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A New Approach to Design a Robust Partial Control Law for the Missile Guidance Problem

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Abstract: In this paper, a new approach to design a control law for a missile guidance problem, based on desirable behavior of the state variables is proposed. The state variables in this problem may have three desirable behaviors, which are stability, asymptotically stability and even un-stability. The proposed approach enables the missile to intercept a maneuverable target within a finite interception time which is less than existing approaches. Indeed, the main purpose of this paper is to decrease the interception time and it is shown that this new approach is realistic for missile guidance problems. Finally, the designed guidance law is simulated to show the effectiveness of the proposed method for interception of maneuvering and non-maneuvering targets.

Keywords: Control Law, Guidance Problem, Robust Partial Control, Finite Time, desirable behavior, desired relative distance.

1. INTRODUCTION

Partial stabilization problems have been introduced in applications that asymptotic stability is not an appropriate behavior for all the states (Fergola et al., 1970; Rumyantsev, 1971; Oziraner et al., 1972; Silakov et al., 1975; Bondi, 1979; Michel et al., 1987; Djaferis, 1998; Vorotnikov, 1998; Michel et al., 2002; Djaferis, 2003; Djaferis, 2006; Costa et al., 2009; Binazadeh et al., 2011; Binazadeh et al., 2012; Shafiei et al., 2012). On the other hand, non-linear control theories have been used to design guidance laws (Rumyantsev, 1971; Vidyasagar, 1978; Tang et al., 1998; Young et al., 1999; Yu et al., 1999; Liaw et al., 2000; Hong et al., 2001; Moon et al., 2001; Yang et al., 2001; Chen et al., 2002; Fisher, 2004; Lechevin et al., 2004; Shieh, 2004; Hong et al., 2005; Idan et al., 2005; Ryoo et al., 2007; Fridman et al., 2008; Lombaerts et al., 2008). Design a guidance law to intercept of maneuvering targets is a difficult problem and therefore, most of existing researches in this field consider only a special case study (Vorotnikov, 2002; Vorotnikov, 2005; Ge et al., 2007; Shafiei et al., 2012). Recently, a new framework for robust partial stabilization of non-linear systems has been proposed (Binazadeh et al., 2011; Shafiei et al., 2012). This framework is based on partial stability theories and in which, the guidance non-linear system is divided into two parts based on desirable behaviors of the state variables (Binazadeh et al., 2011). According to this division, only a subset of the input vector appears in each part. Each subset of the input vector makes the possibility of imposing some constraints on the behavior of the state variables. One of these constraints enables the missile to intercept the target within a finite time.

In this paper, based on the desirable behavior of the state variables, a new approach to design a control law for the missile guidance problem is proposed. This control law leads to intercept a maneuvering target within a small and finite interception-time, in comparison with the other existing approaches. Finally, the designed guidance law is simulated to confirm the effectiveness of the proposed method for interception of maneuvering and non-maneuvering targets.

The reminder of this paper has the following structure: First, the summary of partial stability and some preliminaries about the partial stability are given in Section 2. Section 3 introduces the guidance problem and in Section 4 the proposed approach is applied to design a guidance law. Finally, conclusions are given in Section 5.

2. PRELIMINARIES

In this section, the summary of partial stability and some notations about this concept are presented. Partial stability is defined as the stability of a dynamical system with respect to only some of its state variables. Consider the following unforced non-linear system.

$$\dot{x} = f\left(x\right) \quad , \quad x\left(t_0\right) = x_0 \,, \tag{1}$$

where $x \in R^n$ is the state vector. In the partial stability concept, the non-linear system is divided into two subsystems (x_1, x_2) based on the desirable behavior of system's states (Binazadeh et al., 2011; Shafiei et al., 2012), where $x_1 \in R^{n_1}, x_2 \in R^{n-n_1}$.

