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Finite-time output feedback attitude coordination control for formation flying spacecraft without unwinding

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ABSTRACT

In this paper, two finite-time attitude coordinated controllers for formation flying spacecraft are investigated based on rotation matrix. Because rotation matrix can represent the set of attitudes both globally and uniquely, the two controllers can deal with unwinding that can result in extra fuel consumption. To address the lack of angular velocity measurement, the second attitude coordinated controller is given by using a novel filter. Through homogeneous method and Lyapunov theories, it is shown that the proposed controllers can achieve the finite-time stability. Numerical simulations also demonstrate that the proposed control schemes are effective.

1. Introduction

The concept of spacecraft formation flying (SFF) has been a significant research topic due to the advantages of the lower cost, higher system reliability, and more flexibility than the traditional single spacecraft [1]. Many scholars have investigated various kinds of coordinated controllers for SFF such as leader–follower attitude control laws [2], decentralized attitude coordinated control laws [3,4], and distributed attitude coordinated control laws [5] in the past decades. Since the communication topologies change because of link failure, link reconfiguration, and time delays, the control performance of SFF may be deteriorated. For the sake of dealing with this problem, coordinated controllers with communication delays and switching topologies were developed in [6]. Because the assumed availability of the angular velocity measurement for the spacecraft is not always satisfied in practice, passivity filters were applied in the coordinated controller in [7]. Furthermore, to resolve physical limitations of the actuators, the attitude coordinated controllers with input saturation were investigated in [8,9]. In addition, a distributed attitude coordination control strategy was investigated for a group of flexible spacecraft in [10].

However, the controllers in [2–10] were asymptotically stable which leaded to that the closed-loop systems converged to the equilibrium point as time going to infinity. Finite-time control algorithms that can provide faster convergence rate, higher precision control performance, and better disturbance rejection properties have attracted the interest of researchers recently. The finite-time coordinated control problems were studied based on the terminal sliding mode (TSM) control in [11,12]. However, TSM control has three disadvantages that are the singularity, chattering, and slower convergence speed when the system state is far away from the equilibrium point. In order to improve the convergence speed, the fast TSM controllers for the attitude coordination control were designed in [13,14]. For the purpose of eliminating the singularity problem, the finite-time coordinated controllers were given by using the nonsingular TSM control in [15]. To deal with the drawbacks of singularity, chattering, and slower convergence, the finite-time

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coordinated controllers for spacecraft were addressed by the fast nonsingular TSM control in [16,17]. Besides, the finite-time coordinated controllers for spacecraft were given by using backstepping control [18], adding a power integrator term method [19], and homogeneous method [20].

In the current literatures, the attitude coordination control that can accommodate finite-time control without angular velocity measurement has not received much attention. Indeed, for the sake of reducing implementation cost and spacecraft weight, the question of how to design a finite-time output feedback coordinated controller becomes imperative, especially, when the angular velocity sensors are fault or with heavy noises. The finite-time coordinated controllers without velocity measurement were proposed for multi-agent systems by using the finite-time observers [21,22] and the filters [23,24]. The above controllers can realize finite-time convergence, but it is still a challenging problem to design a finite-time output feedback attitude coordinated controller without unwinding for SFF.

As quaternion and modified Rodrigues parameters (MRP) cannot represent the set of attitudes both globally and uniquely, the above controllers may result in unwinding [25]. Unwinding can result in extra fuel consumption by the spacecraft traveling a large distance before returning to the desired attitude equilibrium point. Because rotation matrix can represent the set of attitudes both globally and uniquely, it can deal with the problem [25–28]. A new attitude error function was proposed for rotation matrix in [26]. Based on the error function in [26], two finite-time controllers were investigated for the attitude control of the spacecraft by adaptive backstepping method in [27]. To synchronize the attitude of SFF, three novel autonomous control schemes without unwinding were given in [28]. However, the coordinated controllers in [28] were asymptotically stable.

Since none of the aforementioned approaches can provide finite-time output feedback attitude coordinated controller without unwinding, we investigate the finite-time coordinated controllers based on rotation matrix. Compared with the listed literatures, the contributions are summarized as follows: (i) Two finite-time coordinated controllers without unwinding are proposed for SFF by homogeneous method. (ii) To address the problem of lack of angular velocity measurements, the second finite-time coordinated controller is given by using a novel filter. (iii) Compared with [26,27], the advantage of the approaches is that we do not need to consider the region of attraction during the controller design.

This paper is organized as follows. An attitude dynamic model is established in the following section. In Section 3, a state error is given, then, two controllers are proposed. Furthermore, the corresponding stability proofs are given as well. Numerical simulations are presented in Section 4. The paper is closed with some concluding remarks.

2. Spacecraft attitude dynamics

Rotation matrix is employed to describe the attitudes of the spacecraft in the formation. Specifically, the attitude dynamics of the i^{th} spacecraft in the formation is given by (1) and (2).

$$\dot{\boldsymbol{R}}_i=\boldsymbol{R}_i\boldsymbol{\omega}_i^{\times} \tag{1}$$

$$\boldsymbol{J}_i\dot{\boldsymbol{\omega}}_i=-\boldsymbol{\omega}_i^{\times}\boldsymbol{J}\boldsymbol{\omega}_i+\boldsymbol{u}_i \tag{2}$$

$$\boldsymbol{\omega}_i^{\times}=\begin{bmatrix}0 & -\omega_{i,3} & \omega_{i,2}\\ \omega_{i,3} & 0 & -\omega_{i,1}\\ -\omega_{i,2} & \omega_{i,1} & 0\end{bmatrix} \tag{3}$$

$\boldsymbol{R}_i$ is the rotation matrix that transforms the i^{th} spacecraft body frame into the inertial frame resolved in the i^{th} spacecraft body frame. $\boldsymbol{\omega}_i\in\mathrm{R}^{3\times1}$is the angular velocity in the i^{th} spacecraft body frame. $\boldsymbol{u}_i\in\mathrm{R}^{3\times1}$is the control torque in the i^{th} spacecraft body frame. $\boldsymbol{J}_i\in\mathrm{R}^{3\times3}$ is the inertia matrix of the i^{th} spacecraft.

