ADVANCED CONTROL OF FLIGHT VEHICLE MANEUVER AND OPERATION

Editors:
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CONTENTS

PREFACE

To meet the requirements of future space missions, the high-precision and high-stability control problem of flight vehicles has become increasingly important. However, many uncertain factors, such as environmental and non-environmental disturbances, parameter uncertainty, and other nonlinear perturbations, widely influence the performance of flight vehicle maneuvers and operations. The present generation of flight vehicles should be capable of high-precision pointing and better robustness to external disturbances and various uncertainties. It should be noted that a distributed flight vehicle system may include multiple flight vehicles distributed in one or more orbits according to certain requirements and cooperating to perform space missions, *e.g.*, observation, communication, reconnaissance, and navigation. It should be mentioned that formation flying and satellite clusters both belong to distributed satellite systems. Consequently, multiple complex disturbances will have a considerable influence on the stability of the flight vehicle leading to degradation in the dynamics and control performance of the system and even instability, which pose a huge challenge for control system designers, and advanced control approaches are required to improve robust performance and control accuracy in maneuver and operation to solve these problems.

In order to understand the behavior of flight vehicle maneuvers and operation properly, it is significant to investigate the advanced controller designs. To this end, Chapter 1 discusses air-breathing hypersonic vehicle, Chapter 2 discusses fast and parallel algorithms for orbit and attitude computation, Chapters 3 and 4 discuss rigid spacecraft, Chapter 5 discusses flexible spacecraft, Chapter 6 discusses vibration control using nonlinear energy sink, Chapter 7 discusses partial space elevators, and Chapters 8 and 9 discuss spacecraft formation flying and satellite cluster, respectively. In particular, Chapter 1 investigates anti-disturbance continuous fixed-time controller design for an air-breathing hypersonic vehicle, where a fast fixed-time integral sliding surface, a continuous fixed-time super-twisting-like reaching law and a uniformly convergent observer are combined. As control efficiency is very important in practice, to efficiently solve nonlinear differential equations in aerospace engineering, fast and parallel algorithms can be a good choice, and this results in the writing of Chapter 2, where a simple adaptive local variational iteration method is developed. Chapter 3 provides detailed derivations of adaptive event-triggered sliding mode controller used for attitude tracking, where the communication burden is decreased significantly. Chapter 4 investigates an adaptive finite-time controller for satellite attitude maneuver, where the singularity problem is dealt with based on the properties of Euler rotations. Chapter 5 develops an output feedback controller for attitude stabilization and vibration suppression of flexible spacecraft using negative imaginary and H_∞ theories. To further investigate the vibration control and energy harvesting properties in aerospace engineering, a nonlinear energy sink approach is developed to deal with the influence of rich and complex dynamic environments in Chapter 6. Chapter 7 describes the mathematical model of partial space elevators, and a configure-keeping technology for stable cargo transportation is investigated. Furthermore, Chapters 8 and 9 discuss the distributed flight vehicle system, where adaptive fixed-time 6-DOF coordinated control for spacecraft formation flying and prescribed time control for satellite cluster reconstruction are investigated, respectively.

This book will be helpful to scientists and engineers who are interested in working on the development of flight vehicle maneuvers and operations. Researchers studying control science and engineering and advanced undergraduate and graduate students and professionals involved in the flight vehicle control field will also benefit from the information given in this book. This book covers a wide range of topics in flight vehicle maneuver and operation, *e.g.*, hypersonic vehicle, orbit and attitude computation, single spacecraft, flexible vibration, space elevators, spacecraft formation flying, satellite cluster, *et al.*

The book has a broad scope and helps students and researchers in universities, industries, and national and commercial laboratories to learn the fundamentals and in-depth knowledge regarding thermal modeling and developments in solar thermal systems in the past few years. It is a research-oriented book in which different researchers have contributed in the form of different chapters. I hope that the book will provide sufficient knowledge regarding solar systems and will not discourage the readers. This book can be used as a reference tool for teaching the solar energy and thermal modeling of solar thermal systems to the students and research fellows in universities and research organizations

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CHAPTER 1

Anti-Disturbance Continuous Fixed-Time Controller Design for Air-breathing Hypersonic Vehicle

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Abstract: Anti-disturbance, continuous fixed-time controller is designed for faulted air-breathing hypersonic vehicle, including a fast fixed-time integral sliding surface (FFIS), a continuous fixed-time super-twisting-like reaching law (CFSTL) and a uniformly convergent observer. Firstly, the model of a hypersonic vehicle is established. Secondly, an FFIS is designed based on a newly presented fast fixed-time high-order regulator (FFTR). Then, a CFSTL is applied to drive the sliding mode vector and its derivative to achieve fixed-time convergence. Finally, lumped disturbances are estimated by a uniformly convergent observer.

