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Integral Backstepping Sliding Mode Guidance Law with Finite Time Convergence

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Abstract

In the present paper, the problem of finite time convergent guidance law design is investigated and a novel guidance scheme with finite time convergence is presented. To improve robustness of the guidance system against highly maneuvering targets, two robust nonlinear techniques are mixed, integral sliding mode and finite time backstepping control. The control loop dynamics are considered as a first order transfer function due to their significant contribution to the guidance loop stability. Furthermore, this guidance law makes the line-of-sight (LOS) angular rate converge to zero in a finite time, before final time of intercepting process. The proposed law is compared to terminal sliding mode guidance law and its superior performance is shown through simulation.

Keywords: *Guidance law, Integral backstepping sliding mode, control loop dynamics*

1. Introduction

The main goal of designing a guidance law is to provide an acceleration command to the interceptor's autopilot in order to decrease miss distance with respect to the target. It is extremely challenging to design a suitable guidance law since the guidance problem is highly nonlinear and the interceptor must hit the target within a short time. Proportional navigation (PN) and its generalizations have been widely used in guidance law design due to their simplicity, efficiency and ease of implement, so researchers are going to improve them [1-2]. However, a considerable miss distance might be resulted by PN guidance law if the target has a highly maneuvering. For highly maneuvering targets, robust guidance laws can be effective. Recently, many approaches have been presented to achieve robust guidance laws, such as H_∞ guidance law [3-4], first-order sliding mode guidance laws [5-7] and Lyapunov-based nonlinear guidance laws [8-10].

In practical applications, the control loop dynamics affect badly on the precision of guidance. However, in the mentioned works, the control loop lag has been neglected. Moreover, since these guidance laws have been established based on Lyapunov theorem on asymptotic stability or exponential stability, they ensure that the LOS angular rate converges to zero as time approaches infinity. However, the time of terminal guidance process is quite short and the guidance law must guarantee finite time convergence of the LOS angular rate.

In recent years, finite-time stabilization problem which was first proposed in [11] has become an attractive discussion among control scholars and it has been expanded in the

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following two decades [12-15]. Many research activities have been done to design finite time convergent guidance laws which are able to guide the LOS angular rate to converge to zero in a finite time; see, for example, [16-18].

The sliding mode control is an effective approach to control uncertain systems. Although it has advantages like robustness, it can cause an undesirable phenomenon called chattering which can damage the system and even cause instability. One way to reduce this problem is to use higher order sliding mode which can generate a continuous control input. This approach has been also employed to design guidance laws. A guidance law has been designed based on integral sliding mode method and using trajectory linearization [19].

In the present paper, an integral backstepping sliding mode guidance law is derived to intercept a target with a large maneuverability. In fact, by applying integral sliding mode and mixing it with finite time backstepping control, a new guidance law with finite time convergence is proposed. The control loop dynamics are considered as a first-order differential equation. It is proved that the proposed guidance law is able to guide the LOS angular rate to zero in finite time.

The reminder of the paper is organized as follows. In the next section, the equation of a planar relative motion is explained. In Section 3, the main results are presented where a finite-time convergent guidance law is developed by combining the integral sliding mode and finite time backstepping approaches. The simulation results are provided in Section 4. Finally, conclusions are addressed in Section 5.

2. Equations of Pursuit-target Engagement

The geometry of planar interception is shown in Figure 1. According to the principle of the kinematics, the corresponding equations of motion between the target and the interceptor can be described by [17]:

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

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

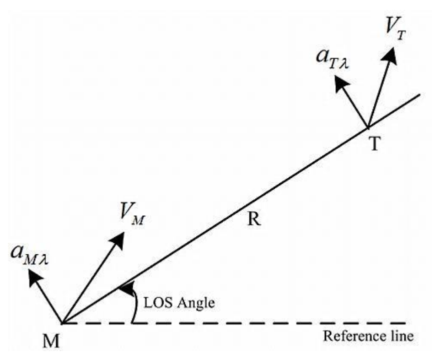

Figure 1. Planar Interception Geometry

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 $a_{M\lambda}$ denote the target and the interceptor acceleration normal to the LOS, respectively.

