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Non-singular terminal dynamic surface control based integrated guidance and control design and simulation

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ABSTRACT

In this paper, a novel cascade type design model is transformed from the simulation model, which has a broader scope of application, for integrated guidance and control (IGC). A novel non-singular terminal dynamic surface control based IGC method is proposed. It can guarantee the missile with multiple disturbances fast hits the target with high accuracy, while considering the terminal impact angular constraint commendably. And the stability of the closed-loop system is strictly proved. The essence of integrated guidance and control design philosophy is reached that establishing a direct relation between guidance and attitude equations by "intermediate states" and then designing an IGC law for the obtained integrated cascade design model. Finally, a series of simulations and comparisons with a 6-DOF nonlinear missile that includes all aerodynamic effects are demonstrated to illustrate the effectiveness and advantage of the proposed IGC method.

1. Introduction

By accounting for the synergism between the guidance and control dynamics, IGC has the potential to improve performance during the terminal guidance phase and yield acceptable miss distances [1]. And the stability of IGC can be strictly proved by Lyapunov theory.

Due to the wide array of potential benefits that an IGC approach can involve, there has been much interest in this area over the past few decades. The ideology of integrated guidance and control was put forward by Williams D E [2,3] in the early stage. Then it was mainly used to solve the homing guidance problems in the development of the past few decades. Various algorithms were used to drive it, such as linearization-LQR [4], adaptive control, robust control, sliding mode control (SMC) [5,6], adaptive SMC, feedback linearization, active disturbance rejection control (ADRC) [7], back-stepping approach [8,9], adaptive dynamic surface control [10,11] and so on. After that IGC was also used in other areas such as reactive obstacle avoidance of UAVs [12], formation flight [13,14], automatic landing of UAVs [15], cooperative attack of multiple missiles [16], reentry process [17,18] and so on. The existing researches involve dealing with IGC design either in the presence of longitudinal missile model only [19–21], or with limited design model [10,11], or without considering impact angle constraints [1,10], or without considering the 'explosion of complexity' of the back-stepping [7–9].

Refs. [10,11] are more relevant to this paper, an integrated guidance and autopilot design method was proposed for homing missiles based on the adaptive block dynamic surface control approach. But its assumption that the missile flies heading to the target at initial time cannot be satisfied in all case. So its design and model is very limited.

The main contributions in this paper are summarized as follows:

(1) A novel IGC design model is established, which has a wider scope of application than the model in [10,11]. It does not need the assumption that the missile flies heading to the target at the initial stage. And the essence of IGC is summarized.
(2) A novel non-singular terminal dynamic surface control (NT_DSC) IGC law is designed combining non-singular terminal sliding mode control (NTSMC) [22,23] and dynamic surface control (DSC) [24]. It can guarantee the missile hits the target with higher accuracy while better satisfying the terminal impact angular constraints. And the practical stability of the overall system is strictly proved based on the Lyapunov stability theorem.

This paper is organized as follows. A novel IGC design model is established and the essence of IGC is summarized in Section 2. NT_DSC IGC law is proposed in Section 3. In Section 4, simulations and comparisons are shown. The paper ends with a few conclusions in Section 5.

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2. Modeling

In this section, the simulation model and a novel IGC design model are established. And the design objective of IGC law is elaborated.

2.1. Simulation model

A-XYZ in Fig. 1 shows the inertial coordinate system. O-xyz is fixed to the missile centroid and parallel to A-XYZ. Firstly, rotate O-xyz counterclockwise by q_2 along O-y axis, and then rotate it counterclockwise by q_1 along O-z axis. One gets line-of-sight (LOS) coordinate system O-$x_4y_4z_4$.

In Fig. 1 q_1 is elevation angle; q_2 is azimuth angle; R is missile-target relative distance.

The guidance equations of the pursuit situation in the three-dimensional space as shown in Fig. 1 can be described by the following nonlinear Eqs. (1) [10,11]

$$\begin{bmatrix}\ddot{q}_1\\ \ddot{q}_2\end{bmatrix}=\begin{bmatrix}-\frac{2\dot{R}}{R}\dot{q}_1-\dot{q}_2^{\,2}\sin q_1\cos q_1\\ -\frac{2\dot{R}}{R}\dot{q}_2+2\dot{q}_1\dot{q}_2\tan q_1\end{bmatrix}+\begin{bmatrix}-\frac{1}{R} & 0\\ 0 & \frac{1}{R\cos q_1}\end{bmatrix}\begin{bmatrix}a_{y4}\\ a_{z4}\end{bmatrix}+\begin{bmatrix}\frac{a_{ty4}}{R}\\ -\frac{a_{tz4}}{R\cos q_1}\end{bmatrix} \tag{1}$$

where $\mathbf{a_{t4}}=[a_{tx4},a_{ty4},a_{tz4}]^{\mathrm{T}}$ and $\mathbf{a_4}=[a_{x4},a_{y4},a_{z4}]^{\mathrm{T}}$ is respectively the acceleration vector of the target and the missile in LOS coordinate system.

