Chinese Journal of Aeronautics, (2016), xxx(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University
Chinese Journal of Aeronautics
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Roll-pitch-yaw autopilot design for nonlinear time-varying missile using partial state observer based global fast terminal sliding mode control

Awad Ahmed, Wang Haoping *

Sino-French International Joint Laboratory of Automatic Control and Signal Processing (LaFCAS), School of Automation, Nanjing University of Science & Technology, Nanjing 210094, China

Received 9 November 2015; revised 18 January 2016; accepted 22 February 2016

KEYWORDS

Flight control system;
Global fast terminal sliding mode control;
Integrated autopilot;
Nonlinear state observer;
Skid-to-turn missile

Abstract The acceleration autopilot design for skid-to-turn (STT) missile faces a great challenge owing to coupling effect among planes, variation of missile velocity and its parameters, inexistence of a complete state vector, and nonlinear aerodynamics. Moreover, the autopilot should be designed for the entire flight envelope where fast variations exist. In this paper, a design of integrated roll-pitch-yaw autopilot based on global fast terminal sliding mode control (GFTSMC) with a partial state nonlinear observer (PSNLO) for STT nonlinear time-varying missile model, is employed to address these issues. GFTSMC with a novel sliding surface is proposed to nullify the integral error and the singularity problem without application of the sign function. The proposed autopilot consisting of two-loop structure, controls STT maneuver and stabilizes the rolling with a PSNLO in order to estimate the immeasurable states as an output while its inputs are missile measurable states and control signals. The missile model considers the velocity variation, gravity effect and parameters' variation. Furthermore, the environmental conditions' dynamics are modeled. PSNLO stability and the closed loop system stability are studied. Finally, numerical simulation is established to evaluate the proposed autopilot performance and to compare it with existing approaches in the literature.

1. Introduction

The acceleration autopilot design for skid-to-turn missile is still considered as one of the most attractive topics for control engineers due to its enormous nonlinear dynamics, the coupling effect between channels, and its rapid parameters' variation.[1] The most significant variation of missile parameters is its velocity which changes rapidly as a result of subjecting the missile to a sudden acceleration during boosting phase

* Corresponding author. Tel.: +86 25 84303971.
E-mail address: hp.wang@njust.edu.cn (H. Wang).
Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2016.04.020
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and deceleration during gliding phase due to aerodynamic drag.[2]

Researches in this field have been started since 1944. One of the commonly used autopilots was the three-loop autopilot topology.[3] The conventional and linear quadratic regulators based on the linearization of model dynamics around fixed operating points were used. This technique is so-called "gain scheduling". In Ref.[4], a classical gain-scheduling design was introduced. In the 1990s, extensions of these techniques had brought many developments, like guaranteed stability margins and performance levels.[5,6] The authors in Ref.[7] presented a linear quadratic Gaussian with loop transfer recovery technique to design gain scheduling autopilot. A gain scheduling based autopilot in the presence of hidden coupling terms is illustrated in Ref.[8] The combined optimal/classical approach was applied to design the optimal controller in Ref.[9] as well. Also, robustness issues were introduced with suitable extensions of H_∞ techniques.[10,11] Clearly, the gain scheduling approach shows a good performance during the entire envelope, but the global stability is guaranteed only in the case of slow variation of both the states and the missile parameters.

The development of linear parameter-varying (LPV) and quasi-LPV approaches in the last two decades had pushed the researchers towards a new systematic and strict methodology. For example, an acceleration autopilot design using the LPV reference model was presented for portable missile.[12] Unfortunately, the disadvantage of these approaches, especially for quasi-LPV autopilot, is the increment of conservative level.[13] Also, most of these approaches except quasi-LPV approach, were still based on the linearization of dynamics around operating points. Other drawbacks of LPV were the difficulty in parameter variation recognition and the demand of an additional filter for parameter estimation as well.[14]