According to the above explanations, the non-linear system (1) may be rewritten as follows:

$$\begin{aligned} \dot{x}_1(t) &= F_1(x_1(t), x_2(t)) \quad , \quad x_1\left(t_0\right) = x_{10} \\ \dot{x}_2(t) &= F_2(x_1(t), x_2(t)) \quad , \quad x_2\left(t_0\right) = x_{20} \,, \end{aligned} \tag{2}$$

where $x_1 \in D \subseteq R^{n_1}$ and D is an open set in the neighborhood of the origin, and $x_2 \in R^{n-n_1}$. Also,

$F_1(x_1, x_2)$ is such that for every x_2, $F_1(0, x_2) = 0$ and the functions $F_1(., x_2)$, $F_2(x_1, .)$ are locally Lipschitz in x_1 and x_2, respectively. The existence and uniqueness of the solution of (2) have been proposed in Binazadeh et al., 2011.

Considering the above explanations about the non-linear system (2), partial stability of this system (*i.e.* stability with respect to x_1) may be defined as follows:

Definition 1: The non-linear dynamical system (2) is Lyapunov stable with respect to x_1, if for every $\varepsilon > 0$ and $x_{20} \in R^{n-n_1}$, there exists $\delta(\varepsilon, x_{20}) > 0$ such that $\|x_{10}\| < \delta(\varepsilon, x_{20})$ implies $\|x_1(t)\| < \varepsilon$, for all $t \geq 0$.

Definition 2: A continuous function $\alpha(.) : [0,a) \to [0,\infty)$ belongs to class k functions if it is strictly increasing and if $\alpha(0) = 0$.

Theorem 1: Considering the non-linear dynamical system (2), if there exist a positive definite, continuously differentiable function $V(x_1)$ and class k functions $\alpha(.)$, $\beta(.)$ and $\gamma(.)$ such that,

$$\begin{aligned} &\alpha(\|x_1\|) \leq V(x_1) \leq \beta(\|x_1\|) \\ &\frac{\partial V(x_1)}{\partial x_1} F_1(x_1, x_2) \leq -\gamma(\|x_1\|). \end{aligned} \tag{3}$$

Then, the non-linear system (2) is partially stable.

Proof: See Chellaboina et al., 2002.

3. MISSILE GUIDANCE PROBLEM AND PROBLEM MODELING

In guidance problems the mathematical model of the missile-target engagement is very essential to have a realistic design. In this section, the kinematics model of 3-dimentional missile-target problem is considered.

3.1 Problem Formulation

The dynamic equations of the missile-target engagement are as follow (Shafiei et al., 2013):

$$\begin{aligned} &\ddot{r} - r\dot{\phi}^2 - r\dot{\theta}^2 \cos^2\phi = \omega_r - u_r \\ &r\ddot{\theta}\cos\phi + 2\dot{r}\dot{\theta}\cos\phi - 2r\dot{\phi}\dot{\theta}\sin\phi = \omega_\theta - u_\theta \\ &r\ddot{\phi} + 2\dot{r}\dot{\phi} + r\dot{\theta}^2\cos\phi\sin\phi = \omega_\phi - u_\phi. \end{aligned} \tag{4}$$

In these equations, r is the relative distance between the missile and target, $\dot{r}$ is the radial component of relative speed and θ, ϕ are yaw and pitch angles of line of sight, respectively. Also, acceleration vectors of the missile and target are described by $u = (u_\phi, u_\theta, u_r)^T$, $\omega = (\omega_\phi, \omega_\theta, \omega_r)^T$ respectively. In this paper, it is assumed that at the time $t = t_0$ the missile is in behind of the target and is approaching it. Finally, $x(t) = [\theta, \phi, \dot{\theta}, \dot{\phi}, r, \dot{r}]^T$ is considered as the state vector.

3.2 Distinguish The Proper Behaviour For Each State Variable

For a successful interception, it is suitable that $r(t)$ becomes zero in a finite time (*i.e.* $r(t_f) = 0$), where this time (t_f) is called the interception time. Thus, it is not desirable for relative distance to asymptotically converge to zero. In order to intercept the target correctly, the time derivative of $r(t)$ during the missile-target engagement must be negative. In some papers, $\dot{r}(t)$ is regulated to a negative value; however, this negative value depends on maneuvers of the target and therefore, they should be predicted during the interception scenario (Ryoo et al., 2007). Since, the targets are highly maneuvering, this approach is not practical. Regarding to other state variables, it is worth noting that the stability behavior is suitable for θ, ϕ and also, asymptotic stability behavior is desirable only for $\dot{\theta}$, $\dot{\phi}$. To have a successful interception, in addition to decreasing the relative distance, the values of θ, ϕ should be as small as possible (Chen et al., 2002; Shafiei et al., 2012; Shafiei et al., 2013). Therefore, according to above explanations and the partial stability theorem, the state vector may be separated as $x_1 = [\theta, \phi, \dot{\theta}, \dot{\phi}]^T$ and $x_2 = [r, \dot{r}]^T$. Now, the state-space equations of the guidance problem can be defined as follow:

$$\dot{x}_1 - subsystem: \begin{cases} \dot{\theta} = \dfrac{V_\theta}{r\cos\phi} \\ \dot{V}_\theta = \dfrac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} + \omega_\theta - u_\theta \\ \dot{\phi} = \dfrac{V_\phi}{r} \\ \dot{V}_\phi = \dfrac{-V_r V_\phi - V_\theta^2 \tan\phi}{r} + \omega_\phi - u_\phi \end{cases}$$

$$\dot{x}_2 - subsystem: \begin{cases} \dot{r} = V_r \\ \dot{V}_r = \dfrac{V_\theta^2 + V_\phi^2}{r} + \omega_r - u_r, \end{cases} \tag{5}$$

where $V_\theta = r\dot{\theta}\cos\phi$, $V_\phi = r\dot{\phi}$ are tangential components of relative speed between the missile and target, respectively.

4. GUIDANCE LAW DESIGN

First, based on the partial stability theorem, the non-linear guidance law is designed versus non-maneuvering targets. Then, in order to have a robust guidance law versus maneuvering targets, the Lyapunov redesign method is used. In this paper, the target acceleration vector is premised as an external disturbance.

4.1 Non-maneuvering Target

Consider $\dot{x}_1 - subsystem$ in equation (5), where $\omega = 0$. For this subsystem, the Lyapunov function may be chosen as follows:

$$V\left(x_1\right) = \frac{1}{2}\left(\theta^2 + \phi^2 + V_\theta^2 + V_\phi^2\right). \tag{6}$$

The time derivative of V in the line of equations (6) is as,

$$\begin{aligned}\dot{V}\left(x_1\right) &= \frac{\theta V_\theta}{r\cos\phi} + \frac{\phi V_\phi}{r} + ..\\ ..&+V_\theta\left(\frac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} - u_\theta\right) + ..\\ ..&+V_\phi\left(\frac{-V_r V_\phi + V_\theta^2 \tan\phi}{r} - u_\phi\right).\end{aligned} \tag{7}$$

According to Section 3.2, the desirable behavior for this subsystem is stability. Therefore, $\dot{V}\left(x_1\right)$ will be negative semi-definite, if the input signals are considered as,

$$\begin{aligned}u_\theta &= \frac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} + \frac{\theta}{r\cos\phi} + NV_\theta\\ u_\phi &= \frac{-V_r V_\phi + V_\theta^2 \tan\phi + \phi}{r} + MV_\phi,\end{aligned} \tag{8}$$

where N, M are positive constants. Thus,

$$\dot{V} = -NV_\theta^2 - MV_\phi^2. \tag{9}$$

Considering (9), this equation is negative semi-definite and therefore, asymptotic stability is guaranteed for only V_θ, V_ϕ. In other word, the desirable behavior has been achieved for $\dot{x}_1 - subsystem$.

Now, using the component of input vector appearing in second-subsystem, the design procedure will be completed.

In this section, in order to reach a smaller amount of interception time, a desired relative distance between the missile and target ($r_d\left(t\right)$) is proposed.

First, let us select $r_d\left(t\right) = r\left(0\right)\cos\left(st\right)$, which is a continuous and non-negative function in $t \in \left[0, t_f\right)$. The guidance scenario is in the time interval $t \in \left[0, t_f\right]$ and only in this interval $r_d\left(t\right)$ is required to be positive. Therefore, the value of s should be chosen such that, $s \le \dfrac{\pi}{2\max(t_f)}$, where $\max(t_f)$ is the maximum possible value of the t_f for our missile.