The missile attitude equations with disturbances are considered as follows [25,26]

$$\begin{cases}\dot{\alpha}=-\frac{Y}{mV\cos\beta}+\frac{g\cos\gamma_V\cos\theta}{V\cos\beta}-\omega_x\cos\alpha\tan\beta\\ \qquad+\omega_y\sin\alpha\tan\beta+\omega_z+d_\alpha\\ \dot{\beta}=\frac{Z}{mV}+\frac{g\sin\gamma_V\cos\theta}{V\cos\beta}+\omega_x\sin\alpha+\omega_y\cos\alpha+d_\beta\\ \dot{\gamma}_V=\frac{Y(\tan\beta+\sin\gamma_V\tan\theta)+Z\cos\gamma_V\tan\theta}{mV}\\ \qquad-\frac{g\cos\gamma_V\cos\theta\tan\beta}{V}+\omega_x\frac{\cos\alpha}{\cos\beta}-\omega_y\frac{\sin\alpha}{\cos\beta}+d_{\gamma_V}\end{cases} \tag{2}$$

$$\begin{cases}\dot{\omega}_z=(I_x-I_y)\omega_x\omega_y/\mathrm{I_z}+M_z/\mathrm{I_z}+d_{\omega z}\\ \dot{\omega}_y=(I_z-I_x)\omega_z\omega_x/\mathrm{I_y}+M_y/\mathrm{I_y}+d_{\omega y}\\ \dot{\omega}_x=(I_y-I_z)\omega_y\omega_z/\mathrm{I_x}+M_x/\mathrm{I_x}+d_{\omega x}\end{cases} \tag{3}$$

where m is mass of missile; g is acceleration of gravity; I_x, I_y, I_z is rolling, yawing and pitching moments of inertia. V is velocity of missile; θ, ψ_V is flight path angle and heading angle; α, β, γ_V is attack angle, sideslip angle and velocity bank angle, and $|\alpha|<90°$, $|\beta|<90°$, $|\gamma_V|<90°$; ω_x, ω_y, ω_z is body-axis rolling, yawing and pitching angular rate; $\overline{\omega}_x$, $\overline{\omega}_y$, $\overline{\omega}_z$ is the dimension- less form of ω_x, ω_y, ω_z, $\overline{\omega}_x=\omega_x\mathrm{L}/V$, $\overline{\omega}_y=\omega_y\mathrm{L}/V$, $\overline{\omega}_z=\omega_z\mathrm{L}/V$; δ_x, δ_y, δ_z is equivalent aileron, rudder and elevator deflection; D, Y, Z is drag, lift and side force in velocity coordinate; M_x, M_y, M_z is rolling, yawing and pitching moment; d_α, d_β, $d_{\gamma V}$, $d_{\omega x}$, $d_{\omega y}$, $d_{\omega z}$ are external disturbances.

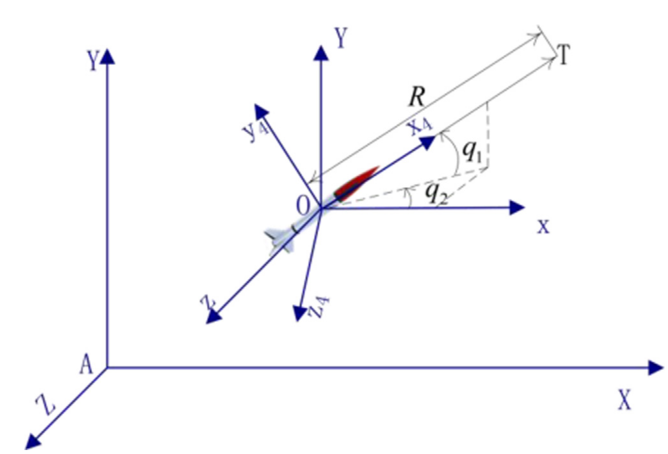

Fig. 1. Coordinate system between missile and target.