Furthermore, the autopilot dynamics can be described by 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.

Assume that $x_1 = \dot{\lambda}$ 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:

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

where

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

Thus, the state space can be described as

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

In Eq. (9), f denotes an external disturbance, i.e. $\|f\| \le \Delta$, where $\Delta = const. > 0$.

According to parallel navigation concept, if LOS direction is kept unchanged with respect to inertial frame relative range between the interceptor and the target becomes lower and lower $(\dot{R} < 0)$, in that case collision will be certain [2]. In other word, the LOS angular rate must be zero.

3. Finite-time Convergent Guidance Law Considering the Autopilot Dynamics

3.1. Finite-time Stability of Nonlinear Systems

Before giving the design procedure, some results about finite-time stability of nonlinear systems, which will be utilized in the following guidance law design, are introduced.

Definition: Consider the following nonlinear system [12]:

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

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 is 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

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

In addition, if $U = R^n$, then $x = 0$ is a global finite-time stable equilibrium.

Theorem 1 [12]: 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: Note that if $\hat{U} = R^n$ and $V(x,t)$ is radially unbounded, the origin is globally finite-time stable [17].

Lemma: For any real numbers x, y and $p \geq 1$ the following inequality holds [20]:

$$\left(|x| + |y|\right)^{1/p} \leq |x|^{1/p} + |y|^{1/p} \tag{13}$$

3.2. Planner Finite-time Convergent Guidance Law

In this section, a combination of the integral sliding mode and finite time backstepping approaches is considered in order to design a new guidance law with finite time convergence.

Theorem 2: Consider the following double integrator system

$$\begin{aligned} \dot{\xi}_1 &= \xi_2 \\ \dot{\xi}_2 &= u_{nom} \end{aligned} \tag{14}$$

If the controller is designed as

$$u_{nom}(\xi_1, \xi_2) = -\alpha\gamma\left|\xi_1\right|^{\gamma-1}\xi_2 - 2\xi_1\left|\xi_2 - K(\xi_1)\right| - 2\alpha\left|\xi_2 - K(\xi_1)\right|^{(\gamma+1)/2}\operatorname{sgn}(\xi_2 - K(\xi_1)) \tag{15}$$

the closed-loop system (14) and (15) is globally finite-time stable, where $\alpha > 0$, $0 < (\gamma = p/q) < 1$. Moreover, p and q are positive odd integer, and $K(\xi_1)$ is

$$K(\xi_1) = -\alpha\left|\xi_1\right|^{\gamma}\operatorname{sgn}(\xi_1) \tag{16}$$

Proof: For the system (14), ξ_2 can be considered as a virtual control input. Assume that $\xi_2 = K(\xi_1)$ exists such that ξ_1 converges to zero in finite time.

Consider a positive definite Lyapunov function as

$$V_1(\xi_1) = \xi_1^2 \tag{17}$$

Differentiating V_1 with respect to time and using Eq. (16) gives

$$\dot{V}_1(\xi_1) = 2\xi_1\dot{\xi}_1 = 2\xi_1\xi_2 = -2\alpha\left|\xi_1\right|^{\gamma+1} = -2\alpha V_1^{(\gamma+1)/2} \tag{18}$$

According to Theorem 1, ξ_1 converges to zero in finite time.

