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NEW APPROACH TO NONLINEAR GUIDANCE LAW DESIGN

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Abstract. *This paper presents a new approach in nonlinear guidance law design. The new guidance law is developed based on partial stability theorem and enables the missile to intercept highly maneuvering targets with zero-miss-distance within a finite interception time. The approach is advantageous from practical view-points since it leads to classification of state variables of the guidance system dynamic with respect to their required stability properties and tries to adapt with practical situations. Effectiveness of the proposed guidance law in achieving zero-miss-distance within a finite interception time is demonstrated analytically and through computer simulations.*
Keywords: Nonlinear guidance law, Partial stability, Interception time

1. Introduction.

The Proportional Navigation (PN) guidance law and its generalizations have been used widely in tactical missiles because of their simplicity and ease of implementation [1,2]. However, increased maneuvering ability of new generation of targets had a huge adverse effect on the performance of these guidance laws.

For highly maneuvering targets, the optimal guidance laws (OGL), derived based on optimal control theory [3] or differential game theory [4], can theoretically result in a significant performance improvement. However, these laws lead to a two point boundary value problem, which is too complicated for real-time implementation. Moreover, the performance of OGL depends on estimation of interception time, which is commonly approximated [3,4]. In practice, especially for unpredictable maneuvering targets, the accurate approximation is impossible.

Recently, nonlinear control theories have been used in design of robust guidance laws. Methods, such as Lyapunov-based nonlinear guidance laws [5,6], first-order sliding mode guidance laws [7-9] and nonlinear H_∞ guidance laws [10,11], were considered in this regard. All these guidance laws were designed based on asymptotic or exponential stability of all states, which is shown in this paper that, in practical situation, such a behavior is not realistic for all states of guidance system.

In this paper, it is shown that, in a practical approach to guidance problem, each state must have a specific behavior and there is no need for asymptotic convergence of all states. It is in contrast to conventional methods in nonlinear control theory that try to force all states to asymptotically converge to the origin (equilibrium point). The proposed guidance law is based on the principle of *partial stability*, which is stability with respect to a part of state variables [12].

In this method, the states vector of the guidance system, i.e., (x), is separated into two parts: x_1 and x_2, where x_1 consists of states whose asymptotic stability behavior is desirable. For components of x_2, stability behavior is not desirable; however, they should satisfy some constraints. Moreover, target acceleration vector is assumed as an external bounded disturbance and only its bound is required in design of guidance law and the accurate measurement of target acceleration, during maneuvering, is not necessary. Effectiveness of the proposed guidance law in achieving zero-miss distance and adjustable finite interception time against highly maneuvering targets is demonstrated analytically and through computer simulations.

The remainder of this paper is organized as follows. In the next section, the nonlinear kinematics of guidance problem is presented. Also, the desirable behavior of each state variable is derived. In Section 3, the partial stability theory is briefly summarized. In Section 4, the new nonlinear guidance law based on partial stability theorem is derived. Numerical simulation results are shown in Section 5. Finally, conclusions are presented in Section 6.

2. Plant Modeling and Design Objective.

2.1. Missile/target kinematics model. The kinematics model of missile-target is as follows [7]:

$$\begin{cases} \ddot{r} - r\dot{\phi}^2 - r\dot{\theta}^2\cos^2\phi = w_r - u_r \\ r\ddot{\theta}\cos\phi + 2\dot{r}\dot{\theta}\cos\phi - 2r\dot{\phi}\dot{\theta}\sin\phi = w_\theta - u_\theta \\ r\ddot{\phi} + 2\dot{r}\dot{\phi} + r\dot{\theta}^2\cos\phi\sin\phi = w_\phi - u_\phi \end{cases} \tag{1}$$

where r is the relative distance between the missile and the target, θ and ϕ are yaw and pitch line of sight (LOS) angles and $w = [w_r, w_\theta, w_\phi]^T$ and $u = [u_r, u_\theta, u_\phi]^T$ are the acceleration vectors of target and missile, respectively.

