 1: Consider the following nonlinear system [8]:

$$\dot{x}(t) = f(x,t), \quad f(0,t) = 0, \quad x \in R^n \tag{10}$$

where $f : U_0 \times R \to R^n$ is continuous on $U_0 \times R$, and U_0 is an open neighborhood of the origin $x = 0$. The equilibrium $x = 0$ of the system is finite-time convergent if for any given initial time t_0 and initial state $x(t_0) = x_0 \in U / \{0\}$, there exists a settling time $T(x_0) > 0$, such that every solution of the system (10), $x(t) = \upsilon(t, x_0) \in U / \{0\}$ satisfies

$$\begin{cases} \lim\limits_{t \to T(x_0)} \upsilon(t, x_0) = 0, & t \in [0, T(x_0)] \\ \upsilon(t, x_0) = 0, & t \geq T(x_0) \end{cases} \tag{11}$$

In addition, if $U = R^n$, then $x = 0$ is a global finite-time stable equilibrium.
The following Theorem provides a useful result for the study of finite time convergent guidance laws.

Theorem 1: Consider the nonlinear system (10). Suppose that there is a C^1 (continuously differentiable) function $V(x,t)$ defined in a neighborhood $\hat{U} \subset R^n$ of the origin, and that there are real numbers $\alpha > 0$ and $0 < \lambda < 1$, such that $V(x,t)$ is positive definite on $\hat{U}$ and that $\dot{V}(x,t) + \alpha V^{\lambda}(x,t) \leq 0$ on $\hat{U}$. Then, the zero solution of system (10) is finite time stable. Furthermore, the settling time is calculated as follows:

$$T \leq \frac{V^{1-\lambda}(x_0, 0)}{\alpha(1-\lambda)} \tag{12}$$

Remark 1: Note that if $\hat{U} = R^n$ and $V(x,t)$ is radially unbounded, then the origin is globally finite-time stable [13].

c) Guidance law with finite-time convergence

In this section, a combination of terminal sliding mode and integral sliding mode is considered so as to design a new guidance law with finite time convergence. The main purpose of combining these two approaches is to increase robustness of the guidance system and achieve finite time convergence property so that the sliding surface s_1 increases the robustness of the guidance system against highly maneuvering targets and the sliding surface s_2 makes the LOS angular rates converge to zero in finite time.

For the time-varying guidance system (9), an integral sliding manifold is described as follows:

$$s_1 = x_2(t) - x_2(t_0) - \int_{t_0}^{t} \omega_{nom} \, d\tau \tag{13}$$

where

$$\omega_{nom} = -\beta\gamma x_2 \left|x_1\right|^{\gamma-1} - k\,\text{sgn}\left(s_2\right) \tag{14}$$

and s_2 is a terminal sliding manifold which can be described as

$$s_2 = x_2 + \beta\left|x_1\right|^{\gamma}\text{sgn}(x_1) \tag{15}$$

where $k>0$, $\beta>0$, $0<(\gamma=p/q)<1$ and both p and q are positive odd integers. Note that $s_1(t_0)=0$ at $t=t_0$, so the system always starts at the sliding manifold.

Theorem 3: Consider the guidance system (9). The finite time convergent guidance law

$$u = -\frac{1}{b}\left(A_1x_1 + A_2x_2 - ba_{M\lambda} - \omega_{nom} + \varepsilon\,\text{sgn}(s_1)\right) \tag{16}$$

ensures the LOS angular rate converges to zero in finite time, where $\varepsilon = \Delta + \eta$ and $\eta > 0$ is a constant.
Proof: Differentiating Eq. (13) with respect to time gives

$$\begin{aligned}\dot{s}_1 &= \dot{x}_2 - \omega_{nom}\\ &= A_1x_1 + A_2x_2 + bu - ba_{M\lambda} + f - \omega_{nom}\\ &= f - \varepsilon\,\text{sgn}(s_1)\end{aligned} \tag{17}$$

Define a Lyapunov function as

$$V_1 = s_1^2 \tag{18}$$

Computing the first-order derivative of V_1 along the trajectories of Eq. (17) results in

$$\begin{aligned}&\dot{V}_1(s_1) = 2s_1\dot{s}_1 = 2\left(s_1 f - \varepsilon\left|s_1\right|\right) \le -2\eta\left|s_1\right|\\ &\dot{V}_1 \le -2\eta V_1^{0.5}\end{aligned} \tag{19}$$