Let $z = \xi_2 - K(\xi_1)$ and $w = u_{nom} - \dot{K}(\xi_1)$. Hence, Eq. (14) can be written as

$$\begin{aligned} \dot{\xi}_1 &= z + K(\xi_1) \\ \dot{z} &= w \end{aligned} \tag{19}$$

Define a Lyapunov function

$$V_2(\xi_1, z) = V_1(\xi_1) + \left|z\right| \tag{20}$$

The derivative of V_2 with respect to time and along system (19) yields

$$\begin{aligned} \dot{V}_2 &= \frac{\partial V_1}{\partial \xi_1}K(\xi_1) + \frac{\partial V_1}{\partial \xi_1}z + w\,\mathrm{sgn}(z) \\ &= -2\alpha V_1^{(\gamma+1)/2} + \frac{\partial V_1}{\partial \xi_1}z + w\,\mathrm{sgn}(z) \end{aligned} \tag{21}$$

Defining $w = -\left|z\right|\frac{\partial V_1}{\partial \xi_1} - 2\alpha\left|z\right|^{(\gamma+1)/2}\mathrm{sgn}(z)$ yields

$$\dot{V}_2 = -2\alpha V_1^{(\gamma+1)/2} - 2\alpha\left|z\right|^{(\gamma+1)/2} \tag{22}$$

According to Lemma, we have

$$\dot{V}_2 = -2\alpha\left(V_1 + \left|z\right|\right)^{(\gamma+1)/2} = -2\alpha V_2^{(\gamma+1)/2} \tag{23}$$

Thus, states (ξ_1, z) converge to zero in finite time. Since $K(0) = 0$, the system (14) is finite time stable. By substituting *w*, *z* and $\dot{K}(\xi_1)$ in u_{nom}, the controller (15) is determined.

To stabilize in finite time the time-varying guidance system (9), let us define the following control scheme:

$$\begin{cases} u = u_{nom} + u_{disc} \\ \dot{x}_{aux} = -u_{nom} \end{cases} \tag{24}$$

where u_{nom} was introduced in Theorem 2 and auxiliary function x_{aux} is utilized to design the sliding variable relevant to the discontinuous control scheme u_{disc}.

Let us define a sliding variable as

$$s = x_2 + x_{aux} \tag{25}$$

Theorem 3: Consider the nonlinear guidance system (9). The guidance law

$$\begin{aligned} u = -\frac{1}{b}\Big(& A_1x_1 + A_2x_2 - ba_{M\lambda} + \alpha\gamma\left|x_1\right|^{\gamma-1}x_2 + 2x_1\left|x_2 - K(x_1)\right| \\ & + 2\alpha\left|x_2 - K(x_1)\right|^{(\gamma+1)/2}\mathrm{sgn}(x_2 - K(x_1)) + \varepsilon\,\mathrm{sgn}(s)\Big) \end{aligned} \tag{26}$$

guarantees the LOS angular rate converges to zero in finite time. Moreover, α , γ and $K(x_1)$ have been defined in (15) and (16), $\varepsilon = \Delta + \eta$ and $\eta > 0$ is a constant.

Proof: Differentiating Eq. (25) with respect to time and using Eq. (9) yields

$$\begin{aligned}\dot{s} &= \dot{x}_2 + \alpha\gamma\left|x_1\right|^{\gamma-1} x_2 + 2x_1\left|x_2 - K(x_1)\right| + 2\alpha\left|x_2 - K(x_1)\right|^{(\gamma+1)/2}\operatorname{sgn}(x_2 - K(x_1)) \\ &= A_1x_1 + A_2x_2 + bu - ba_{M\lambda} + f + \alpha\gamma\left|x_1\right|^{\gamma-1} x_2 + 2x_1\left|x_2 - K(x_1)\right| \\ &\quad + 2\alpha\left|x_2 - K(x_1)\right|^{(\gamma+1)/2}\operatorname{sgn}(x_2 - K(x_1)) \\ &= f - \varepsilon\operatorname{sgn}(s)\end{aligned} \tag{27}$$

Define a Lyapunov function as

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

Computing the first order derivative of V_3 along the trajectories of Eq. (27), one obtains

$$\begin{aligned}\dot{V}_3(s) &= 2s\dot{s} = 2\left(sf - \varepsilon\left|s\right|\right) \le -2\eta\left|s\right| \\ \dot{V}_3 &\le -2\eta V_3^{0.5}\end{aligned} \tag{29}$$

According to Theorem 1, Eq. (29) expresses the manifold $s = 0$ can be reached in finite time in spite of the target maneuvers. Substituting $u = u_{nom} + \varepsilon\operatorname{sgn}(s)$ into (9), the equivalent closed-loop guidance system can be obtained as the same nominal system (14). Thus, based on Theorem 1, a higher order sliding mode with respect to the system trajectories converge to zero in finite time.