Because $\boldsymbol{R}_i$ is a matrix, it cannot be used to design the controller directly. A new attitude error is constructed in [26], which is defined as (4). The map $^{\vee}$ transforms a skew-symmetric matrix to a vector [26]. For example $(\boldsymbol{a}^{\times})^{\vee}=\boldsymbol{a}$ and $(\boldsymbol{A}^{\vee})^{\times}=\boldsymbol{A}$ where $\boldsymbol{a}\in\mathrm{R}^{3\times1}$ and $\boldsymbol{A}$ is a skew-symmetric matrix.

$$\boldsymbol{e}_i=\frac{1}{2\sqrt{1+\mathrm{tr}(\boldsymbol{R}_i)}}(\boldsymbol{R}_i-\boldsymbol{R}_i^{\mathrm{T}})^{\vee} \tag{4}$$

In combination with (1)–(4), the attitude dynamics of the spacecraft in the formation is given by (5) and (6).

$$\dot{\boldsymbol{e}}_i=\boldsymbol{E}_i\boldsymbol{\omega}_i \tag{5}$$

$$\boldsymbol{J}_i\dot{\boldsymbol{\omega}}_i=-\boldsymbol{\omega}_i^{\times}\boldsymbol{J}_i\boldsymbol{\omega}_i+\boldsymbol{u}_i \tag{6}$$

$$\boldsymbol{E}_i=\frac{1}{2\sqrt{1+\mathrm{tr}(\boldsymbol{R}_i)}}(\mathrm{tr}(\boldsymbol{R}_i)\boldsymbol{I}-\boldsymbol{R}_i^{\mathrm{T}}+2\boldsymbol{e}_i\boldsymbol{e}_i^{\mathrm{T}}) \tag{7}$$

By using (5) and (6), we can get (8).

$$\boldsymbol{M}_i\ddot{\boldsymbol{e}}_i+\boldsymbol{C}_i\dot{\boldsymbol{e}}_i=\boldsymbol{E}_i^{-\mathrm{T}}\boldsymbol{u}_i \tag{8}$$

$$\boldsymbol{M}_i=\boldsymbol{E}_i^{-\mathrm{T}}\boldsymbol{J}_i\boldsymbol{E}_i^{-1} \tag{9}$$

$$\boldsymbol{C}_i=-(\boldsymbol{E}_i^{-\mathrm{T}}\boldsymbol{J}_i\boldsymbol{E}_i^{-1}\dot{\boldsymbol{E}}_i\boldsymbol{E}_i^{-1}+\boldsymbol{E}_i^{-\mathrm{T}}(\boldsymbol{J}_i\boldsymbol{E}_i^{-1}\dot{\boldsymbol{e}}_i)^{\times}\boldsymbol{E}_i^{-1}) \tag{10}$$

We define

$$\begin{aligned}&\boldsymbol{e}=[\boldsymbol{e}_1,\cdots,\boldsymbol{e}_n]^{\mathrm{T}},\dot{\boldsymbol{e}}=\left[\dot{\boldsymbol{e}}_1,\cdots,\dot{\boldsymbol{e}}_n\right]^{\mathrm{T}},\\ &\boldsymbol{\omega}=[\boldsymbol{\omega}_1,\boldsymbol{\omega}_2,\cdots,\boldsymbol{\omega}_n]^{\mathrm{T}},\boldsymbol{E}=\mathrm{diag}(\boldsymbol{E}_i),\\ &\boldsymbol{R}=\mathrm{diag}(\boldsymbol{R}_i),\boldsymbol{J}=\mathrm{diag}(\boldsymbol{J}_i),\\ &\boldsymbol{u}=[\boldsymbol{u}_1,\boldsymbol{u}_2,\cdots,\boldsymbol{u}_n]^{\mathrm{T}},\boldsymbol{M}=[\boldsymbol{M}_1,\boldsymbol{M}_2,\cdots,\boldsymbol{M}_n]^{\mathrm{T}},\\ &\boldsymbol{C}=[\boldsymbol{C}_1,\boldsymbol{C}_2,\cdots,\boldsymbol{C}_n]^{\mathrm{T}}.\end{aligned} \tag{11}$$

In combination with (8) and (11), the model can be rewritten as (12).

$$\mathrm{M}\ddot{e}+C\dot{e}=E^{-T}u \tag{12}$$

Since (12) has Euler–Lagrange form, it has the nature as follows.

Property 1. The matrix $\boldsymbol{M}$ is symmetric positive definite.

Property 2. The matrix $\dot{\boldsymbol{M}}-2\boldsymbol{C}$ is skew-symmetric. It means that $\xi^{\mathrm{T}}(\dot{\boldsymbol{M}}-2\boldsymbol{C})\xi=0,\xi\in\mathrm{R}^{3n\times1}$.