By virtue of Theorem 1, Eq. (19) shows that the manifold $s_1=0$ can be reached in presence of the target maneuver. When $s_1=0$, we have

$$s_1 = x_2(t) - x_2(t_0) - \int_{t_0}^{t}\omega_{nom}\,d\tau = 0 \tag{20}$$

The Eq. (20) can be rewritten as

$$\begin{aligned}\dot{s}_1 = \dot{x}_2 - \omega_{nom} = 0\\ \Rightarrow \dot{x}_2 = \omega_{nom}\end{aligned} \tag{21}$$

Also, we already had

$$\dot{x}_1 = x_2 \tag{22}$$

According to the Eqs. (21) and (22) we can state

$$\begin{aligned}\dot{x}_1 &= x_2\\ \dot{x}_2 &= \omega_{nom}\end{aligned} \tag{23}$$

For the system (23), a terminal sliding manifold can be selected as Eq. (15). For the TSM in (15), its derivative along the system (23) is

$$\begin{aligned}\dot{s}_2 &= \dot{x}_2 + \beta \dot{x}_1 \left|x_1\right|^{\gamma-1} \\ &= \omega_{nom} + \beta x_2 \left|x_1\right|^{\gamma-1} = -k\,\mathrm{sgn}(s_2)\end{aligned} \tag{24}$$

Now consider a positive definite Lyapunov function as

$$V_2 = s_2^2 \tag{25}$$

By differentiating V_2 and utilizing Eq. (24), one has

$$\dot{V}_2(s_2) = 2s_2\dot{s}_2 = -2k\left|s_2\right| = -2kV_2^{0.5} \tag{26}$$

According to the Theorem 1, the system states reach the sliding mode $s_2 = 0$ in finite time. It is clear that in the sliding mode $s_2 = 0$, the following equation is satisfied

$$x_2 + \beta\left|x_1\right|^{\gamma}\,\mathrm{sgn}(x_1) = 0 \tag{27}$$

Define a Lyapunov function as

$$V_3 = x_1^2 \tag{28}$$

Differentiating V_3 along the trajectory of Eq. (27) gives

$$\begin{aligned}\dot{V}_3 &= 2x_1\dot{x}_1 = 2x_1x_2 = 2x_1\left(-\beta\left|x_1\right|^{\gamma}\,\mathrm{sgn}(x_1)\right) \\ &= -2\beta\left|x_1\right|^{\gamma+1} = -2\beta V_3^{(\gamma+1)/2}\end{aligned} \tag{29}$$

According to the Theorem 1, the system states converge to zero in finite time. The proof is completed.

In the meantime, in practical applications, the rate of relative range $\dot{R}$ can be approximately viewed as a constant, i.e.

$$V_c = -\dot{R} = c, \quad c = const. > 0, \qquad \ddot{R} = 0 \tag{30}$$

By combining Eq. (5) with Eq. (30), and simple algebraic calculations, one has

$$A_1 = 0, \quad A_2 = \frac{3c}{R}, \quad b = -\frac{1}{R\tau} \tag{31}$$

Hence, substituting Eq. (31) into the guidance law (16) results in

$$u = 3c\tau x_2 + a_{M\lambda} + R\tau\left(\beta\gamma x_2\left|x_1\right|^{\gamma-1} + k\,\mathrm{sgn}\left(s_2\right) + \varepsilon\,\mathrm{sgn}(s_1)\right) \tag{32}$$

Remark 2: It can be seen that the proposed law involves the signum function, so it can cause the chattering phenomenon. An approximation of the signum function by a saturation function with a high slope $(1/\delta)$ is considered to alleviate this problem.

