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High angle of attack command generation technique and tracking control for agile missiles

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ABSTRACT

This paper proposes a new tracking control design for agile missiles at high angle of attack regime. Firstly, mathematical descriptions of the problem are presented, taking aerodynamic uncertainties into consideration. Based on the dynamics inverse modeling in a neural network (NN) architecture, the angle of attack command augmented by a variable structure technique is then generated to correspond with the desired turn rate. Subsequently, a nonlinear adaptive control approach using sliding mode control (SMC) technique is employed to track the angle of attack command. Due to the introduction of extended state observer (ESO), the proposed approach is able to online estimate the system uncertainties and calculate derivatives of signals required for composing the control law. Finally, to demonstrate the feasibility and validity of the proposed methodology, the numerical simulation of the agile missile intercepting a target in the rear hemisphere is presented.

1. Introduction

In accordance with the requirement for the omni-directional attack of the carrier fighter, the capability of intercepting the target in the rear hemisphere for an agile missile is essential. To this end, the missile is forced to operate a large angle maneuver after launching, which is called agile turn. During the agile turn, the improvement of supermaneuvering is achieved by high angle of attack flight under post stall control. Nevertheless, aerodynamic control is ineffective in high angle of attack domain, and as a consequence, an alternative actuator such as Reaction-jet Control System (RCS) or Thrust Vector Control (TVC) is adopted to possess larger maneuverability envelopes [1].

In the past decades, a number of designs involving control system of agile missiles have been proposed. Due to the strong nonlinear characteristics of missile dynamics at high angle of attack, various control methods with strong robustness were exploited to address the design of autopilot for agile turn. The control approach proposed in [2] was based on Sliding Mode Control (SMC), in which autopilot using Aero/RCS compound control was synthesized to perform a missile maneuver of heading reversal. In [3], the designed missile autopilot was benefited from the effect of neural network (NN), which enhanced the performance of approximate dynamic inversion for control of uncertain nonlinear systems. Other robust control approaches were also investigated to synthesize the agile missile autopilot based on H_∞ control [4], pole-placement [5], back-stepping [6] and so on. Recently, a novel strategy only using aerodynamic control was proposed in [7], in order to demonstrate a simple potential scheme of agile turn. Furthermore, detailed investigations for this strategy including theoretical analysis and numerical simulation were carried out in [8]. It should be noted that the majority of control system implementations in previous literatures is dependent on precise or basically precise aerodynamic data for an agile missile. Commonly, it is assumed that aerodynamic coefficients at high angle of attack can be obtained by engineering estimation or wind tunnel test. Aerodynamic characteristics at high angle of attack, however, are very difficult to predict, leading to a viewpoint that aerodynamic performance in high angle of attack domain is not available to control design [9].

Moreover, suitable command structures of the agile missile autopilot are required in order to attain high overall performance [10]. From launching to target acquisition during the agile turn, a practical and effective guidance command should be employed to make the missile correct large leading angle error in velocity. Commonly used instruction in missile guidance is acceleration reference which is employed to change the direction of velocity vector to intercept the target. A lot of studies mentioned above have designed angle of attack control system, implying a transformation from desired acceleration command to equivalent angle of attack command. To this end, the relationship between missile turn rate and angle of attack was discussed in [6,11], in which a

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Nomenclature

a_{nc}	normal acceleration command .... $\mathrm{m\,s^{-2}}$
C_a, C_n	aerodynamic axial force coefficient and normal force coefficient
C_m	aerodynamic pitching moment coefficient
C_{ma}, C_{md}	approximate value and disturbed value of C_m
C_{na}, C_{nd}	approximate value and disturbed value of C_n
D	reference length .... m
F_x, F_z	aerodynamic forces in missile body coordinate system .... N
g	acceleration of gravity .... $\mathrm{m\,s^{-2}}$
h	missile flight altitude .... m
J_y	pitching moment of inertia .... $\mathrm{kg\,m^2}$
l_R	distance between the point of RCS action and the center of mass .... m
m	missile mass .... kg
M_y	aerodynamic pitching moment .... N m
M_{yu}	pitching moment produced by control forces ..... N m
q	missile pitch rate .... $\mathrm{rad\,s^{-1}}$
q_c	pitch rate command .... $\mathrm{rad\,s^{-1}}$
R	range between missile and target .... m
S	reference area .... $\mathrm{m^2}$
T	thrust force of main engine .... N
$u_{R\max}$	maximum thrust at steady state of RCS .... N
u_z	control force in z-body direction .... N
V	missile velocity .... $\mathrm{m\,s^{-1}}$
V_T	target velocity .... $\mathrm{m\,s^{-1}}$
α	angle of attack .... rad
α_c	angle of attack command .... rad
$\alpha_{\max}$	angle of attack corresponding to the maximum turn rate .... rad
δ_R	RCS switching coefficient
γ	flight path angle of missile .... rad
γ_T	flight path angle of target .... rad
ρ	air density .... $\mathrm{kg\,m^{-3}}$
σ	line of sight (LOS) angle .... rad
ψ	leading angle error of missile .... rad