Keywords: Air-breathing hypersonic vehicle, Disturbance observer, Fixed-time control, Sliding mode control.

INTRODUCTION

The air-breathing hypersonic vehicle has recently received great attention [1, 2]. It is necessary to investigate the control algorithm with highly fault-tolerant ability for flexible air-breathing hypersonic vehicle (FAHV). There have been various control algorithms developed for fault tolerant control of hypersonic flight vehicles such as back-stepping control [3, 4], neural networks control, fuzzy control [5], sliding mode control [6, 7] *etc*. Considering the advantages of finite-time convergence laws, such as faster convergence speed and higher precision, sliding mode control is strongly recommended on account of its characteristics of finite-

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time convergence and robustness. Considering FAHV is statically unstable, system states should be rapidly stabilized before they escape to infinity under abrupt actuator faults. Therefore, in this paper, an anti-disturbance continuous fixed-time control algorithm (ACFTC) is proposed to achieve high-precision fast control for FAHV under actuator faults with three components: novel fast fixed-time integral sliding surface (FFIS), continuous fixed-time super-twisting-like reaching law (CFSTL) and uniformly convergent observer.Many sliding surfaces have been proposed such as , linear sliding surfaces, terminal sliding surfaces, integral sliding surfaces *etc*. The linear sliding surface could only drive states to converge exponentially. The terminal sliding surface is able to realize finite-time convergence of states, but the singularity phenomenon is inevitable, which restricts its application. In view of it, a non-singular sliding surface is proposed by Feng [8], but its superiority is lost when applied to a system with an order higher than two. An integral sliding surface is a kind of sliding surface that can avoid singularity by means of using a finite-time regulator [9, 10]. In [11], Basin proposes a fixed-time high-order regulator to improve the conventional finite-time regulator, which can achieve fixed-time convergence. In this paper, we present a fast fixed-time high-order regulator (FFTR) based on the method in [11]. FFTR can accelerate the system's response speed by simply adjusting the values of two gains. Then, FFIS is established to make tracking errors of FAHV to achieve fixed-time convergence based on FFTR.

Traditional reaching laws mainly include: constant rate reaching law, exponential reaching law, power rate reaching law and so on. The super twisting algorithm can be used as a reaching law to realize finite-time convergence. Basin in [12] designs a continuous fixed-time super-twisting-like reaching law (CFSTL). It is more simplified in form than the conventional method in [13]. By combing FFIS, CFSTL and uniformly convergent observer, an ACFTC is designed to enhance the fault-tolerant ability, in which uniformly convergent observer can estimate lumped disturbances accurately in fixed time.

The paper's organization is as follows: Section 2 provides the model of FAHV. In Section 3, the input/output feedback linearization technique is designed. Section 4 presents ACFTC. In Section 5, simulations are shown to verify the effectiveness of ACFTC.

FLEXIBLE HYPERSONIC VEHICLE MODEL

The longitudinal dynamics of FAHV are given below

$$\begin{aligned}
&\dot{V} = \left(T\cos\alpha - D\right)/m - g\sin\gamma \\
&\dot{h} = V\sin\gamma \\
&\dot{\gamma} = \left(L + T\sin\alpha\right)/\left(mV\right) - g/V\cos\gamma \\
&\dot{\alpha} = Q - \dot{\gamma} \\
&\dot{Q} = \left(M + \tilde{\psi}_1\ddot{\eta}_1 + \tilde{\psi}_2\ddot{\eta}_2\right)/I_{yy} \\
&k_1\ddot{\eta}_1 = -2\zeta_1\omega_1\dot{\eta}_1 - \omega_1^2\eta_1 + N_1 - \tilde{\psi}_1 M/I_{yy} - \tilde{\psi}_1\tilde{\psi}_2\ddot{\eta}_2/I_{yy} \\
&k_2\ddot{\eta}_2 = -2\zeta_2\omega_2\dot{\eta}_2 - \omega_2^2\eta_2 + N_2 - \tilde{\psi}_2 M/I_{yy} - \tilde{\psi}_2\tilde{\psi}_1\ddot{\eta}_1/I_{yy}
\end{aligned} \tag{1}$$