3. THREE-DIMENSIONAL GUIDANCE LAW WITH FINITE-TIME CONVERGENCE

Consider the spherical LOS coordinate system (r,θ,ϕ) with origin fixed at gravity center of the interceptor. Let (e_r, e_θ, e_ϕ) be the unit vectors along the coordinate axes. The three-dimensional interceptor-target geometry is illustrated in Fig. 2. According to the principles of kinematics, the components of the relative acceleration can be described as follows [27]:

$$\ddot{R} - R\dot{\phi}^2 - R\dot{\theta}^2\cos^2\phi = a_{TR} - a_{MR} \equiv a_R \tag{33}$$

$$R\ddot{\theta}\cos\phi + 2\dot{R}\dot{\theta}\cos\phi - 2R\dot{\phi}\dot{\theta}\sin\phi = a_{T\theta} - a_{M\theta} \equiv a_\theta \tag{34}$$

$$R\ddot{\phi} + 2\dot{R}\dot{\phi} + R\dot{\theta}^2 \sin\phi\cos\phi = a_{T\phi} - a_{M\phi} \equiv a_\phi \tag{35}$$

Moreover, the autopilot dynamics can usually be considered as follows

$$\dot{a}_{M\theta} = -\frac{1}{\tau}a_{M\theta} + \frac{1}{\tau}u_1 \tag{36}$$

$$\dot{a}_{M\phi} = -\frac{1}{\tau}a_{M\phi} + \frac{1}{\tau}u_2 \tag{37}$$

The target acceleration is assumed as an external disturbance so that only its upper bound is available. Since Thrust Vector Control does not exist and the acceleration normal to velocity of interceptor can only be adjusted, we just consider the relative motion normal to the LOS. The control objective is to nullify the LOS angular rate $\dot{\theta}$ and $\dot{\phi}$ in finite time. If ϕ is a small variable, it yields $\sin\phi \approx 0$ and $\cos\phi \approx 1$. Hence, Eq. (34) and Eq. (35) decoupled into

$$\ddot{\theta} = -\frac{2\dot{R}}{R}\dot{\theta} - \frac{a_{M\theta}}{R} + \frac{a_{T\theta}}{R} \tag{38}$$

$$\ddot{\phi} = -\frac{2\dot{R}}{R}\dot{\phi} - \frac{a_{M\phi}}{R} + \frac{a_{T\phi}}{R} \tag{39}$$

It is clear that Eq. (38) and (39) are completely similar to Eq. (2), so the decoupled three-dimensional LOS angular motion is equivalent to two planar LOS angular motions and two planar finite time convergent guidance laws are then designed [13].

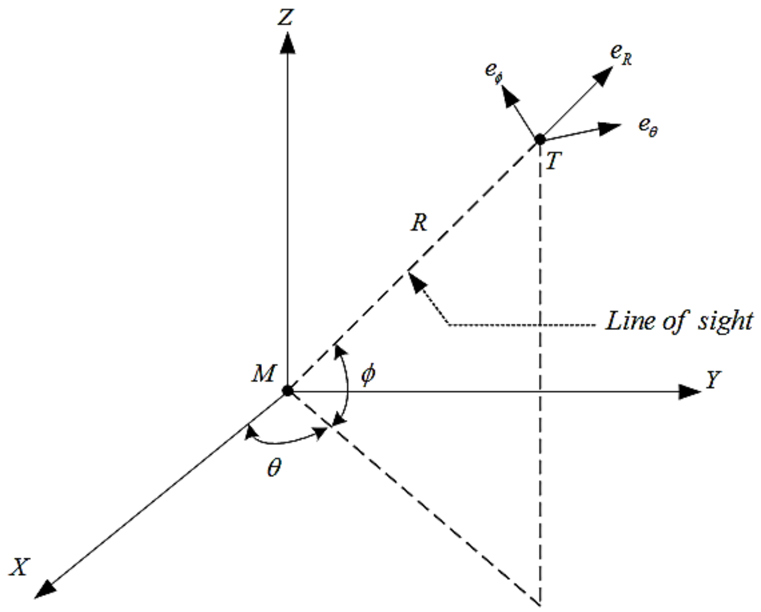

Fig. 2. Three-dimensional missile-target geometry

Based on the results obtained in Section 3.1, the two guidance laws with finite time convergence considering the autopilot lag can be proposed as follows:

$$u_\theta = 3c\tau\dddot{\theta} + a_{M\theta} + R\tau\left(\beta\,\gamma\,\ddot{\theta}\left|\dot{\theta}\right|^{1-\gamma} + k_1\,\mathrm{sgn}(s_2) + \varepsilon_1\,\mathrm{sgn}(s_1)\right) \quad (40)$$

$$u_\phi = 3c\tau\dddot{\phi} + a_{M\phi} + R\tau\left(\beta\,\gamma\,\ddot{\phi}\left|\dot{\phi}\right|^{1-\gamma} + k_2\,\mathrm{sgn}(s_4) + \varepsilon_2\,\mathrm{sgn}(s_3)\right) \quad (41)$$