Now, the 2nd order time derivative of $r\left(t\right)$ is as,

$$\ddot{r}\left(t\right) = \dot{V}_r\left(t\right) = -s^2 r\left(0\right)\cos(st). \tag{10}$$

In this paper, it is desirable to make ($r\left(t\right) = r_d\left(t\right)$). Thus, 2nd order time derivatives of these variables have been set identical in the equations. Therefore,

$$\ddot{r}_d\left(t\right) = \ddot{r}\left(t\right) = \dot{V}_r\left(t\right) = -s^2 r\left(0\right)\cos(st).$$

Then, according to second-subsystem, one has,

$$\dot{V}_r = \frac{V_\theta^2 + V_\phi^2}{r} - u_r. \tag{11}$$

Now, if the input component u_r is designed to have the desired relative distance between the missile and target ($r\left(t\right) = r_d\left(t\right)$), the following control law will be obtained:

$$u_r = \frac{V_\theta^2 + V_\phi^2}{r} + s^2 r\left(0\right)\cos(st). \tag{12}$$

Note 1: By integrating from equation (10), the equation of $V_r\left(t\right)$ may be obtained. This equation satisfies $V_r\left(t\right) < 0 \quad \forall t \in \left[0, t_f\right)$.

Therefore, the guidance law versus non-maneuvering target is as,

$$\begin{aligned}u_\theta &= \frac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} + \frac{\theta}{r\cos\phi} + NV_\theta\\ u_\phi &= \frac{-V_r V_\phi + V_\theta^2 \tan\phi + \phi}{r} + MV_\phi\\ u_r &= \frac{V_\theta^2 + V_\phi^2}{r} + s^2 r\left(0\right)\cos(st).\end{aligned} \tag{13}$$

This control law has one degree of freedom in term s , which may be tuned to gain the best possible performance.

Note 2: Increasing the value of s leads to a better interception time; however, this may increase the control effort.

4.2 Maneuvering Target

In this section, suppose that $\omega \ne 0$. In order to have a robust guidance law versus maneuvering targets, the Lyapunov redesign method is used (Wu et al., 2011; Khalil, 2003).

First, for $u_{\theta c}$ and $u_{\phi c}$ it is assumed that:

$$u_{\theta c} = u_\theta + v_\theta = \frac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} + ..$$
$$..+ \frac{\theta}{r\cos\phi} + NV_\theta + v_\theta$$
$$u_{\phi c} = u_\phi + v_\phi = \frac{-V_r V_\phi + V_\theta^2 \tan\phi + \phi}{r} + .. \tag{14}$$
$$.. + MV_\phi + v_\phi,$$

where v_θ and v_ϕ will be designed based on Lyapunov redesign method (Khalil, 2003).

The resulting $\dot{V}$ with this new control inputs is as follows:

$$\dot{V} = -NV_\theta^2 - MV_\phi^2 - ..$$
$$.. - V_\theta\left(v_\theta - \omega_\theta\right) - V_\phi\left(v_\phi - \omega_\phi\right). \tag{15}$$

Now, the additional terms v_θ and v_ϕ, should be designed, such that desirable behavior for the first-subsystem is ensured. Assume that an upper bound on the target acceleration is known *i.e.* $\left|\omega_\theta\right| \le \eta_\theta$ and $\left|\omega_\phi\right| \le \eta_\phi$. (This assumption is completely realistic (Khalil, 2003)). Therefore,

$$-V_\theta\left(v_\theta - \omega_\theta\right) - V_\phi\left(v_\phi - \omega_\phi\right) \le -V_\theta v_\theta + ..$$
$$.. + \left|V_\theta\right|\eta_\theta - V_\phi v_\theta + \left|V_\phi\right|\eta_\phi. \tag{16}$$

By taking $v_\theta = \eta_\theta \operatorname{sgn}(V_\theta)$ and $v_\phi = \eta_\phi \operatorname{sgn}(V_\phi)$, one has:

$$-V_\theta\left(v_\theta - \omega_\theta\right) - V_\phi\left(v_\phi - \omega_\phi\right) \le -\left|V_\theta\right|\eta_\theta + ..$$
$$.. + \left|V_\theta\right|\eta_\theta - \left|V_\phi\right|\eta_\phi + \left|V_\phi\right|\eta_\phi = 0. \tag{17}$$