3.3. Three-Dimensional Finite-Time Convergent Guidance Laws

Consider the spherical LOS coordinate system (R, θ, ϕ) with origin fixed at gravity center of the interceptor, that it describes the relative motion between the interceptor and the target. Let (e_r, e_θ, e_ϕ) be the unit vectors along the coordinate axes. The three-dimensional interceptor-target geometry is illustrated in Figure 2. According to the principle of the kinematics, the components of the relative acceleration can be described as follows [21]:

$$\ddot{R} - R\dot{\phi}^2 - R\dot{\theta}^2\cos^2\phi = a_{TR} - a_{MR} \equiv a_R \tag{30}$$

$$R\ddot{\theta}\cos\phi + 2\dot{R}\dot{\theta}\cos\phi - 2R\dot{\phi}\dot{\theta}\sin\phi = a_{T\theta} - a_{M\theta} \equiv a_\theta \tag{31}$$

$$R\ddot{\phi} + 2\dot{R}\dot{\phi} + R\dot{\theta}^2\sin\phi\cos\phi = a_{T\phi} - a_{M\phi} \equiv a_\phi \tag{32}$$

Moreover, the autopilot dynamics can be usually considered as follows

$$\dot{a}_{M\theta} = -\frac{1}{\tau}a_{M\theta} + \frac{1}{\tau}u_1 \tag{33}$$

$$\dot{a}_{M\phi} = -\frac{1}{\tau}a_{M\phi} + \frac{1}{\tau}u_2 \tag{34}$$

The target acceleration is assumed as an external disturbance so that only its upper bound is available. Since we don’t have thrust vector control (TVC) and just the acceleration normal to velocity of interceptor can be adjusted, we only 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 the Pitch LOS angle is a small variable, it yields $\sin\phi \approx 0$ and $\cos\phi \approx 1$. Hence, two Eq. (31) and Eq. (32) are quite similar together and decoupled into

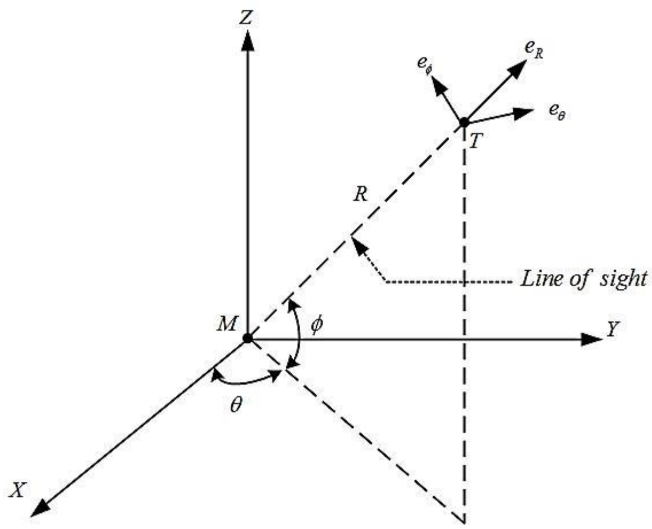

Figure 2. Three-dimensional Interceptor-target Geometry

$$\ddot{\theta} = -\frac{2\dot{R}}{R}\dot{\theta} - \frac{a_{M\theta}}{R} + \frac{a_{T\theta}}{R} \tag{35}$$

$$\ddot{\phi} = -\frac{2\dot{R}}{R}\dot{\phi} - \frac{a_{M\phi}}{R} + \frac{a_{T\phi}}{R} \tag{36}$$

It is clear that Eq. (35) and (36) are completely similar to Eq. (2), so we can design two planner guidance laws for the decoupled three-dimensional LOS angular motion [17].