where $V, h, \gamma, \alpha, Q, \eta_1, \eta_2$ are vehicle velocity, altitude, flight path angle, angle of attack, pitch rate, and generalized modal coordinates respectively. m, g, I_{yy} are mass, gravitational acceleration and moment of inertia. $\zeta_i, \omega_i, \tilde{\psi}_i$ are damping ratio, natural frequency and inertial coupling parameter. k_i satisfy with $k_i = 1 + \tilde{\psi}_i^2/I_{yy}$. T, D, L, M, N_i are thrust, drag, lift, pitching moment and generalized forces which are expressed using curve-fitted approximations as follows

$$\begin{aligned}
&T = C_T^{\alpha^3}\alpha^3 + C_T^{\alpha^2}\alpha^2 + C_T^{\alpha}\alpha + C_T^0 \\
&D = \bar{q}S\left(C_D^{\alpha^2}\alpha^2 + C_D^{\alpha}\alpha + C_D^{\delta_e^2}\delta_e^2 + C_D^{\delta_e}\delta_e + C_D^0\right) \\
&L = \bar{q}S\left(C_L^{\alpha}\alpha + C_L^{\delta_e}\delta_e + C_L^0\right) \\
&M = z_T T + \bar{q}S\bar{c}\left(C_{M,\alpha}^{\alpha^2}\alpha^2 + C_{M,\alpha}^{\alpha}\alpha + C_{M,\alpha}^0 + c_e\delta_e\right) \\
&N_1 = N_1^{\alpha^2}\alpha^2 + N_1^{\alpha}\alpha + N_1^0 \\
&N_2 = N_2^{\alpha^2}\alpha^2 + N_2^{\alpha}\alpha + N_2^{\delta_e}\delta_e + N_2^0 \\
&\bar{q} = \rho V^2/2 \quad \rho = \rho_0\exp\left[-\left(h - h_0\right)/h_s\right] \\
&C_T^{\alpha^3} = \beta_1\left(h,\bar{q}\right)\Phi + \beta_2\left(h,\bar{q}\right) \quad C_T^{\alpha^2} = \beta_3\left(h,\bar{q}\right)\Phi + \beta_4\left(h,\bar{q}\right) \\
&C_T^{\alpha} = \beta_5\left(h,\bar{q}\right)\Phi + \beta_6\left(h,\bar{q}\right) \quad C_T^0 = \beta_7\left(h,\bar{q}\right)\Phi + \beta_8\left(h,\bar{q}\right)
\end{aligned} \tag{2}$$

where δ_e, Φ are elevator angular deflection and fuel-to-air ratio. In order to compensate for non-minimum phase behavior, the canard δ_c is responded to ensure $C_L^{\delta_e}\delta_e + C_L^{\delta_c}\delta_c = 0$. Therefore, the lift L is expressed as

$$L = \bar{q}S\left(C_L^{\alpha}\alpha + C_L^0\right) \tag{3}$$

CHAPTER 2

Fast and Parallel Algorithms for Orbit and Attitude Computation

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Abstract: This chapter provides a simple Adaptive Local Variational Iteration Method (ALVIM) that can efficiently solve nonlinear differential equations and orbital problems of spacecrafts. Based on a general first-order form of nonlinear differential equations, the iteration formula is analytically derived and then discretized using Chebyshev polynomials as basis functions in the time domain. It leads to an iterative numerical algorithm that only involves the addition and multiplication of sparse matrices. Moreover, the Jacobian matrix is free from inversing. Apart from that, a straightforward adaptive scheme is proposed to refine the configuration of the algorithm, involving the length of time steps and the number of collocation nodes in a time step. With the adaptive scheme, the prescribed accuracy can be guaranteed without manually tuning the configuration of the algorithm. Since the refinement is adjusted automatically, our algorithm reduces over-calculation for smooth and slowly changing problems. Examples such as large amplitude pendulum and perturbed two-body problem are used to verify this easy-to-use adaptive method's high accuracy and efficiency.

Keywords: Orbital propagation, orbit-attitude coupling, Local Variational Iteration Method.

INTRODUCTION

In orbital mechanics, the accuracy and efficiency of numerical methods are mostly concerned. Highly accurate results require a very small step size for classical integration methods such as finite-difference methods. In this aspect, the collocation method shows superiority because the solution of collocation can be semi-analytical and the approximation can be made in large intervals. No need to say that the collocation method only results in a few coefficients that are related to

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basic functions, while the classical integration methods need to save a large amount of discrete data [1]. The governing system and the related boundary conditions can be reduced as algebraic equations of the states at collocation nodes for either the initial value problem or the two-point boundary value problem. Applications of the collocation method have been very successful in orbital problems of spacecraft. However, there is a need to construct nonlinear algebraic equations, which are usually solved by Newton-like algorithm that involves the inversion of Jacobian matrices. This process is made much simpler by introducing the Picard iteration with orthogonal basis functions to approximate the solution. In the Picard-based algorithms, there is no need to invert a Jacobian matrix. Such a method was named the modified Chebyshev-Picard iteration (MCPI) method in literature [2-5].