The requirements of high maneuverability and the development of nonlinear control methods pushed the research towards new control design approaches that consider essential nonlinear dynamics. This led to the first generation of nonlinear autopilots which were based on both the inversion of dynamics[15] and the feedback linearization techniques.[16] New approaches were introduced in the last decades based on recent control techniques, such as Lyapunov stabilization techniques[17], sliding mode control (SMC)[18,19], adaptive SMC[20], adaptive block dynamic surface control[21], l_1 adaptive control[22], simple adaptive control algorithm[23], adaptive fussy sliding mode control[24], robust hybrid control[25], immersion and invariance control[26], backstepping control[27], state-dependent Riccati equation (SDRE) approach[28], adaptive SDRE with neural networks[29], and fuzzy control.[30] The approaches introduced in the nonlinear and/or adaptive context failed when massive unstructured dynamics existed. Moreover, the strict requirements needed for the response speed cannot often be achieved due to adaptation laws. Therefore, robust nonlinear approaches based on the geometric theory as in Ref.[31] and the extensive use of Lyapunov direct criterion as in Ref.[32] were presented, demonstrating good performance at a high angle of attack. It should be mentioned that the approaches based on these methods have been only applied to simple single-input/single-output cases, disregarding the coupling and nonlinearities occurring between pitch and yaw planes.

A few works paid attention to presenting the integrated autopilot to overcome the coupling effect between channels. For example, a robust backstepping approach has been applied to multi-input/multi-output (MIMO) model to achieve both bank-to-turn and skid-to-turn (STT) maneuvers[1], a three-axis autopilot design using the classical three-loop autopilot approach[33], and an acceleration autopilot based on a linear robust control scheme was presented to control roll, pitch, and yaw channels in an integrated way.[34] These works showed a good performance while considering the missile velocity constant, and the controller design is still based on linearization except in Ref.[1]. Ref.[35] presented a sliding mode based integrated attitude control scheme considering velocity change. It showed good results, but the acceleration control was not presented. In Ref.[2], a sliding mode based roll-pitch-yaw integrated attitude and acceleration autopilot for a time-varying velocity STT missile was proposed. It showed a good performance, but a complete state vector is essential and the velocity variation was considered as a function of time. Likewise, gravity effect, missile parameters' variation, chattering phenomenon, and environmental dynamics were neglected.

Thus, to achieve a good tracking performance of the integrated acceleration autopilot in presence of the above referred neglected factors without seeking for chattering elimination or complete state vector feedback, an integrated roll-pitch-yaw autopilot using a partial state nonlinear observer (PSNLO) based global fast terminal sliding mode control (GFTSMC) approach is proposed for a skid-to-turn nonlinear time-varying (STTNTV) missile model. The missile model has taken into account the coupling effect, gravity effect, missile parameters' variation, environmental conditions' dynamics, and nonlinear aerodynamics. In a similar manner, the missile velocity and its height have been considered as a function of its states. GFTSMC with a suggested sliding surface is provided to avoid the chattering phenomena of SMC, the singularity problem of normal GFTSMC, and the demand for a relation between the second derivative of system states and its inputs. These sliding mode surfaces are suggested and used in the integrated two-loop autopilot structure to nullify the integral error. PSNLO is presented to estimate the immeasurable states (angle of attack α and side slip angle β) used to feedback the autopilot. The stability of closed loop system including PSNLO stability is discussed.

The remaining paper is organized as follows: In Section 2, system description and modeling are provided. In Section 3, integrated roll-pitch-yaw autopilot design, PSNLO design and its stability analysis, and the closed loop stability analysis are presented. The integrated autopilot design includes outer-loop controller design based on GFTSMC with acceleration dynamics modeling and inner-loop controller design based on GFTSMC. In Section 4, numerical simulations are presented, and Section 5 is devoted to summary and concluding remarks.

2. System description and modeling

The STTNTV missile model is aerodynamically controlled via canard fins, and it has an axis-symmetric and cruciform shape. Thus, the next general assumptions can be considered:

(1) The moments of inertia $I_{yy}(t)$ and $I_{zz}(t)$ are identical and products of inertia moments can be discarded.
(2) For short-range missiles, the Earth has been considered flat and non-rotating.

Please cite this article in press as: Awad A, Wang H Roll-pitch-yaw autopilot design for nonlinear time-varying missile using partial state observer based global fast terminal sliding mode control, *Chin J Aeronaut* (2016), http://dx.doi.org/10.1016/j.cja.2016.04.020