According to the results of the Section 3.2, the two guidance laws with finite time convergence with autopilot lag can be proposed as follows:

$$u_\theta = 3c\tau\ddot{\theta} + a_{M\theta} + R\tau\left(\alpha\gamma\left|\dot{\theta}\right|^{\gamma-1}\ddot{\theta} + 2\dot{\theta}\left|\ddot{\theta} - K(\dot{\theta})\right| + 2\alpha\left|\ddot{\theta} - K(\dot{\theta})\right|^{(\gamma+1)/2}\operatorname{sgn}(\ddot{\theta} - K(\dot{\theta})) + \varepsilon\operatorname{sgn}(s_1)\right) \tag{37}$$

$$u_\phi = 3c\tau\ddot{\phi} + a_{M\phi} + R\tau\left(\alpha\gamma\left|\dot{\phi}\right|^{\gamma-1}\ddot{\phi} + 2\dot{\phi}\left|\ddot{\phi} - K(\dot{\phi})\right| + 2\alpha\left|\ddot{\phi} - K(\dot{\phi})\right|^{(\gamma+1)/2}\operatorname{sgn}(\ddot{\phi} - K(\dot{\phi})) + \varepsilon\operatorname{sgn}(s_2)\right) \tag{38}$$

where

$$s_1 = \ddot{\theta}(t) - \ddot{\theta}(t_0) + \int_{t_0}^{t}(\alpha\gamma\left|\dot{\theta}\right|^{\gamma-1}\ddot{\theta} + 2\dot{\theta}\left|\ddot{\theta} - K(\dot{\theta})\right| + 2\alpha\left|\ddot{\theta} - K(\dot{\theta})\right|^{(\gamma+1)/2}\operatorname{sgn}(\ddot{\theta} - K(\dot{\theta})))d\tau \tag{39}$$

and

$$s_2 = \ddot{\phi}(t) - \ddot{\phi}(t_0) + \int_{t_0}^{t}(\alpha\gamma\left|\dot{\phi}\right|^{\gamma-1}\ddot{\phi} + 2\dot{\phi}\left|\ddot{\phi} - K(\dot{\phi})\right| + 2\alpha\left|\ddot{\phi} - K(\dot{\phi})\right|^{(\gamma+1)/2}\operatorname{sgn}(\ddot{\phi} - K(\dot{\phi})))d\tau \tag{40}$$

4. Simulation Results

In this section, a three-dimensional interception problem is investigated. An inertial reference coordinate system can be described as shown in **Error! Reference source not found.**. Initial position coordinates of the interceptor are $x_{M0} = 0\ m$, $y_{M0} = 0\ m$ and

$z_{M0} = 0\ m$. Its initial velocity is $V_{M0} = 3000\ m/s$, and its initial heading angles and flight path are $\psi_{M0} = 56\deg$ and $\varphi_{M0} = 19\deg$ respectively. Initial position coordinates of the target are $x_{T0} = 80\ km$, $y_{T0} = 24\ km$ and $z_{T0} = 40\ km$. Its initial velocity is $V_{T0} = 7000\ m/s$, and its initial heading angles and flight path are $\psi_{T0} = 180\deg$ and $\varphi_{T0} = -25\deg$ respectively. This scenario has been adapted from [17]. As $t < 5\ \sec$, the target accelerations in the azimuth loop and the elevation loop are considered as $a_{T\theta} = -20g\ \sin(0.1t + \pi/6)$ and $a_{T\phi} = 20g\ \cos(0.1t + \pi/4)$, respectively. As $t \ge 5\ ses$, the target accelerations are adjusted to be $a_{T\theta} = 20g\ \sin(0.1t + \pi/6)$ and $a_{T\phi} = -20g\ \cos(0.1t + \pi/4)$, respectively. Furthermore, the parameters of the proposed law are chosen as $\alpha = 1.4$, $\gamma = 0.9$, $\varepsilon = 0.001$ and $\tau = 0.1$.