The kinematics (1) known as engagement equations and can be rewritten in the following nonlinear state-space equation:

$$\dot{x}(t) = F(x(t)) + Bu(t) + Dw(t) \tag{2}$$

where the state vector, the vector field and constant matrixes are defined as:

$$x = \begin{bmatrix} r \\ V_r \\ \theta \\ V_\theta \\ \phi \\ V_\phi \end{bmatrix} F(x) = \begin{bmatrix} V_r \\ \dfrac{V_\theta^2 + V_\phi^2}{r} \\ \dfrac{V_\theta}{r\cos\phi} \\ -\dfrac{V_r V_\theta}{r} + \dfrac{V_\theta V_\phi \tan\phi}{r} \\ \dfrac{V_\phi}{r} \\ -\dfrac{V_r V_\phi}{r} - \dfrac{V_\theta^2\tan\phi}{r} \end{bmatrix} B = \begin{bmatrix} 0 & 0 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} D = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

where $V_r = \dot{r}$ is the radial velocity and $V_\theta = r\dot{\theta}\cos\phi$ and $V_\phi = r\dot{\phi}$ are tangential relative velocities. The reason of choosing V_θ and V_ϕ instead of $\dot{\theta}$ and $\dot{\phi}$ as state variables is that it avoids appearance of the term $1/r$ in the control and disturbance coefficient matrix.

Note: Initial conditions of terminal phase are usually in a way that $r_0 > 0$ and $V_{r_0} < 0$. It means that the target is in front of the missile and the missile is approaching it.

2.2. Desirable behaviors for each state variable. For the interception, it is sufficient that $r(t)$ becomes zero in an instance ($r(t_f) = 0$, where t_f is interception time) and there is no need for $r(t)$ to asymptotically converge to zero. In other words, the asymptotic convergence is not an ideal behavior for it. It should be noted that asymptotic convergence behavior means that the missile initially approaches the target very fast; however, near the target, the relative distance reduces slowly and the missile touches the target in an infinite time. It is evident that such a behavior is not a desirable behavior. For this purpose, it is sufficient that the relative radial speed between the missile and the target satisfy the following Proposition.

Proposition 2.1. *In order to intercept the target within a finite time interval, it is sufficient that the relative radial speed between the missile and the target* (V_r) *satisfies the following condition:*

$$\exists t_1 \in [t_0, t_f) \ \ s.t.\ V_r(t) \le -\zeta < 0 \ \ \forall t \in [t_1\, t_f] \tag{4}$$

Proof: See [18].

Remark 2.1. *A common approach in relevant papers is to regulate V_r to a negative constant c, which is not efficient for interception of highly maneuvering targets in an acceptable interception time. In such a case, to improve performance, c should be time varying and its accurate determination depends on the knowledge of the model of target maneuver while it is not always known in practice* [6].

Regarding the other state variables, i.e., θ, V_θ, ϕ, V_ϕ, in contrast to two first states, i.e., r and V_r, asymptotic convergence behavior is desirable. An appropriate guidance law in addition to decreasing of relative distance must keep the pitch and yaw LOS-angular rates as small as possible [13]. It means that it is desirable to have V_θ, $V_\phi \to 0$, $\theta \to c_1$ and $\phi \to c_2$, where c_1 and c_2 may be free or pre-specified constants.

3. **Partial Stability Analysis.** For many of engineering problems application of Lyapunov stability theory is required [14-16]. However, there are other physical systems where partial stability is necessary [17]. Partial stability is defined as stability of a dynamical system with respect to only a part of the state variables. This approach is essential in many of engineering fields.