Thus,

$$\dot{V} = -NV_\theta^2 - MV_\phi^2. \tag{18}$$

Therefore, $\dot{V}$ satisfies partial stability condition when ω_θ and ω_ϕ are non-zero. In the case of 3th component of acceleration vector of target, assume $\left|\omega_r\right| \le \eta_r$. Now, based on the proposed approach and the Lyapunov redesign method, consider $u_{rc} = u_r + v_r$. By taking $v_r = -\eta_r \operatorname{sgn}(V_r)$, the resulting $\dot{V}_r$ with this new control input is as follows:

$$\dot{V}_r\left(t\right) = -s^2 r\left(0\right)\cos(st) + \omega_r + \eta_r \operatorname{sgn}(V_r). \tag{19}$$

According to Section 3.2, the time derivative of $r\left(t\right)$ during the interception must be negative. Therefore, $\operatorname{sgn}(V_r) = -1$. Thus one has,

$$\dot{V}_r\left(t\right) = -s^2 r\left(0\right)\cos(st) + ..$$
$$..+\omega_r - \eta_r \le -s^2 r\left(0\right)\cos(st) + .. \tag{20}$$
$$..+\eta_r - \eta_r = -s^2 r\left(0\right)\cos(st).$$

Thus,

$$V_r\left(t\right) \le V_r\left(0\right) - ..$$
$$.. - sr\left(0\right)\sin(st) < V_r\left(0\right) < 0 \qquad \forall t \in \left[0, t_f\right). \tag{21}$$

Therefore, the desirable behavior for $V_r\left(t\right)$ with choosing proper values of s, when $\omega_r \ne 0$ is ensured. Therefore, the guidance law versus maneuvering target is as,

$$u_{\theta c} = \frac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} + \frac{\theta}{r\cos\phi} + ..$$
$$.. + NV_\theta + \eta_\theta \operatorname{sgn}(V_\theta)$$
$$u_{\phi c} = \frac{-V_r V_\phi + V_\theta^2 \tan\phi + \phi}{r} + .. \tag{22}$$
$$.. + MV_\phi + \eta_\phi \operatorname{sgn}(V_\phi)$$
$$u_{rc} = \frac{V_\theta^2 + V_\phi^2}{r} + s^2 r\left(0\right)\cos(st) + \eta_r.$$

In order to avoid chattering, an acceptable approximation of sign function (*i.e.* $\operatorname{sgn}(x)$) by a saturation function (*i.e.* $sat(\alpha x)$) may be replaced. Clearly, higher values of the slope (*i.e.* α) makes a better approximation (Binazadeh et al., 2011; Shafiei et al., 2012).

Consequently, the missile guidance law versus a maneuvering target is as,

$$u_{\theta c} = \frac{-V_r V_\theta + V_\theta V_\phi \tan\phi}{r} + \frac{\theta}{r\cos\phi} + ..$$
$$.. + NV_\theta + \eta_\theta \operatorname{sat}(\alpha V_\theta)$$
$$u_{\phi c} = \frac{-V_r V_\phi + V_\theta^2 \tan\phi + \phi}{r} + .. \tag{23}$$
$$.. + MV_\phi + \eta_\phi \operatorname{sat}(\alpha V_\phi)$$
$$u_{rc} = \frac{V_\theta^2 + V_\phi^2}{r} + s^2 r\left(0\right)\cos(st) + \eta_r.$$

Since, our main goal in this paper is decreasing the interception time, so it may be an error between $r\left(t\right)$ and $r_d\left(t\right)$. However, when the interception in a finite time is guaranteed by equation (21), the difference between $r(t), r_d(t)$ is not critical for us.

4.3 Numerical Simulations For The Missile guidance Problem

In this section, Computer simulations are performed to show the performance of the proposed guidance law. Also, in this paper, it is assumed that at the time $t = t_0$ the missile is in behind of the target and is approaching it. The initial state values of the state variables are taken from (Binazadeh et al., 2011; Shafiei et al., 2012) as follow:

$$\begin{aligned} & r_0 = 5000m, \theta_0 = \phi_0 = \frac{\pi}{3} rad, \\ & V_{r_0} = -300 \, {}^{m}\!/_{s}, V_{\theta_0} = 200 \, {}^{m}\!/_{s}, V_{\phi_0} = 300 \, {}^{m}\!/_{s}. \end{aligned} \tag{24}$$

Also, $\alpha = N = M = 1, s = \frac{\pi}{20}$.