Since the terminal sliding mode guidance law (TSMG), which is presented in [18], is a guidance law with finite time convergence containing first-order autopilot dynamics, it is simulated under the same condition to verify the effectiveness and robustness of the proposed guidance law. In [18] it is shown the TSMG has obtained better results, compared with the finite-time convergent guidance law [17] and the adaptive sliding-mode guidance law [6]. In this section, the following simulation results will prove that the proposed guidance law has gained the better performance in comparison with TSM guidance law. Numerical simulations are shown in **Error! Reference source not found.** to 7.

Error! Reference source not found. 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^{-19}). So, the reaching mode has been omitted. **Error! Reference source not found.** and 5 indicate that under the proposed guidance law the LOS angular rates in both the elevation loop and the azimuth loop converge to zero in finite time, but the TSMG cannot guide the LOS angular rate to zero.

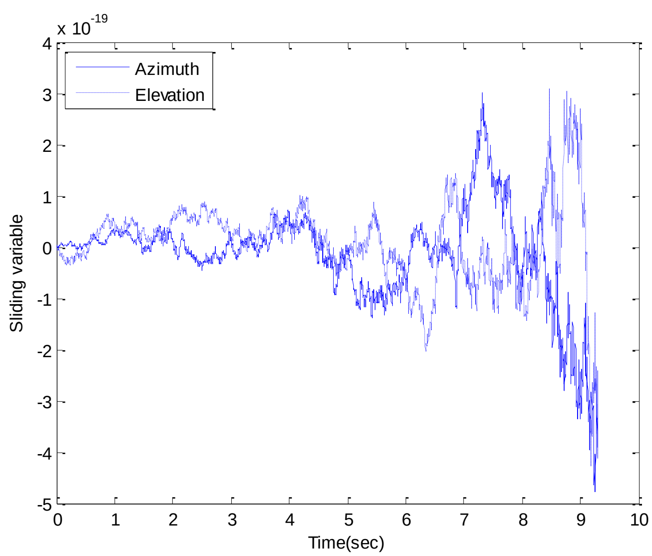

Figure 3. The Sliding Variable

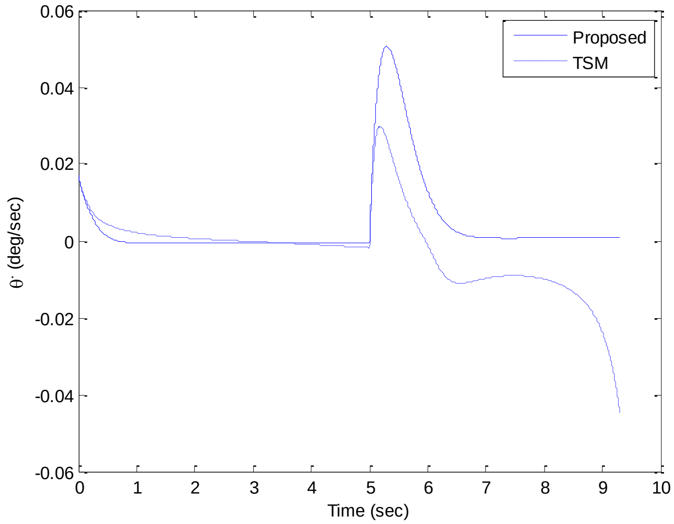

Figure 4. The LOS Angular Rate in Azimuth Loop

Error! Reference source not found. and 7 illustrate the acceleration commands. Although the TSMG cannot guide the LOS rates to converge to zero and only the proposed law is able to nullify the LOS rates, the acceleration of the proposed law and TSMG is almost similar. Furthermore, the maximum acceleration of the proposed guidance law is less than the corresponding acceleration in TSMG. This scenario showed that the proposed law is very effective and robust against target maneuver.