Consider the following nonlinear dynamical system:

$$\dot{x} = f(x), \quad x(t_0) = x_0 \tag{5}$$

where $x \in R^n$ is the state vector. Let vectors x_1 and x_2 denote the partitions of the state vector. Therefore, $x = (x_1^T, x_2^T)^T$ where $x_1 \in R^{n_1}$, $x_2 \in R^{n_2}$ and $n_1 + n_2 = n$. As a result, the nonlinear system (5) can be divided into two subsystems;

$$\begin{aligned} \dot{x}_1(t) &= F_1(x_1(t), x_2(t)), \quad x_1(t_0) = x_{10} \\ \dot{x}_2(t) &= F_2(x_1(t), x_2(t)), \quad x_2(t_0) = x_{20} \end{aligned} \tag{6}$$

where $x_1 \in D \subseteq R^{n_1}$, D is an open set including the origin, $x_2 \in R^{n_2}$ and $F_1 : D \times R^{n_2} \to R^{n_1}$ is such that for every $x_2 \in R^{n_2}$, $F_1(0, x_2) = 0$ and $F_1(., x_2)$ is locally Lipschitz in x_1. Also, $F_2 : D \times R^{n_2} \to R^{n_2}$ is such that for every $x_1 \in D$, $F_2(x_1, .)$ is locally Lipschitz in x_2, and $I_{x_0} = [0, \tau_{x_0})$, $0 < \tau_{x_0} \le \infty$ is the maximal interval of existence of solution $(x_1(t), x_2(t))$ of (10) $\forall t \in I_{x_0}$. Under the above constraints, the existence and uniqueness of solution can be ensured. Moreover the main advantage of considering the condition $F_1(0, x_2) = 0$ for every x_2, is that it makes the possibility of investigating the partial stability even if a part of system's states (i.e., x_2) goes to infinity. In order to analyse partial stability, the following theorem and its corollary are taken from [17].

Theorem 3.1. *Consider dynamical system (6). If there exist a continuously differentiable function $V : D \times R^{n_2} \to R$ and a class K functions $\alpha(.)$ such that:*

$$V(0, x_2) = 0, \quad x_2 \in R^{n_2} \tag{7}$$

$$\alpha(\|x_1\|) \le V(x_1, x_2), \quad (x_1, x_2) \in D \times R^{n_2} \tag{8}$$

$$\dot{V}(x_1, x_2) \le 0, \quad (x_1, x_2) \in D \times R^{n_2} \tag{9}$$

then, the dynamical system (6) is stable with respect to x_1.

Proof: See [17].

Corollary 3.1. *Consider dynamical system (6). If there exists a continuously differentiable, positive definite function $V : D \to R$ such that:*

$$V'(x_1)F_1(x_1, x_2) \le 0 \qquad (x_1, x_2) \in D \times R^{n_2} \tag{10}$$

then dynamical system (6) is stable with respect to x_1.

Now, consider the state Equation (2). The state vector may be separated into $x_1 = \begin{bmatrix} \theta & V_\theta & \phi & V_\phi \end{bmatrix}^T$ and $x_2 = \begin{bmatrix} r & V_r \end{bmatrix}^T$ where stable behavior only for x_1 is desirable. By modeling the guidance system in $x_1 - x_2$ coordinates, the following can be obtained:

$$\dot{x}_1 = \begin{bmatrix} \dfrac{V_\theta}{r\cos\phi} \\ -\dfrac{V_r V_\theta}{r} + \dfrac{V_\theta V_\phi \tan\phi}{r} - u_\theta - w_\theta \\ \dfrac{V_\phi}{r} \\ -\dfrac{V_r V_\phi}{r} - \dfrac{V_\theta^2 \tan\phi}{r} - u_\phi - w_\phi \end{bmatrix}, \quad \dot{x}_2 = \begin{bmatrix} V_r \\ \dfrac{V_\theta^2 + V_\phi^2}{r} - u_r - w_r \end{bmatrix} \tag{11}$$

4. **Guidance Law Design.** In this section, partial stability principle is used to derive the nonlinear guidance law. In design procedure first, a guidance law is derived against non-maneuvering targets and then by using Lyapunov redesign method, additional feedback control terms are designed so that the overall guidance law have a robust manner against maneuvering targets and lead to target interception.

