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Nonlinear attitude tracking control for spacecraft formation with multiple delays

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Abstract

This paper addresses the attitude tracking control for spacecraft formation with delay free and communication delays. With help of the idea of sliding control, an adaptive attitude synchronization control architecture is established. Furthermore, by introducing a nonsmooth feedback function, a new class of nonlinear controllers for the attitude tracking of spacecraft is developed. Both parameter uncertainties and unknown external disturbances are dealt with via the kind of controllers. Finally, some simulation results are given to demonstrate the effectiveness and advantages of the proposed results.

Keywords: Spacecraft formulation; Attitude tracking; Nonlinear control; Adaptive control; Multiple delays

1. Introduction

Inspired by biology and human sociological studies such as flocking in birds, schooling in fish, and other natural systems, research on multi-agent systems has attracted much attention in the past two decades. There are many potential advantages of such systems over a single body, including greater flexibility, adaptability and performance. With regard to these benefits, the concept of multi-agent has been studied extensively in the literature with application to the wireless sensor networks (Cortes, 2008), multi-manipulator collaborative assembly (Li et al., 2010), UAVs formation (Singh et al., 2000), satellite formation (Beard et al., 2001) and deep space exploration of spacecraft (Smith and Hadaegh, 2009). In the space industry, the concept of spacecraft formation flying is emerging as an attractive alternative to traditional monolithic spacecraft for both scientific and military applications. It is a mature concept which provides the idea of distributing a large spacecraft assignment to several simpler, cheaper and smaller spacecraft to get better space mission performance in the future. During spacecraft formation, it is important that the attitude of spacecraft be synchronized. Therefore, the problem of attitude tracking control for spacecraft formation receives more and more attention in recent years, such as in (e.g., Chung et al., 2009; Malik and Asghar, 2014; Jung et al., 2013; Bai et al., 2008; Yoo et al., 2013) and so on.

In application, individual spacecrafts cooperate with each other through communication for information sharing and eventually reach an agreement on their orientations. During the information exchange, time delays are inevitably exist, which may degrade the control performance of the formation and even destabilize the entire system (Malik and Asghar, 2014). Furthermore, the model parameters of a spacecraft in the formation are not usually known exactly, and the spacecraft is always

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subject to external disturbances. All of the above issues make it difficult to achieve ideal control performance for spacecraft attitude tracking. Previous studies have proposed various approaches to solve this problem. The adaptive control algorithms are proposed for spacecraft attitude tracking without angular velocity measurements in Costic et al. (2000). A H_∞ control law is proposed in Luo et al. (2004), in which the inverse optimal control method has been applied to attitude tracking control with extended disturbances. When the effect of the motion of the flexible appendages is considered, the attitude tracking control problem becomes more complicated (Jin and Sun, 2009). Some studies have proposed diverse control algorithms to solve the attitude tracking problem of flexible spacecraft under different conditions, such as in (e.g., Shahravi et al., 2006; Gennaro, 2002). In addition, some other control approaches have also been investigated for the attitude tracking control problem, including backstepping control (Ali et al., 2010), combined adaptive sliding mode control (Xiao et al., 2012), output feedback control (Wong et al., 2002) and neural network control (Zou et al., 2011), and so on. But there are few papers using the nonlinear proportional derivative control method which is proposed in active disturbance rejection control for spacecraft formation flying. This motivated us for the study in this paper.