First, the effectiveness of the designed guidance law versus non-maneuvering target is considered. The interception time is 7.1692 s. Figure 1 displays that each state has its proper behavior according to Section 3.2.

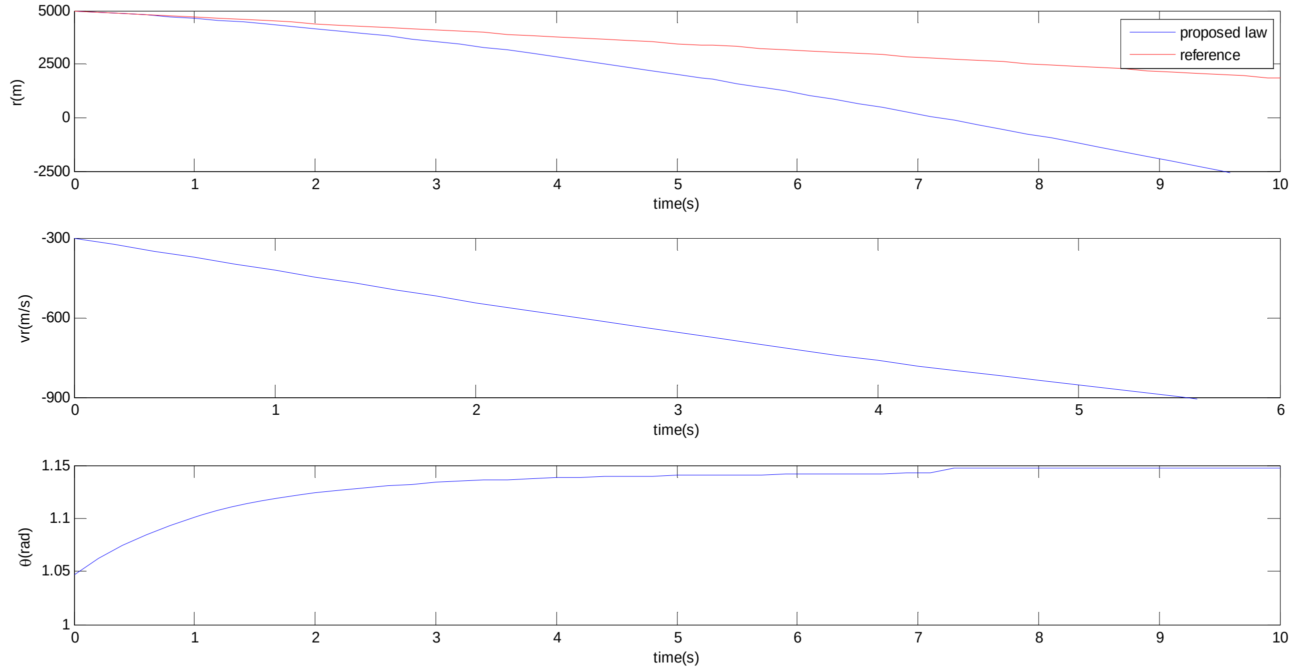

Fig. 1.a. Time evolutions of the system states, where $\omega = 0$.