4.1. **Non-maneuvering target.** A non-maneuvering target means that in engagement equations $w_r = w_\theta = w_\phi = 0$. Now, consider a Lyapunov function candidate $V(x_1)$ in the form:

$$V(x_1) = \frac{1}{2}\left(\theta^2 + \phi^2 + V_\theta^2 + V_\phi^2\right) \tag{12}$$

The time derivative of $V(x_1)$ in the line of system's trajectory is;

$$\dot{V} = \theta\frac{V_\theta}{r\cos\phi} + \phi\frac{V_\phi}{r} + V_\theta\left(\frac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} - u_\theta\right) + V_\phi\left(-\frac{V_r V_\phi + V_\theta^2 \tan\phi}{r} - u_\phi\right) \tag{13}$$

In order to satisfy partial stability, we consider:

$$\begin{aligned} u_\theta &= \frac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} + \frac{\theta}{r\cos\phi} + N_1 V_\theta \\ u_\phi &= -\frac{V_r V_\phi + V_\theta^2 \tan\phi}{r} + \frac{\phi}{r} + N_2 V_\phi \end{aligned} \tag{14}$$

where N_1 and N_2 are positive real numbers. As a result,

$$\dot{V}(x_1) = -N_1 V_\theta^2 - N_2 V_\phi^2 \tag{15}$$

Therefore, according to Corollary 3.1 the asymptotically stable behavior for x_1 is achieved. Now, the appropriate behavior for x_2 could be obtained by u_r. By choosing

$$u_r = \frac{V_\theta^2 + V_\phi^2}{r} - \sigma V_r; \quad \sigma > 0 \tag{16}$$

one has $V_r(t) = V_{r_0} e^{\sigma t}$; $V_{r_0} < 0$, which means $V_r(t) \le V_{r_0} < 0$. Therefore, Proposition 2.1 is satisfied and the relative distance will turn into zero within a finite time. Clearly, higher values of σ make a shorter time of interception but its adjustment should be done with respect to physical limitations.

Consequently, the missile guidance law against non-maneuvering target is:

$$\begin{cases} u_r = \dfrac{V_\theta^2 + V_\phi^2}{r} - \sigma V_r \\ u_\theta = \dfrac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} + \dfrac{\theta}{r\cos\phi} + N_1 V_\theta \\ u_\phi = -\dfrac{V_r V_\phi + V_\theta^2 \tan\phi}{r} + \dfrac{\phi}{r} + N_2 V_\phi \end{cases} \tag{17}$$

4.2. **Maneuvering target.** In this case, the acceleration vector of target (i.e., w) is nonzero. The additional control components, (υ_θ, υ_ϕ, υ_r) will design such that the guidance law meets the design specifications in the presence of target's maneuvers. Therefore, by taking,

$$\begin{aligned} u_{\theta_{new}}(x) &= u_\theta(x) + \upsilon_\theta(x) \\ &= \frac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} + \frac{\theta}{r\cos\phi} + N_1 V_\theta + \upsilon_\theta(x) \end{aligned} \tag{18}$$

$$\begin{aligned} u_{\phi_{new}}(x) &= u_\phi(x) + \upsilon_\phi(x) \\ &= -\frac{V_r V_\phi + V_\theta^2 \tan\phi}{r} + \frac{\phi}{r} + N_2 V_\phi + \upsilon_\phi(x) \end{aligned} \tag{19}$$

one has:

$$\dot{V}(x_1) = -N_1 V_\theta^2 - N_2 V_\phi^2 - V_\theta(\upsilon_\theta - w_\theta) - V_\phi(\upsilon_\phi - w_\phi) \tag{20}$$

where the last two terms, i.e., $-V_\theta(\upsilon_\theta - w_\theta) - V_\phi(\upsilon_\phi - w_\phi)$, are the effects of the control components υ_θ and υ_ϕ, and disturbance terms w_θ and w_ϕ. Assume $|w_\theta| \le \eta_\theta$, $|w_\phi| \le \eta_\phi$, therefore,

$$-V_\theta(\upsilon_\theta - w_\theta) \le -V_\theta \upsilon_\theta + \eta_\theta |V_\theta| \tag{21}$$

By choosing $\upsilon_\theta = \eta_\theta sgn\,(V_\theta)$, one has:

$$-V_\theta(\upsilon_\theta - w_\theta) \le -\eta_\theta |V_\theta| + \eta_\theta |V_\theta| = 0 \tag{22}$$

