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Relative position keeping in satellite formation flying with input saturation

Young-Hun Lim, Hyo-Sung Ahn*

School of Mechatronics, Gwangju Institute of Science and Technology (GIST), 123 Cheomdangwagi-ro, Buk-gu, Gwangju 500-712, Republic of Korea

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Abstract

This paper studies a relative position keeping problem in satellite formation flying with input saturation. The relative motion dynamics is designed with polytopic-type uncertainties by considering elliptic and noncoplanar formation, and unknown angular rate and acceleration within some boundary. A composite nonlinear feedback control law is developed by using a low-and-high gain control scheme with an algebraic Riccati inequality (ARI). In the presence of input saturation and disturbances, finite-gain L_∞ stability of the relative motion dynamics is ensured using the proposed control law. Additionally, the domain of attraction for the stability is evaluated by formulating an optimization problem. Through numerical simulations, the validity of the proposed scheme is illustrated.

1. Introduction

For the successful mission completion in current and future satellite systems, the concept of satellite formation flying (SFF) has been actively studied for the last two decades [1,2]. The SFF has several advantages including cost efficiency, safety, mission flexibility, and easy maintenance of space systems. Thus, it has attracted a significant amount of research interest from many researchers and engineers. To realize the SFF in actual space operation, recently several control schemes have been developed. For example, based on the Clohessy–Wiltshire (CW) equation, [3] developed a discrete time controller using pulse-based actuators. In [4], a control problem of the SFF using hybrid control scheme was studied. However, the CW equation

*Corresponding author. Tel.: +82 10 3304 6495.
E-mail addresses: hoonnim@gist.ac.kr (Y.-H. Lim), hyosung@gist.ac.kr (H.-S. Ahn).

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is a linear approximation assuming circular or near circular reference orbit without uncertainties and external disturbances. Therefore, several researchers have studied the control problem considering an elliptic reference orbit, uncertainties and disturbances. In the case of the elliptic reference orbit, [5] developed a nonlinear relative motion dynamics and Lyapunov-based nonlinear output feedback control law in the presence of uncertainties and disturbances. In [6], a new relative motion dynamics allowing elliptic and noncoplanar formation was derived. In [7], an uncertainty model from a nonlinear relative position model under the variations of eccentricity and semi-major axis was derived. In [8], θ-D method was used to approximate analytical solution of Hamilton–Jacobi–Bellman equation that provides a new suboptimal technique for the control of relative formation dynamics. Furthermore, in [9,10], the SFF control problem for the six degree-of-freedom coupled translation and attitude motion dynamics was studied.

However, all of the aforementioned approaches did not consider the problem of input saturation that cannot be ignored in practical applications. Since the input saturation affects not only the performance of systems, but also the stability of systems, the problem of input saturation has become one of the most important issues in control engineering [11–15]. In the case of SFF system, the control problems that explicitly consider input saturation have received increasing attention over the last few years. In [16], adaptive neural network controller was proposed, and they showed that it requires small control input to achieve the uniform ultimate boundedness of all signals in the closed-loop system. In [17], the problem of input saturation was solved using low-pass filter and anti-windup controller such that the generated control could remain implementable. However, all the research mentioned above did not consider the problem of input saturation directly. In [18], based on the sector-boundedness of saturation nonlinearity, the condition for stability of SFF system was expressed under LMI forms. However, the disturbances and the performance of the system were not considered.

In this paper, a feedback controller design method for a relative position keeping is investigated in the presence of input saturation and disturbances. First, for the relative position keeping problem [19], the relative motion dynamics allowing elliptic and noncoplanar formation that was proposed in [6] is considered. In this setup, it is supposed that angular velocities and its derivation of leader satellite are unknown parameters within some boundary. From this assumption, we propose the polytopic-type uncertain dynamics. Second, based on the low-and-high gain feedback control law [13], we propose a composite nonlinear feedback (CNF) control law obtained by solving an algebraic Riccati inequality (ARI). Since the proposed polytopic-type uncertain dynamics contains uncertain nonlinear terms, it is difficult to apply the low-and-high gain approach directly. To reject the nonlinear terms, the robust control technique using a sign function is widely used [17,19]. However, the sign function may lead to a chattering phenomenon. Chattering is highly undesirable in practice because it may excite high frequency unmodeled plant dynamics. Therefore, we apply a high-slope saturation function, and then, the closed-loop dynamics contains a nested saturation. Finally, by the use of quadratic Lyapunov function, the finite-gain L_∞ stability of the SFF system is achieved and the domain of attraction is estimated. Thus, the main contribution of this paper is the direct analysis of the input saturation problem in the SFF system by using the low-and-high gain approach. Additionally, the polytopic-type parameter uncertainties are considered to analyze the overall system stability.

The outline of this paper is as follows. The relative motion dynamics proposed in [6] is briefly described in Section 2. In Section 3, we review briefly the low-and-high gain feedback controller and the condition of finite-gain L_∞ stability, and provide the problem formulation. In Section 4, the relative motion dynamics with time-varying polytopic uncertainties and the control strategy is provided, and finite-gain L_∞ stability is derived. Furthermore, in Section 4, based on the proposed