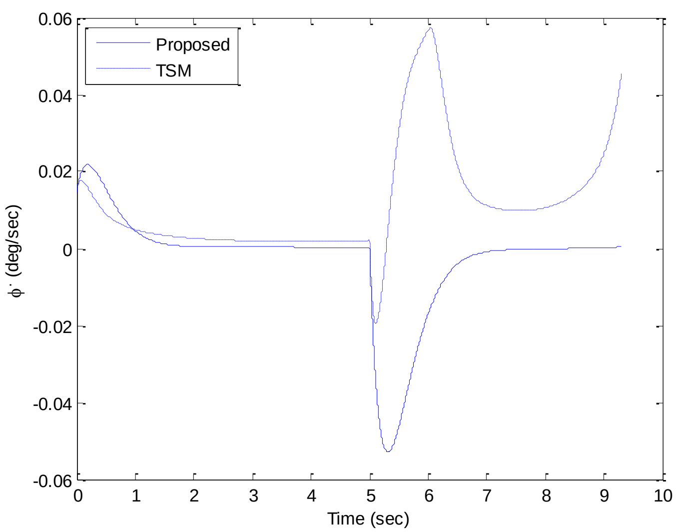

Figure 5. The LOS Angular Rate in Elevation Loop

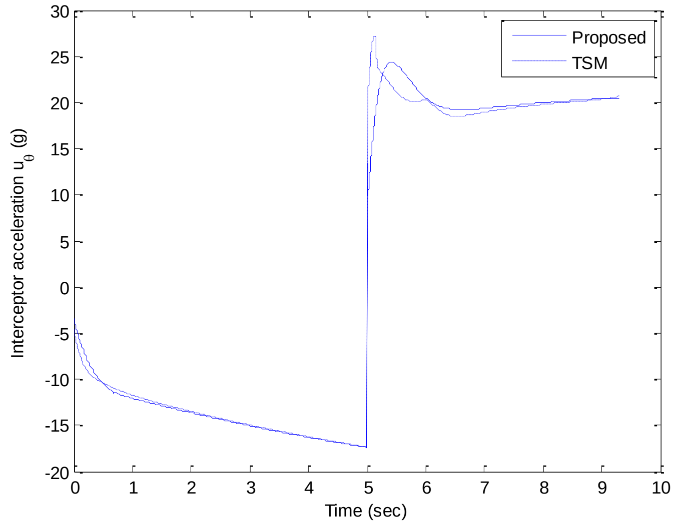

Figure 6. The Acceleration Command in Azimuth Loop

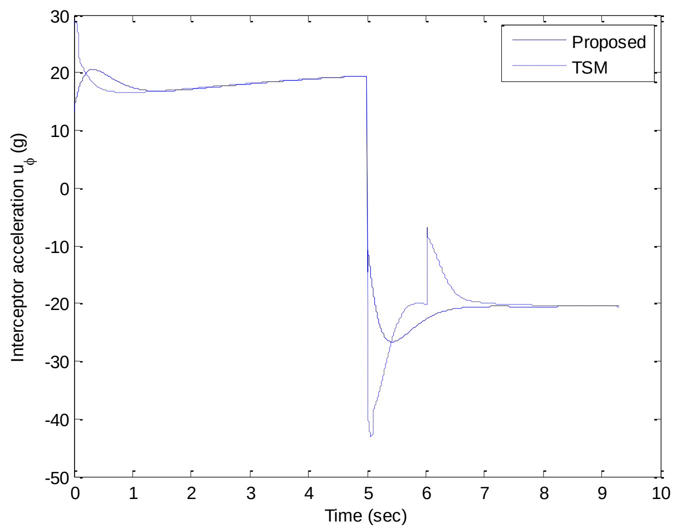

Figure 7. The Acceleration Command in Elevation Loop

5. Conclusion

In this paper, by considering control loop dynamics as a first order lag, a novel finite time convergent guidance law with compensation for the control loop lag was derived. Since the proposed law is based on a combination of finite time backstepping and integral sliding mode control, it is robust against highly maneuvering targets. The measurement or estimation of the target maneuver is not necessary. Moreover, the proposed law is able to guide the LOS angular rate to zero in spite of autopilot dynamics and target maneuvers. The effectiveness and robustness of the proposed guidance law against maneuvering target were shown through numerical simulations.

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