where

$$\begin{aligned} s_1 &= \ddot{\theta}(t) - \ddot{\theta}(t_0) + \int_{t_0}^{t}\left(\beta\gamma\ddot{\theta}\left|\dot{\theta}\right|^{\gamma-1} + k_1\,\mathrm{sgn}\left(s_2\right)\right)d\tau = 0 \\ s_2 &= \ddot{\theta} + \beta\left|\dot{\theta}\right|^{\gamma}\,\mathrm{sgn}(\dot{\theta}) \end{aligned} \quad (42)$$

and

$$\begin{aligned} s_3 &= \ddot{\phi}(t) - \ddot{\phi}(t_0) + \int_{t_0}^{t}\left(\beta\gamma\ddot{\phi}\left|\dot{\phi}\right|^{\gamma-1} + k_2\,\mathrm{sgn}\left(s_4\right)\right)d\tau = 0 \\ s_4 &= \ddot{\phi} + \beta\left|\dot{\phi}\right|^{\gamma}\,\mathrm{sgn}(\dot{\phi}) \end{aligned} \quad (43)$$

4. SIMULATION RESULTS

Numerical simulations are performed to examine the performance of the proposed guidance law against a highly maneuvering target. The initial conditions of the simulations are taken as $R_0 = 5\,km$, $\dot{R}_0 = -300\,m/s$, $\theta_0 = \pi/3$, $\phi_0 = \pi/3$, $\dot{\theta}_0 = 0.08\,rad/s$ and $\dot{\phi}_0 = 0.06\,rad/s$. Assume that the target accelerations are $a_{T\theta} = 30\sin(0.3t + \pi/4)$ and $a_{T\phi} = 20\cos(0.2t)$. Furthermore, the parameters of the proposed law are chosen as $\beta = 8$, $\gamma = 0.9$, $k_1 = 0.003$, $k_2 = 0.002$, $\varepsilon_1 = \varepsilon_2 = 0.01$ and $\tau = 0.1$.

The terminal sliding mode guidance law (TSMG) presented in [22] is simulated under the same condition to verify the effectiveness and robustness of the proposed guidance law. This is because the TSMG is a guidance law with finite time convergence containing first-order autopilot lag. In [22], it has been shown the TSMG is better than the finite-time convergent guidance law (FTCG) [13] and the adaptive sliding-mode guidance law (ASMG) [28]. It is worth noting that the author in [22] only used the sliding surface s_2 and we are about to show the effect of adding the sliding surface s_1 in guidance law design procedure. In this section, the following simulation results will prove that the proposed guidance law has gained better performance compared to the TSMG. Numerical simulations are shown in Fig. 3 to Fig. 7.

