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Neural network-based sliding mode control for atmospheric-actuated spacecraft formation using switching strategy

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Abstract

This paper presents an adaptive neural networks-based control method for spacecraft formation with coupled translational and rotational dynamics using only aerodynamic forces. It is assumed that each spacecraft is equipped with several large flat plates. A coupled orbit-attitude dynamic model is considered based on the specific configuration of atmospheric-based actuators. For this model, a neural network-based adaptive sliding mode controller is implemented, accounting for system uncertainties and external perturbations. To avoid invalidation of the neural networks destroying stability of the system, a switching control strategy is proposed which combines an adaptive neural networks controller dominating in its active region and an adaptive sliding mode controller outside the neural active region. An optimal process is developed to determine the control commands for the plates system. The stability of the closed-loop system is proved by a Lyapunov-based method. Comparative results through numerical simulations illustrate the effectiveness of executing attitude control while maintaining the relative motion, and higher control accuracy can be achieved by using the proposed neural-based switching control scheme than using only adaptive sliding mode controller.

Keywords: Satellite formation; Aerodynamic force; Neural network; Adaptive sliding mode; Switching control

1. Introduction

As compared with conventional large single satellites, satellite formation flying (SFF) has been seen as a significant technology in current and future space missions (Sabol et al., 2001; Kapila et al., 2000). Small satellites in formations have many advantages over single satellites such as higher system reliability, simpler design, and greater launch flexibility. Since formations tend to break down because of various perturbations, relative motion control is required for SFF (D'Amico and Montenbruck, 2006; Wang et al., 2009, 2012). Traditionally, formation control is conducted using thrusters which require fuel consumption and may result in plume contamination to the sensors onboard. Hence, propellantless methods for formation control are of great interest. In Low Earth orbits (LEO), differential aerodynamic forces can be used as a control in SFF due to the promising ability of saving propellant. The idea to use the differential aerodynamic drag to provide control over the relative motion of the satellites in LEO, was first proposed by Leonard et al. (1989).

A potential application of relative orbital control using differential aerodynamic force has raised research interest. Bevilacqua and Romano (2008) used differential drag (DD) to achieve rendezvous based on the Schweighart-Sedwick equations (Schweighart and Sedwick, 2002). Ben-Yaacov and Gurfil (2013) developed DD-based cluster keeping algorithm for long term missions using relative orbital elements. Harris and Açkmeşe (2014) presented a

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method to solve the minimum time rendezvous problem using DD. Mazal et al. (2016) designed DD-based cooperative maneuvers by considering uncertainties in the drag model. A serious drawback of using DD is that it only allows control over the relative motion in the orbital plane (Horsley et al., 2013). Horsley et al. (2013) first described a method for controlling the relative positions both in-plane and out-of-plane using differential lift and drag.

The aforementioned literature has only focused on the orbital control problem. For typical SFF applications such as, synthetic aperture radars, optical interferometers, satellite inspections, and as well as capture and removal of orbital debris, simultaneous control of translational and rotational motion of the spacecraft is required. Pastorelli et al. (2015) described a novel DD-based method to control both the in-plane position and ram attitude based on a decoupled virtual thruster strategy. Sun et al. (2017) first suggested a method to completely control the coupled orbit-attitude dynamics in a formation using only aerodynamic forces.

In SFF applications, uncertainties and external disturbances have effects on controlling the relative position and attitude of the spacecraft in the formation. The presence of the external perturbations and parameter uncertainties makes the roto-translational control for atmospheric-actuated spacecraft more complicated. The sliding mode control (SMC) technique was used by Sun et al. (2017) to account for the density uncertainty. It has to be pointed out that the proposed controller was designed based on the assumption that the upper bounds of the uncertainty are known. However, in practical situations, uncertainties are not just included in atmospheric model, and the range of the uncertainties cannot be determined exactly, which will cause the degradation of the SMC controller. Neural networks (NNs) have been used to compensate for the nonlinear uncertainties in system dynamics, since NNs can represent any continuous functions on a compact sets (Zou and Kumar, 2010; Bae and Kim, 2012; Zhao and Jia, 2016; Zou and Zheng, 2015; Huang et al., 2017; Sun et al., 2011; Liu et al., 2016). As a result, prior knowledge about the upper bound of the uncertainties is not required.

The NNs-based controller can approximate uncertainties with arbitrary control accuracy. As pointed out by Xia and Huo (2016a), to satisfy the high accuracy, the NNs have to add more nodes when the application range arises, which leads to a complex structure and high calculation. Thus, constructing the NNs with a large active region is not necessary. Additionally, it should be noticed that the stability of the closed-loop system is guaranteed based on the condition that the NNs stay valid for all time. However, such a condition is difficult to verify beforehand, which may cause the deterioration of tracking performance or even instability of the entire system (Huang, 2012). To alleviate these concerns, Xia and Huo (2016b) developed a switching controller by combining direct adaptive control approach and backstepping technique, which consists of a conventional adaptive neural controller in the neural active region and an extra robust controller outside the region.

In the paper, the problem of roto-translational control for atmospheric-actuated spacecraft under unknown uncertainties is considered. It is assumed that both satellites in a formation, namely the chief and deputy, process several large flat plates, which have the ability to rotate and extend. Aerodynamic accelerations for translational control are produced by rotating the plates, and control torques for rotational motion are generated by the extensions/retractions of the plates. A coupled orbit-attitude model is established based on the arrangement for the actuators. A novel switching controller is developed by combining the adaptive SMC technique and neural control approach, with an adaptive NNs-based controller dominating in the neural active region and an adaptive sliding mode controller working outside the region. In the neural active region, the system uncertain nonlinearities are approximated by the radial basis function NNs (RBFNNs), and control gains in the sliding mode controller are tuned adaptively to estimate the upper bound of the uncertainties outside the region. The proposed switching strategy can efficiently reduce real-time computation burden of the controller and avoid the invalidation of the neural networks destroying stability of the system. An optimal method is suggested to calculate the control commands for the plates system. The asymptotic stability of the closed-loop system is proved by using the Lyapunov stability theorem. The performance of the control scheme is evaluated through numerical simulations.

The paper is organized as follows. Aerodynamic models and coupled dynamic equations are described in Section 2. The switching controller is developed in Sections 3. This is followed by introducing an optimal method to compute the control commands. The numerical simulations are presented in Section 4 to testify the proposed control strategy. Finally, Section 5 concludes the paper.

2. Problem formulation

2.1. Coordinate frames

The coordinate reference frames exploited in the paper are presented as follows: The Earth-centered inertial (ECI) frame $\boldsymbol{I} \triangleq \{\mathbf{O}x_i y_i z_i\}$ is located in the center of the Earth $\mathbf{O}$. The x_i axis points in the direction of the vernal equinox, the z_i axis is along the rotation axis of the Earth towards the celestial North Pole, and the y_i axis completes the right hand orthogonal frame system. The local-vertical local-horizontal (LVLH) frame $\boldsymbol{L} \triangleq \{\mathbf{C}x_l y_l z_l\}$ is fixed at the center of mass of the chief $\mathbf{C}$. The x_l axis points in the direction of the ray from the center of Earth to the origin of the system, the y_l axis is along the orbital track, and the z_l axis completes the right hand orthogonal coordinate system. The orbital frame $\boldsymbol{O} \triangleq \{\mathbf{D}x_o y_o z_o\}$ is fixed at the center of mass of the deputy $\mathbf{D}$. The x_o axis points in the direction

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