The equations of aerodynamic forces and moments are described by

$$\begin{bmatrix}D\\ Y\\ Z\end{bmatrix}=\mathrm{QS}\begin{bmatrix}c_D^\alpha\alpha+c_D^\beta\beta+c_D^{\delta_x}\delta_x+c_D^{\delta_y}\delta_y+c_D^{\delta_z}\delta_z\\ c_Y^\alpha\alpha+c_Y^\beta\beta+c_Y^{\delta_x}\delta_x+c_Y^{\delta_y}\delta_y+c_Y^{\delta_z}\delta_z\\ c_Z^\alpha\alpha+c_Z^\beta\beta+c_Z^{\delta_x}\delta_x+c_Z^{\delta_y}\delta_y+c_Z^{\delta_z}\delta_z\end{bmatrix} \tag{4}$$

$$\begin{bmatrix}M_z\\ M_y\\ M_x\end{bmatrix}=\mathrm{QSL}\begin{bmatrix}c_m^\alpha\alpha+c_m^\beta\beta+c_m^{\overline{\omega}_z}\overline{\omega}_z+c_m^{\delta_x}\delta_x+c_m^{\delta_y}\delta_y+c_m^{\delta_z}\delta_z\\ c_n^\alpha\alpha+c_n^\beta\beta+c_n^{\overline{\omega}_y}\overline{\omega}_y+c_n^{\delta_x}\delta_x+c_n^{\delta_y}\delta_y+c_n^{\delta_z}\delta_z\\ c_l^\alpha\alpha+c_l^\beta\beta+c_l^{\overline{\omega}_x}\overline{\omega}_x+c_l^{\delta_x}\delta_x+c_l^{\delta_y}\delta_y+c_l^{\delta_z}\delta_z\end{bmatrix} \tag{5}$$

where S is reference area; L is reference length; $\mathrm{Q}=0.5\rho V^2$ is dynamic pressure; ρ is air density; c_y^x is partial derivative of aerodynamic force and aerodynamic moment coefficient for the corresponding variable, meaning of partial derivative y to x.

2.2. Design model

The desired design model towards designing IGC law should be obtained by a series of transformation of the simulation model.

In [10,11] the relationship between the LOS angles and the acceleration in the velocity coordinate is established by assuming that the missile flies heading to the target at initial time, so the missile velocity coordinate system approximately coincides with LOS coordinate system. But this cannot be satisfied in any cases. In order to break through this limitation, a novel relationship between LOS angles and acceleration components in the ballistic coordinate system is firstly established

Transform $\mathbf{a}_2=[a_{x2},a_{y2},a_{z2}]$ to O-xyz coordinate system and then to O-$x_4y_4z_4$ coordinate system, one gets (6)

$$\begin{bmatrix}a_{x4}\\ a_{y4}\\ a_{z4}\end{bmatrix}=\mathbf{L}(q_1)\mathbf{L}(q_2)\mathbf{L}^{-1}(\psi_V)\mathbf{L}^{-1}(\theta)\begin{bmatrix}a_{x2}\\ a_{y2}\\ a_{z2}\end{bmatrix} \tag{6}$$

In (6), $\mathbf{L}(q_1)$, $\mathbf{L}(q_2)$, $\mathbf{L}^{-1}(\theta)$, $\mathbf{L}^{-1}(\psi_V)$ is transfer matrix.

$$\mathbf{L}(q_1)=\begin{bmatrix}\cos q_1 & \sin q_1 & 0\\ -\sin q_1 & \cos q_1 & 0\\ 0 & 0 & 1\end{bmatrix},\quad \mathbf{L}(q_2)=\begin{bmatrix}\cos q_2 & 0 & -\sin q_2\\ 0 & 1 & 0\\ \sin q_2 & 0 & \cos q_2\end{bmatrix}$$

$$\mathbf{L}^{-1}(\theta)=\begin{bmatrix}\cos\theta & -\sin\theta & 0\\ \sin\theta & \cos\theta & 0\\ 0 & 0 & 1\end{bmatrix},\quad \mathbf{L}^{-1}(\psi_V)=\begin{bmatrix}\cos\psi_V & 0 & \sin\psi_V\\ 0 & 1 & 0\\ -\sin\psi_V & 0 & \cos\psi_V\end{bmatrix}$$

Combining (1) and (6), one gets

$$\begin{bmatrix}\ddot{q}_1\\ \ddot{q}_2\end{bmatrix}=\mathbf{f}_{\Sigma 0}+\mathbf{B}_0\begin{bmatrix}a_{x2}\\ a_{y2}\\ a_{z2}\end{bmatrix}+\mathbf{\Delta a}_{t0} \tag{7}$$

where

$$\mathbf{B}_0=\begin{bmatrix}0 & -\frac{1}{R} & 0\\ 0 & 0 & \frac{1}{R\cos q_1}\end{bmatrix}\mathbf{L}(q_1)\mathbf{L}(q_2)\mathbf{L}^{-1}(\psi_V)\mathbf{L}^{-1}(\theta),$$