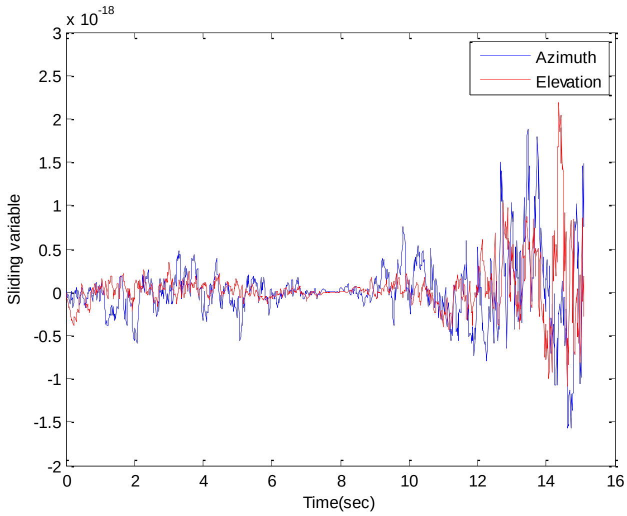

Fig. 3. The sliding variable

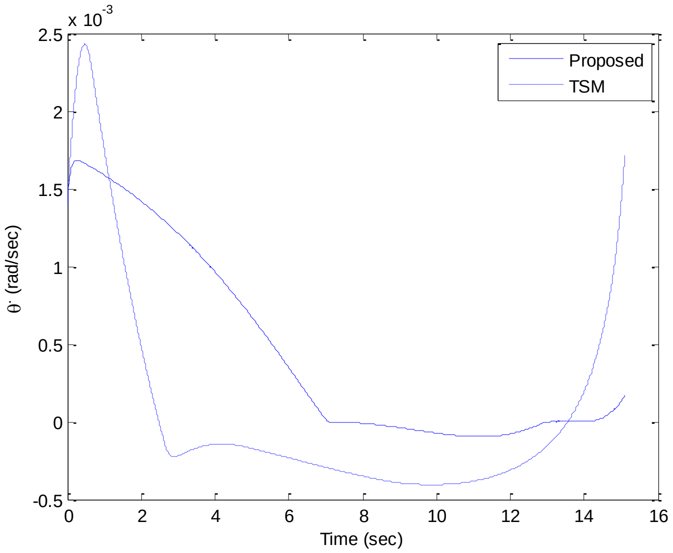

Fig. 4. The LOS angular rate in azimuth loop

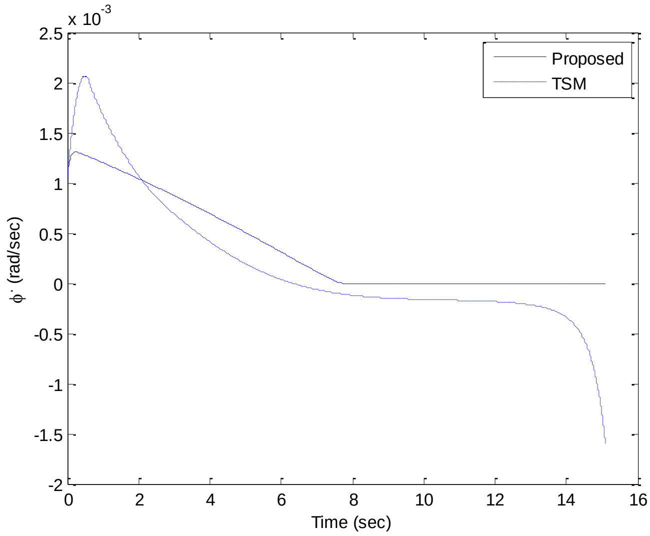

Fig. 5. The LOS angular rate in elevation loop

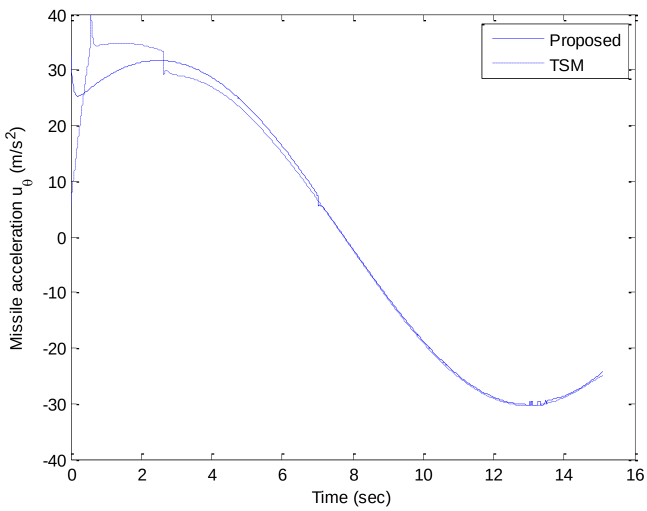

Fig. 6. The acceleration command in azimuth loop

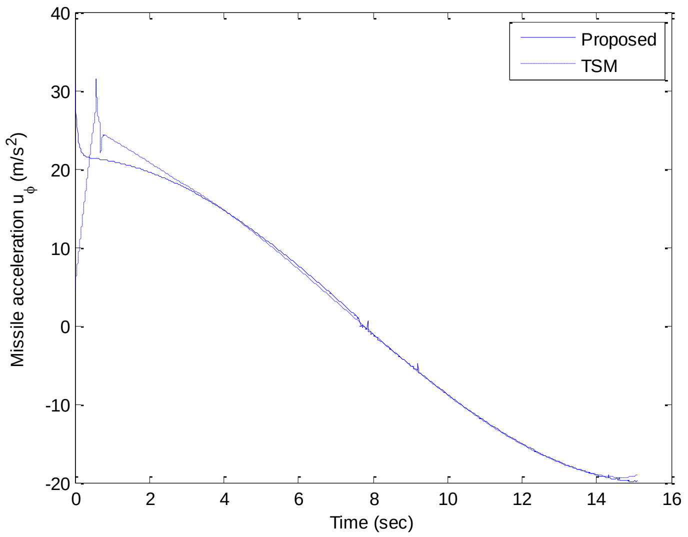

Fig. 7. The acceleration command in elevation loop

Figure 3 shows that under the proposed guidance law the integral sliding variables start from zero and they remain in a very small neighborhood of origin (10^{-18}). So the reaching mode has been omitted. Figures 4 and 5 illustrate that the proposed guidance law has better performance to nullify the LOS angular rates.