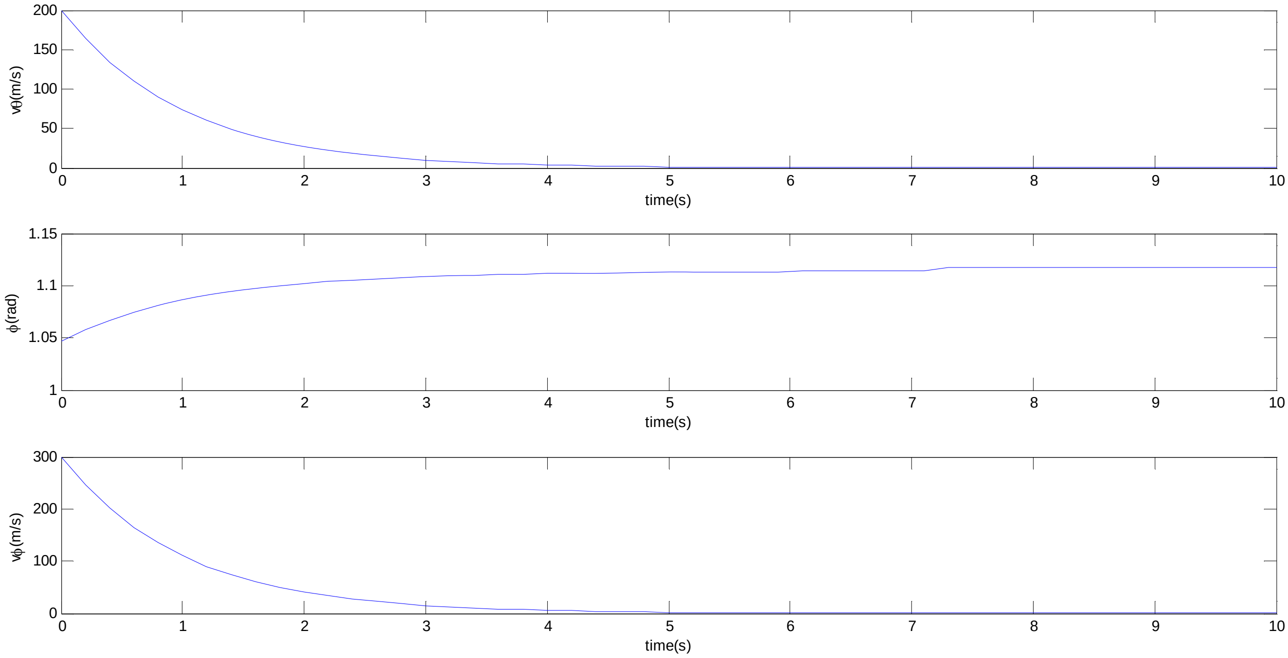

Fig. 1.b. Time evolutions of the system states, where $\omega = 0$.

Now, the effectiveness of the designed guidance law versus a maneuvering target is shown. Target maneuvering is taken from (Shafiei et al., 2012) as follow:

$$\omega = \begin{pmatrix} \omega_\phi & \omega_\theta & \omega_r \end{pmatrix}^T = ..$$

$$.. = \begin{bmatrix} 70\cos(0.5t) \\ 70\sin(0.5t+\frac{\pi}{4}) \\ 70\sin(0.5t) \end{bmatrix}. \quad (25)$$

In this paper, assume that $\eta_\phi = \eta_\theta = \eta_r = 70$.

Figures 2, 3 contains the time evolutions of $r(t), V_r(t), V_\theta(t), V_\phi(t)$ and u_r respectively. Figures 1, 2 shows that the interception time for the proposed guidance law (23) is less compared with that of reference (Shafiei et al., 2012). Figure 3 show that this new approach is realistic for missile guidance problem. Also, according to Section3.2 the proper behavior for each state variable has been ensured (Friedland, 1998; Binazadeh et al., 2011; Binazadeh et al., 2012; Shafiei et al., 2012).

5. CONCLUSION

In this paper, a new approach to design a guidance law for the missile guidance problem based on the partial stability theorem and proper behaviour for each state variable was proposed, which the non-linear system based on the partial stability theorem is divided into two subsystems. The main advantage of this approach is to reduce the interception time. Also, based on the Lyapunov redesign method a new robust guidance law was designed such that the proper behavior for all the state variables is ensured. Finally the effectiveness of this new approach via computer simulations was shown.