Similarly, this is the case for $-V_\phi(\upsilon_\phi - w_\phi)$ by taking $\upsilon_\phi = \eta_\phi sgn\,(V_\phi)$. Now, the additional term υ_r could be designed in such a way that the control law, $u_{r_{new}}(x) = u_r(x) + \upsilon_r(x)$, guarantees the specified behavior for x_2 in the presence of w_r. In this way, we have:

$$u_{r_{new}}(x) = \frac{V_\theta^2 + V_\phi^2}{r} - \sigma V_r + \upsilon_r \tag{23}$$

Assume $|w_r| \le \eta_r$ and take $\upsilon_r = -\eta_r sgn(V_r)$. Since V_r is supposed to be negative, hence $\upsilon_r = \eta_r$. By substituting $u_{r_{new}}$ in $\dot{x}_2$-subsystem in Equation (11), one has:

$$\dot{V}_r = \sigma V_r - \eta_r + w_r \tag{24}$$

Thus,

$$\begin{aligned} V_r(t) &= V_{r0} e^{\sigma t} + \textstyle\int_0^t (-\eta_r + w_r) e^{\sigma(t-\tau)} d\tau \\ &\le V_{r0} e^{\sigma t} - \textstyle\int_0^t \eta_r e^{\sigma(t-\tau)} d\tau + \int_0^t \eta_r e^{\sigma(t-\tau)} d\tau \\ &\le V_{r0} e^{\sigma t} \end{aligned} \tag{25}$$

Choosing $-\zeta = V_{r0} < 0$, result in $V_r(t) \le -\zeta < 0$ for $t \in [0\, t_f]$. In this way, Proposition 2.1 is satisfied for the maneuvering targets.

Since discontinuous controllers suffer from chattering, one way to alleviate this problem is to consider an approximation of the sign function by a saturation function with a high slope $(1/\varepsilon)$. Consequently, it was shown that the following guidance law guarantees interception of the maneuvering target within a finite interception time and zero-miss distance. Furthermore, the convergence rate of V_θ and V_ϕ and the interception time may be adjusted by N_1, N_2 and σ, respectively.

$$\begin{cases} u_{r_{new}}(x) = \dfrac{V_\theta^2 + V_\phi^2}{r} - \sigma V_r + \eta_r, & \sigma, \eta_r > 0 \\ u_{\theta_{new}}(x) = \dfrac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} + \frac{\theta}{r\cos\phi} + N_1 V_\theta + \eta_\theta sat(\frac{V_\theta}{\varepsilon}), & N_2, \eta_\theta > 0 \\ u_{\phi_{new}}(x) = -\dfrac{V_r V_\phi + V_\theta^2 \tan\phi}{r} + \dfrac{\phi}{r} + N_2 V_\phi + \eta_\phi sat(\dfrac{V_\phi}{\varepsilon}), & N_2, \eta_\phi > 0 \end{cases} \tag{26}$$

5. **Computer Simulations.** Numerical Simulations are performed to illustrate the effectiveness of the proposed nonlinear guidance law. It is assumed that the guidance command is not constrained. At the first stage, a non-maneuvering target is considered and then, a highly maneuvering target is assumed.

5.1. **Engagement case 1: Non-maneuvering target.** In this part, the performance of the nonlinear guidance law (17) is investigated. The initial state values are chosen as $r_0 = 5$ km, $\theta_0 = \pi/3$, $\phi_0 = \pi/3$, $V_{r_0} = -300$ m/s, $V_{\theta_0} = 200$ m/s and $V_{\phi_0} = 300$ m/s. Also, N_1, N_2 and σ are selected as 1, 1 and 0.01, respectively.

The initial values of missile speed components can be obtained based on the initial relative speed components (V_{r_0}, V_{θ_0}, V_{ϕ_0}) and the initial value of target speed. Figure 1 displays the time responses of the system states for the non-maneuvering case. As expected, each state has its desirable behavior mentioned in Section 2.2. The interception time is 9.81 sec ($r(9.81) = 0$). As shown in Figure 1, r and V_r do not have an asymptotically stable behavior, but other states have such a behavior.

