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Robust terminal guidance law design for missiles against maneuvering targets

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ABSTRACT

This paper describes an application of a new terminal guidance law for missiles against maneuvering targets in three-dimensional (3D) environment during the terminal phase. This novel approach is suitable for practical implementation of the guidance law under the circumstance of a guided missile against a maneuvering target. The design procedure is divided into two steps. First, a feedback linearization control scheme is designed to approximately achieve desired tracking of the uncertain missile–target system. Next, a combined optimal robust control scheme is employed to minimize the worst-case effect arising from external disturbances (target's maneuvers) in improving the tracking performance. Simulation examples are presented to illustrate engagement performance of the proposed approach.

1. Introduction

Terminal missile guidance law designs are well-known to control engineers and attract a lot of attention, hence many technologies have been developed to improve guidance performance and to accommodate environmental disturbance [1,2]. In [2], lots of terminal guidance laws have been investigated with different design concepts in the past and most popular terminal guidance laws include line-of-sight (LOS) guidance, LOS rate guidance, command-to-line-of-sight (CLOS) guidance and other advanced guidance laws such as, augmented proportional navigation guidance (APNG) [3,4], advanced proportional navigation guidance (PNG) [5,6] and so on. Of the current techniques, guidance commands which are proportional to the LOS angle rate are generally utilized by most tracking missiles to correct missile course in terminal phase. This approach is quite successful against nonmaneuvering targets and is referred to as PNG. However PNG possesses optimal performance only with constant-velocity targets, it is not effective for targets with uncertain maneuvers and always leads to unacceptable miss distances [7]. Therefore, as a well-considered terminal guidance law design, robustness of engagement performance with respect to the external disturbances (uncertain target's maneuvers) must be considered in the design process.

Based on the above reasons, it is of course highly desirable to apply advanced control techniques in developing an effective terminal guidance law which can enhance engagement performance for tactical missiles during the homing phase. For treating this issue, a novel terminal guidance approach that is combined with feedback linearization and optimal H_∞ control is presented in this paper. As a well-known control design concept, the feedback linearization has been widely applied to treat the tracking problems, such as the control of helicopters, high performance aircraft, industrial robots, and biomedical devices [8]. Generally, feedback linearization is an efficient method for the system without external disturbances, however, external disturbances (i.e. target's maneuver here) are inevitable and always exist in missile–target engagement system hence the effects of external disturbances will strongly affect the tracking performance of the feedback linearization control scheme.

To handle exogenous disturbances, H_∞ control techniques have been proposed over years. Their successful applications to aerospace engineering include space station control [9], missile autopilot design [10,11], and satellite attitude control [12,13]. As to studies of missile terminal guidance law designs utilized robust control concepts, relative researches are rare. Earlier, one robust guidance law based on the solution of Hamilton–Jacobi inequality is derived [14] for a two-dimensional (2D) model. Generally speaking, this is not a realistic design because missiles cannot be decomposed into two 2D planar motions for a large roll rate is always required for high maneuverability in terminal phase; hence full three-dimensional (3D) guidance laws are necessary. Recently, one robust 3D terminal guidance law [15] is developed based on the sliding mode control. From the 3D tracking performance tests,

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Nomenclature

r	Relative distance between the missile and the target	$V_r = \dot{r}$	Relative velocity along LOS
ϕ	Pitch line-of-sight angle (PLOS)	$V_\phi = r\dot{\phi}$	Relative velocity normal to PLOS
θ	Yaw line-of-sight angle (YLOS)	$V_\theta = r\dot{\theta}\cos\phi$	Relative velocity normal to YLOS
$\vec{e}_r$	Unit vector along the LOS	$\ddot{r}$	Relative acceleration along to LOS
$\vec{e}_\phi$	Unit vector along the PLOS	$\ddot{\phi}$	Angular acceleration of ϕ
$\vec{e}_\theta$	Unit vector along the YLOS	$\ddot{\theta}$	Angular acceleration of θ
$\vec{a}_T = w_r\vec{e}_r + w_\theta\vec{e}_\theta + w_\phi\vec{e}_\phi$	Acceleration vector of the target	$\dot{\phi}$	Angular velocity of ϕ
$\vec{a}_M = u_\theta\vec{e}_\theta + u_\phi\vec{e}_\phi$	Acceleration vector of the missile	$\dot{\theta}$	Angular velocity of θ