The active disturbance rejection controller, which is firstly proposed by Han (2009), consists of tracking differentiator, extended state observer and nonlinear proportional derivative controller, please refer to Xia and Fu (2013); Xia et al. (2012) and the references therein. Note that extended state observer is the key link for active disturbance rejection controller and it is taken off as an efficient technology in numerous successful engineering applications. By regarding the lumped disturbances which consists of internal dynamics and external disturbances as a new state of the system, extended state observer can estimate both the states and the lumped disturbances. Extended state observer based control schemes has been well studied and applied successively in many researches, such as (e.g., Li et al., 2012; Liu and Li, 2012; Zhu et al., 2012; Talole et al., 2010) and so on. In Xia et al. (2011a), a sliding mode controller is designed by combining backstepping technique and extended state observer approach. To deal with the problem of spacecraft attitude tracking control, both adaptive control law and extended state observer are used for the controller design in Xia et al. (2011b). In the design of extended state observer, an efficient nonsmooth feedback function is used to guarantee its high efficiency in accomplishing the nonlinear dynamic estimation. It is the key factor that extended state observer can estimate the uncertainties along with the states of system, thus enabling disturbances rejection or compensation. The nonsmooth feedback function is inherently robust against plant variations and can reject the disturbances in the form of orders of magnitude. Hence, it is also introduced to the nonlinear proportional derivative controller design in Xia et al. (2007). All of these special feedback mechanism make the active disturbance rejection controller has a particularly satisfactory performance in the system control. There are many research results which introduce the active disturbance rejection into the wide industrial applications, please refer to (e.g., Zheng et al., 2009; Wu and Chen, 2009; Wu and Chen, 2013; Xing et al., 2013) and so on.

Most spacecraft have the characteristics as unknown model parameters, coupling time delays and uncertain disturbances. To explore the advanced control strategy which is suitable for the characteristics of spacecraft, a nonsmooth feedback function is used in the spacecraft attitude tracking control for both delay free and multiple time delay cases. Furthermore, inspired by the recent results for bilateral teleoperator in Nuño et al. (2010), an adaptive control architecture which allows for unknown parameters and external disturbances is also established. In addition, by introducing the "virtual leader" (Cao and Ren, 2012) concept in this paper, it is demonstrated that arbitrary desired attitude synchronization and tracking can be achieved.

The main contributions of this paper are summarized as below:

(i) A new kind of nonsmooth feedback controllers is designed for spacecraft attitude tracking with the delay free and multiple time delay cases.
(ii) There exists better control effect than the linear feedback control law in Min et al. (2012) by using the adaptive nonlinear control law proposed in this paper.
(iii) In the proof of controller design with multiple time delays, Laplace transform method is introduced to deal with the multiple time delays.

The remainder of this paper is organized as follows. In Section 2, backgrounds on the attitude dynamics of spacecraft and the problem formulation are presented. Besides, the graph theory notions used throughout this paper are also presented. Sections 3 is the main parts of this paper focusing on the attitude tracking control of spacecraft formulation with delay free and multiple time delay topologies, respectively. Several simulation examples are presented in Section 4. Conclusion is given in Section 5.

Notation. In the following, if not explicitly stated, matrices are assumed to have compatible dimensions. $\|\cdot\|$ is the Euclidean norm of a vector. The shorthand $diag\{M_1\ M_2\ \cdots\ M_N\}$ denotes a diagonal matrix with diagonal blocks $M_1, M_2, \ldots, M_N$. $\mathbf{R} := (-\infty, \infty)$, $\mathbf{R}_{>0} := (0, \infty)$, $\mathbf{R}_{\geqslant 0} := [0, \infty)$. $\mathbf{R}^n$ denotes the n-dimensional Euclidean space. For any function $\mathbf{f} : \mathbf{R}_{\geqslant 0} \to \mathbf{R}^n$, the L_∞-norm is defined as $\|\mathbf{f}\| = sup_{t\geqslant 0}|\mathbf{f}(t)|$, and the L_2-norm as $\|\mathbf{f}\|_2^2 = \int_0^\infty |\mathbf{f}(t)|^2 dt$. The L_∞ and L_2 spaces are defined as the sets $\{\mathbf{f} : \mathbf{R}_{\geqslant 0} \to \mathbf{R}^n : \|\mathbf{f}\|_\infty < \infty\}$ and $\{\mathbf{f} : \mathbf{R}_{\geqslant 0} \to \mathbf{R}^n : \|\mathbf{f}\|_2 < \infty\}$, respectively. $\otimes$ is the standard Kronecker product. I_N is the identity matrix with dimension N. $1_N = (1, 1, \ldots 1)^\top$ is the unit vector with N-dimension. Letting