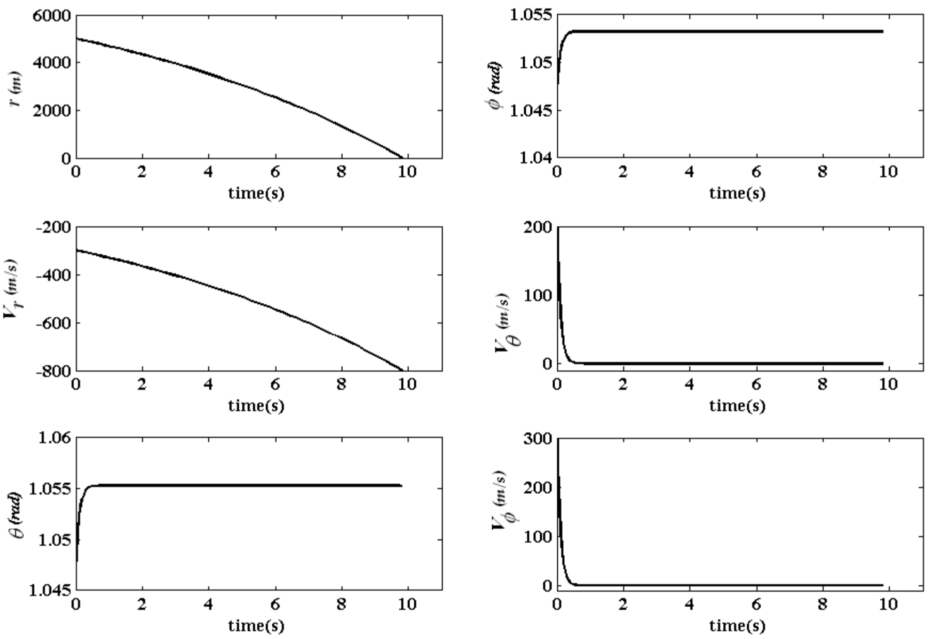

FIGURE 1. Time response of system states (case 1)

5.2. **Engagement case 2: Maneuvering target.** In this case, the target is maneuvering at the following trajectory:

$$w(t) = 70\sin(0.5t)\vec{e}_r + 70\sin(0.5t + \pi/4)\vec{e}_\theta + 70\cos(0.5t)\vec{e}_\phi \tag{27}$$

The initial conditions and value of parameters are the same as case 1. In addition, $\varepsilon = 1$ and $\eta_r = \eta_\theta = \eta_\phi = 70$ are selected. The designed guidance law (26) is compared with the sliding mode guidance law presented in [7]. The interception time for the proposed guidance law was 9.86 sec while for the sliding mode guidance law this time was 12.34 sec. Moreover, the control effort for the proposed law was less than the sliding mode control effort. The trajectories of the missile and the target are illustrated in Figure 2, where C1 and C2 are the collision points for the proposed guidance law and the sliding mode guidance law, respectively. Figure 3(a) shows the time response of the relative

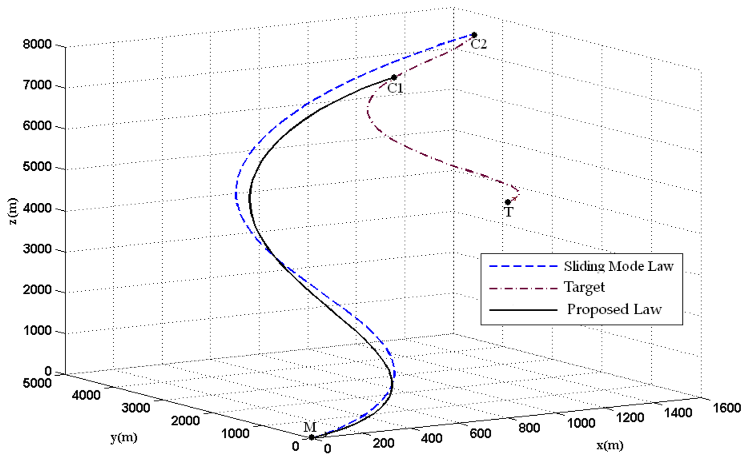

FIGURE 2. Trajectories of the missile and the target (case 2)

distance between the missile and the target. It indicates that the interception time for the proposed guidance law is less than that for the sliding mode law. At last, the time response of radial and tangential components of relative speed vector, are illustrated in Figures 3(b), 3(c) and 3(d), respectively.