this revealed investigation [15] achieves satisfactory results; nevertheless, sliding-mode control based methodologies have been commonly recognized as one kind of robust control designs which naturally possesses an inevitable drawback: the chattering effect. Instability of tracking missiles will occur due to this chattering effect in practice. Besides, in these two revealed studies, the controlled longitudinal force of the tracking missile which is never considered in practical implementation was taken into account in the control loop and this is not a suitable design because the thrust of the tracking missiles usually exhausted before entering the terminal stage. For solving the drawbacks of above investigations and treating the terminal guidance law design more realistically, one novel nonlinear robust terminal guidance law which didn't consider the longitudinal force in the control loop based on the combination of feedback linearization and optimal robust control concepts is proposed for the 3D tracking design of missiles. The overall guidance law structure of this proposed method includes two parts: 1. one feedback linearization control scheme, and 2. one robust fine-turning scheme. The feedback linearization control scheme is used to simplify and stabilize the original nonlinear kinematics between the missile and the target as a disturbed linear tracking error system, and the robust fine-tuning scheme is then developed to eliminate the effects of unknown targets' maneuvers in this system globally. For verifying the 3D tracking performance of this proposed method, several tough testing scenarios are arranged based on three random targets' maneuvers and geometry relationships between missiles and targets. From the simulation results, this proposed method delivers really promising contributions for missile terminal guidance law designs.

2. Plant modeling and design objective

Three-dimensional (3D) pursuit geometry of a tracking missile and a maneuverable target in terminal phase is generally described in the spherical coordinates as in Fig. 1. Fig. 1 is a pursuit-evasion geometry between the missile and target where the relative position vector along the line of sight is expressed by $\vec{r}$. The 3D relative velocity can be obtained by differentiating $\vec{r}$ as

$$\dot{\vec{r}} = \dot{r}\vec{e}_r + r\dot{\theta}\cos\phi\vec{e}_\theta + r\dot{\phi}\vec{e}_\phi \tag{1}$$

The above equation yields the relative accelerations as [16]

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

where the relative distance r, the pitch line-of-sight angle ϕ and the yaw line-of-sight angle θ, can be measured by the homing sensor: seeker, in terminal phase.

The nonlinear kinematics between the missile and the target for terminal guidance law design in (2) can be furthermore recast into the following state-space equation:

$$\dot{x}(t) = F\big(x(t)\big) + G_1u(t) + G_2w(t) \tag{3}$$

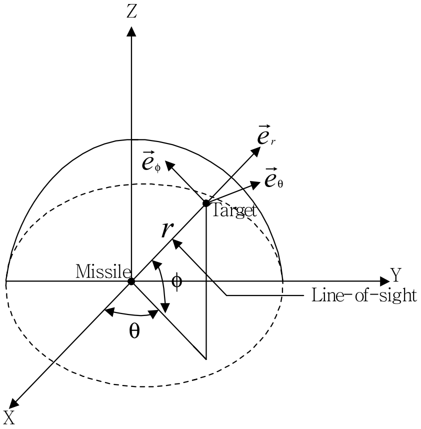

Fig. 1. Three-dimensional pursuit-evasion geometry.

where the state vector $x(t)$, the vector field $F(x(t))$, the missile acceleration vector $u(t)$ and the target acceleration vector $w(t)$ (unknown targets' maneuvers) are defined, respectively, as follows

$$x(t) = \begin{bmatrix} r \\ \theta \\ \phi \\ V_r \\ V_\theta \\ V_\phi \end{bmatrix}, \quad F\big(x(t)\big) = \begin{bmatrix} V_r \\ \frac{V_\theta}{r\cos\phi} \\ \frac{V_\phi}{r} \\ \frac{V_\theta^2+V_\phi^2}{r} \\ -\frac{V_rV_\theta}{r} + \frac{V_\theta V_\phi\tan\phi}{r} \\ -\frac{V_rV_\phi}{r} - \frac{V_\theta^2\tan\phi}{r} \end{bmatrix},$$

$$u(t) = \begin{bmatrix} u_\theta \\ u_\phi \end{bmatrix}, \tag{4}$$

$$w(t) = \begin{bmatrix} w_r \\ w_\theta \\ w_\phi \end{bmatrix}, \quad G_1 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ -1 & 0 \\ 0 & -1 \end{bmatrix}, \quad G_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Preliminary studies have shown that the aspect angle of the interceptor at seeker lock-on near 180 degree (head-on condition) is a fundamental requirement for achieving small miss distance against a target with very high speed and unknown maneuvers [17]. Such a geometric arrangement will minimize the lateral acceleration level for effectively engaging hypersonic and maneuverable targets. To attain this aim, we denote the system output $y(t) = [V_\theta \;\; V_\phi]^T$ as

$$y(t) = Lx(t) \tag{5}$$

where

$$L = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$