Figures 6 and 7 show the acceleration commands. As it can be seen, the proposed law needs less effort than the TSMG. Figure 8 illustrates the trajectories of the interceptor and the target. Figure 8 verifies that the proposed law is able to intercept the target.

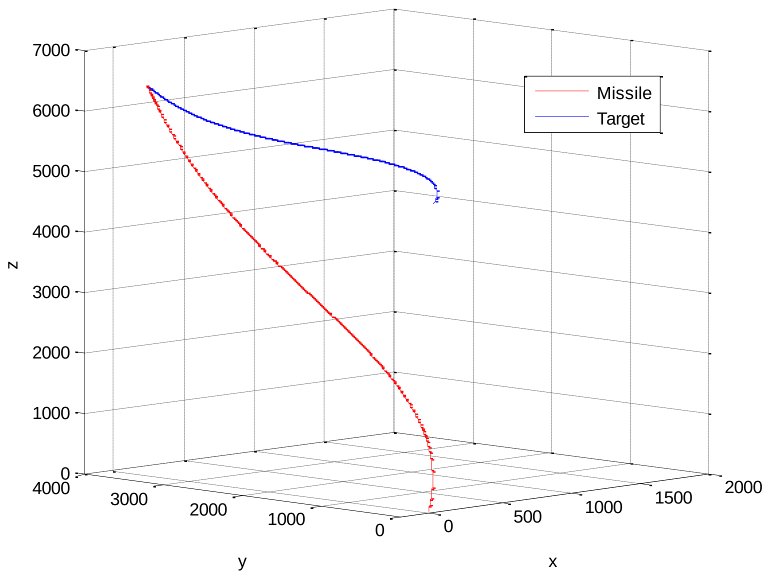

Fig. 8. Trajectory of the interceptor and the target

5. CONCLUSION

In this paper, by considering the dynamics of an interceptor's autopilot as a first-order lag, a guidance law with finite time convergence was proposed based on variable structure control. Higher order sliding mode based on integral sliding mode control method was used to design the proposed finite time convergent guidance law under which the line-of-sight angular rate converges to zero in finite time. The new guidance law is also robust against highly maneuvering targets. Finally, the superiority of the proposed method was substantiated by simulation results in comparison with terminal sliding mode guidance law.