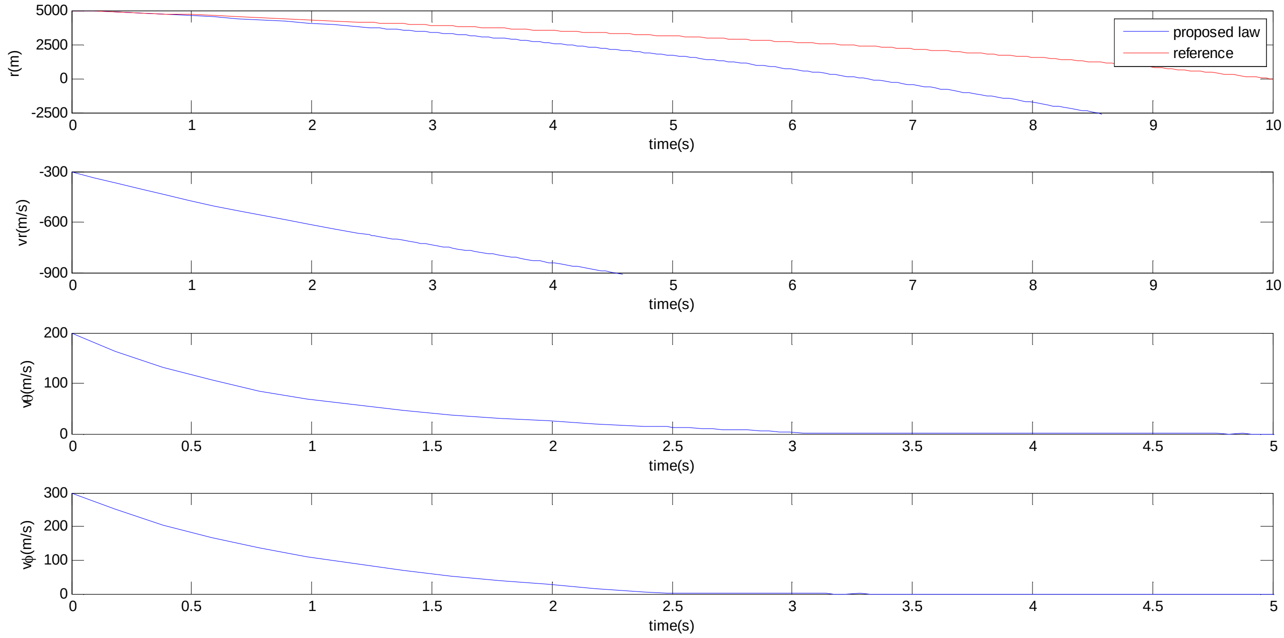

Fig. 2. Time evolutions of the system states, where $\omega \neq 0$.

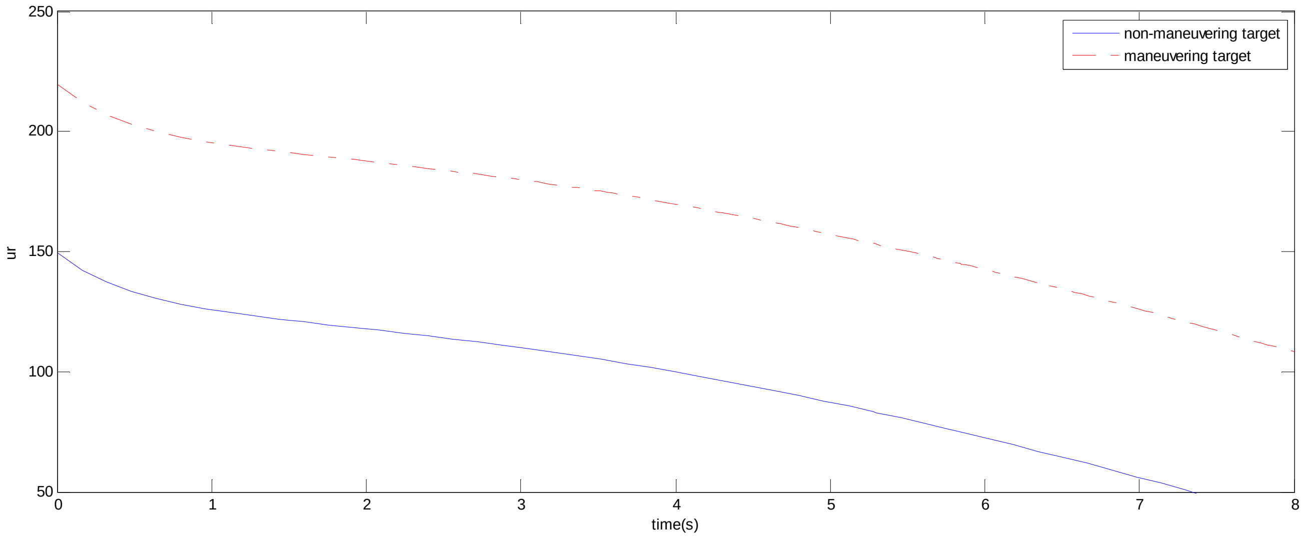

Fig. 3. Time evolutions of 3th control signal.

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