turn rate command was transformed to angle of attack command after approximative linearization. Similarly, under the assumption that the missile body acceleration is proportional to angle of attack, a PI controller approach has been proposed in [10,12] in order to generate a desired angle of attack signal used for tracking body acceleration reference in agile turn. No matter which generation approach of angle of attack command is taken, high angle of attack flight is necessary for a missile to complete the agile turn. Nonetheless, missile dynamics under high angle of attack featured with nonlinearity, strong coupling and uncertainty complicate the relationship between the guidance output signal and the equivalent angle of attack. It should be stressed that the linear treatment of the transformation between the two commands is not reliable enough, leading to degradation of performance on tracking guidance command.

Furthermore, missile tracking control of high angle of attack command is difficult to implement as well. It is well known that agile missile dynamics in high angle of attack domain have the characteristics of strong aerodynamic uncertainties. In conventional designs for agile missiles, the effects of uncertainties in plant dynamics are counteracted by the robustness of control system itself, resulting in control performance degradation and energy consumption increasing. Hence, how to deal with the system uncertainties plays a critical role in improving the control performance. Control design of agile missiles presented in [9] did not need any aerodynamic data based on the assumption that the terms related to aerodynamics in missile kinetic equations are regarded as unknown quantities. In [10], a time-delay adaptation scheme was employed to estimate the unmodeled dynamics containing aerodynamic uncertainties for agile missile autopilot design, but only small angle of attack flight ($\alpha < 35°$) was addressed in this literature. Therefore, it can be perceived that the disturbance estimation approach is an effective strategy to improve the robustness of the agile missile controller in the presence of aerodynamic uncertainties.

Guidance and control methods have been studied independently among most of the researches involving agile turn. Few of these researches have been put forth to investigate the problem of the angle of attack command generation in terms of a guidance signal when the desired turn rate is fairly large. The usual assumption is that the relationship between turn rate and angle of attack is approximated by a linear function. This paper, however, aims to establish a more precise nonlinear inverse model of missile turn rate dynamics by neural network approach, especially for high angle of attack regime. This inverse model can calculate the equivalent angle of attack for a given turn rate, which is used as a basis for generating angle of attack command. Naturally, high angle of attack tracking becomes another issue that needs to be addressed. As a solution to this problem, an autopilot is designed following the thought that the aerodynamic data regarded as uncertainty is unavailable to the autopilot implementation. As the key part of active disturbance rejection control (ADRC) method, extended state observer (ESO) is employed to estimate total uncertainties in real time. What makes the proposed control scheme different is the disturbance rejection capability resulted from the real-time compensation for the system uncertainties. Such ability of online estimation and compensation enables the control system to possess the disturbance rejection mechanism in the presence of strong system uncertainties.

The remainder of this paper is organized as follows. A description of the issues and mathematical modeling are presented in Section 2. In Section 3, based on the analysis of the turn rate dynamics of agile missiles, an NN-based dynamics inverse model is established to approximate the relationship between missile turn rate and angle of attack, in order to generate the angle of attack signal. Furthermore, In Section 4, angle of attack tracking control using back-stepping scheme and SMC method is designed in conjunction with ESO technique which can estimate the system uncertainties and calculate derivatives of signals. Subsequently, stability analysis of the closed-loop system is studied. The simulation results of target interception are presented in Section 5, followed by conclusions summarized in Section 6.

2. Problem formulation

For agile turn of a missile, the bank-to-turn (BTT) steering technique is often recommended. This paper focuses on the missile longitudinal dynamics due to the assumption that the missile maneuvers in a certain expected maneuvering plane. As shown in Fig. 1, the system dynamics models are based on a slender body equipped with both the RCS system and the rear control dominated by cruciform rudders. The dynamics of the missile are given as

$$\begin{cases} \dot{\gamma} = [(T + F_x)\sin\alpha - (F_z + u_z)\cos\alpha - mg\cos\gamma]/(mV) \\ \dot{\alpha} = q - \dot{\gamma} \\ \dot{q} = (M_y - M_{yu})/J_y \end{cases} \tag{1}$$