REFERENCES

1. Zarchan, P. (2002). *Tactical and Strategic Missile Guidance*. AIAA Series.
2. Shneydor, N.A. (1998). *Missile guidance and pursuit; kinematics, dynamics*. Horwood Series in Engineering Science.
3. Tan, S. C., Lai, Y. M. & Tse, C. K. (2008). General design issues of sliding-mode controllers in DC–DC converters. *IEEE Transactions on Industrial Electronics*, Vol. 55, No. 3, p. 1160–1174.
4. Tan, S. C., Lai, Y. M., Tse, C. K. & Cheung, M. K. H. (2006). Adaptive feedforward and feedback control schemes for sliding mode controlled power converters. *IEEE Transactions on Power Electronics*, Vol. 21, No. 1, pp. 182–192.
5. Moon, J., Kim, K. & Kim, Y. (2001). Design of Missile Guidance Law via Variable Structure Control. *Journal of Guidance, Control, and Dynamics*, Vol. 24, No. 4, pp. 659-664.
6. Sun, S., Zhang, H. M. & Zhou, D. (2013). Sliding mode guidance law with autopilot lag for terminal angle constrained trajectories. *Journal of Astronautics*, Vol. 34, No. 1, pp. 69-78.
7. Shafiei, M. H. & Binazadeh, T. (2013). Application of partial sliding mode in guidance problem. *ISA Transactions*, Vol. 52, pp. 192-197.
8. Hong, Y. G. (2002). Finite time stabilization and stability of a class of controllable systems. *Systems & Control Letters*, Vol. 46, No. 4, pp. 231-236.
9. Hong, Y. G., Huang, J. & Xu, Y. S. (2001). On an output feedback finite-time stabilization problem. *IEEE Transactions on Automatic Control*, Vol. 46, No. 2, pp. 305-309.
10. Levant, I. (2001). Universal single-input–single-output (SISO) sliding-mode controllers with finite-time convergence. *IEEE Transactions on Automatic Control*, Vol. 46, No. 9, pp. 1447-1451.
11. Orlov, Y. (2004). Finite time stability and robust control synthesis of uncertain switched systems. *SIAM Journal on Control and Optimization*, Vol. 43, No. 4, pp. 1253-1271.
12. Ding, S.H., Li, S.H. & Luo, S. (2011). Guidance law design based on continuous finite-time control technique. *Journal of Astronaut*, Vol. 32, No. 4, pp. 727-733.
13. Zhou, D., Sun, S. & Teo, K.L. (2009). Guidance laws with finite time convergence. *Journal of Guidance, Control, and Dynamics*, Vol. 32, No. 6, pp. 1838-1846.
14. De-haia, Y., Zuo-eb, F. & Xian-junb, S. (2011). Design of a maneuver terminal sliding mode guidance law with impact angle constraints. *Journal of Naval Aeronautical and Astronautical University*.
15. Xu, Z., Hu-min, L., Hua, Z. & Liang-zhi, Z. (2011). A guidance law based on terminal sliding mode. *Journal of Ballistics*.
16. Zhao, W., Li, S. & Shumin, F. (2009). Nonsingular terminal sliding mode guidance law. *Journal of Southeast University(Natural Science Edition)*, S1.
17. Kumar, S., Rao, S. & Ghos, D. (2014). Nonsingular terminal sliding mode guidance with impact angle constraints. *Journal of Guidance, Control, and Dynamics*, Vol. 37, No. 4, pp. 1114-1130.
18. Xionga, S., Wanga, W., Liu, X. & Chen, Z. (2014). Guidance law against maneuvering targets with intercept angle constraint. *ISA Transactions*, Vol. 53, No. 4, pp. 1332–1342.
19. Wang, W., Xiong, S. & Liu, X. (2014). Adaptive nonsingular terminal sliding mode guidance law against maneuvering targets with impact angle constraint. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*.
20. He, S. & Lin, D. (2014). Adaptive nonsingular sliding mode based guidance law with terminal angular constraint. *Int'l J. of Aeronautical & Space Sci.*, Vol. 15, No. 2, pp. 146–152.

21. Mohammadzaman, I. & Momeni, H. (2011). Nonlinear guidance law with finite time convergence considering control loop dynamics. *Journal of Aerospace Science and Technology*, Vol. 8, No. 2, pp. 69-75.
22. Sun, S., Zhou, D. & Hou, W.T. (2013). A guidance law with finite time convergence accounting for autopilot lag. *Aerospace Science and Technology*, Vol. 25, pp. 132-137.
23. Golestani, M., Mohammadzaman, I. & Vali, A. R. (2014). Finite-time convergent guidance law based on integral backstepping control. *Aerospace Science and Technology*, Vol. 39, pp. 370–376.
24. Feng, C. C. (2011). *Integral sliding-based robust control, recent advances in robust control - novel approaches and design methods*. Mueller, A., Ed. In Tech.
25. Soltani, J. & Abjadi, N. R. (2003). A modified reaching phase sliding mode controller for a speed sensorless inducting motor drive using feedback linearization theory. *Iranian Journal of Science and Technology Transactions of Electrical Engineering*, Vol. 27, No. 4, pp. 679-689.
26. Sang, B., Jiang, C. & Qian, C. (2008). An integral sliding mode terminal guidance law based on trajectory linearization control for space interception system. *Chines Control and Decision Conference*.
27. Yang, C. D. & Yang, C. C. (1996). Analytical solution of three-dimensional realistic true proportional navigation. *Journal of Guidance, Control, and Dynamics*, Vol. 19, No. 3, pp. 569-557.
28. Zhou, D.,Mu, C. D. & Xu, W. L. (1999). Adaptive sliding-mode guidance of a homing missile. *Journal of Guidance, Control, and Dynamics*, Vol. 22, No. 4, pp. 589-594.