6. **Conclusions.** This paper has presented a new viewpoint to the three-dimensional missile guidance problem based on partial stabilization. It has become clear that in a successful missile guidance scenario, which leads to target interception, the desirable behavior of state variables is different with respect to each other and the asymptotic convergence behavior is not ideal for all state variables. Therefore, based on partial stability theorem, a new robust guidance law was developed. The proposed guidance law guarantees interception of highly maneuvering targets with zero miss distance within a finite interception time. Moreover, it is also possible to adjust the time of interception by adjustment of some coefficients. Numerical simulations have showed effectiveness of the proposed guidance law.

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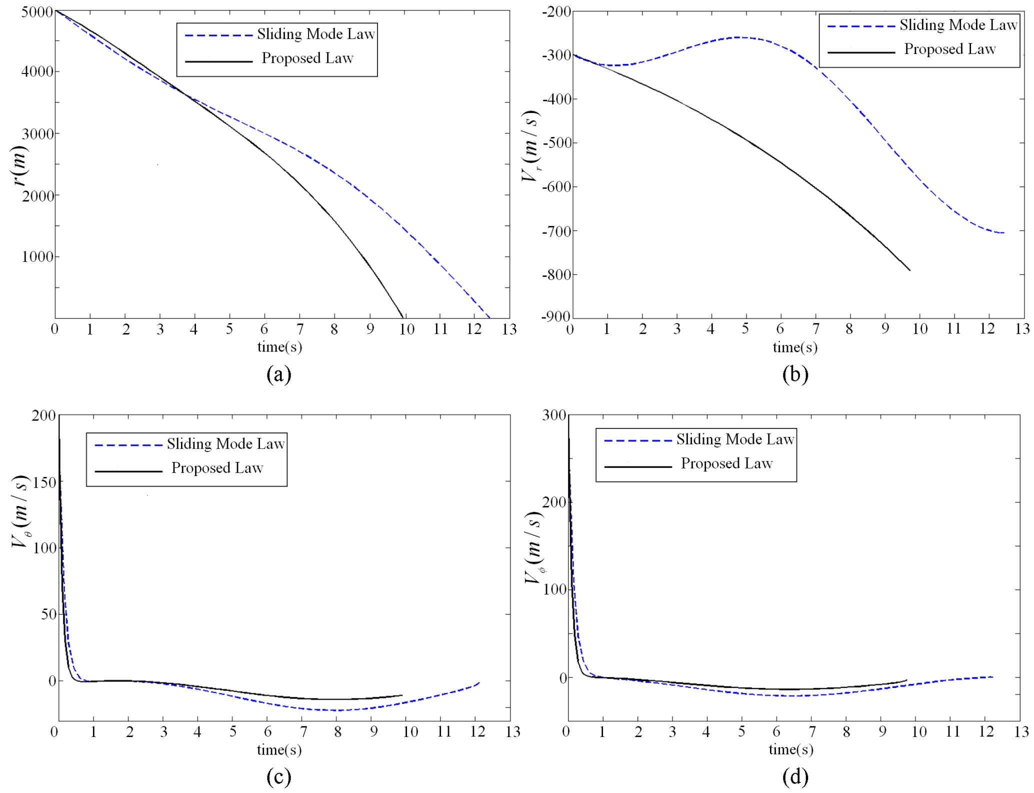

FIGURE 3. (a) Relative distances between the missile and the target, (b) radial relative velocity (V_r), (c) tangential relative velocity (V_θ), (d) tangential relative velocity (V_ϕ)

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