In this chapter, we show that the Local Variational Iteration Method (LVIM) method can be a highly efficient and accurate alternative to traditional numerical methods. Numerical examples such as the orbit propagation problem and Lambert's problem are used to verify the convergence, accuracy and efficiency of LVIM.

In addition, for solving two-point boundary value problems (TPBVPs), a novel quasi-linearization method is introduced to transform TPBVPs into initial value problems (IVPs). Particularly, in conservative problems, a so-called Fish-Scales-Growing Method (FSGM) is further proposed. Compared with the multiple shooting method and the modified simple shooting method, the proposed Fish-Scales-Growing Method is based on the principle of least action for a Hamiltonian system, instead of using Newton's iterative algorithm or a an asymptotic homotopy strategy. In a conservative system, the solution of a two-point boundary value problem is determined by the principle of least action. A piecewise solution obtained by solving multiple two-point boundary value problems is used as an approximation of the true solution, using the Fish-Scales-Growing Method. Then by changing the boundary conditions of the multiple two-point boundary value problems, the piecewise solution will iteratively evolve in a pattern that looks like the growing of fish scales. In this pattern, the action along the piecewise trajectory is guaranteed to decrease. Theoretically, the piecewise solution will eventually approach the true solution in a conservative system. In the Fish-Scales-Growing Method, the two-point boundary value problem to be solved is converted into multiple two-point boundary value problems that can be solved much more easily. Since the principle of least action theoretically guarantees the convergence of the piecewise solutions obtained by Fish-Scales-Growing Method, the initial guess can be selected rather arbitrarily, although different initial guesses may affect the convergence speed. Moreover, in each iteration step of the Fish-Scales-Growing Method, the multiple two-point boundary value problems are independent to each other. Thus, it can be conveniently coded for parallel computation to enhance computational efficiency. At last, for each solution of the multiple two-point boundary value problems, only one time instant and its corresponding positions and velocities need to be recorded for the next iteration, so the Fish-Scales-Growing method is very efficient and memory-saving.

In addition, this chapter also discusses the relative motion modeling of spacecraft. The relative motion of spacecraft in space is a six degree of freedom system, including relative attitude and orbit motions. When describing the motion of a spacecraft in space, generally speaking, the rotation relative to the center of mass and translation of the center of mass can be used to describe the whole motion of a spacecraft in three-dimensional space. The relative motion of two spacecraft can be described by relative attitude and centroid position, or by the relative position of any two points on the spacecraft to establish the corresponding motion model according to the corresponding description method. In order to accurately predict and control the motion of a spacecraft in space, an accurate and practical model is essential. A good motion model can be more convenient for the study and reveal the essence of the problem.

At present, considerable progress has been made in establishing the motion model of spacecraft. In traditional methods, attitude and orbit are modeled separately. Attitude can be described by Euler angle, directional cosine matrix and quaternion; the orbit can be described by a rectangular coordinate system and orbital elements. The traditional method is simple, but it is often difficult to accurately describe the actual motion of spacecraft, and it is not convenient for the controller design. Therefore, we need a more accurate model. In terms of attitude orbit coupling modeling, there are two main methods. One is to model the attitude and orbit separately, and then introduce the coupling term to modify the attitude orbit model to achieve the description and control of attitude orbit coupling; The other is the integrated modeling of attitude and orbit, and the attitude and orbit are described by the same tool. This method can not only reflect the actual motion of spacecraft, but also facilitate the design of the controller. This chapter mainly discusses the attitude orbit integration modeling method. Therefore, we introduce two mathematical tools: dual quaternion and spinor. Using the advantages of these two tools, we describe all the state variables of spacecraft in space, and deduce the motion model and dynamic model

.

CHAPTER 3

Adaptive Event-triggered Sliding Mode Control for Spacecraft Attitude Tracking

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Abstract: The spacecraft attitude tracking control problem with limited communication is addressed by employing event-triggered based sliding mode control theory. The attitude dynamics are directly developed on the Special Orthogonal Group SO(3), and singularities and ambiguities associated with other attitude representations are avoided successfully, taking model uncertainties and external disturbances into consideration. Based on the developed model, an adaptive event-triggered sliding mode controller is designed to ensure the closed-loop system that is uniformly ultimately bounded, by using fuzzy logic theory to deal with the disturbance. Due to the application of the event-triggered theory, the control signal is only updated and transmitted at some discrete instants. Therefore, the communication burden is decreased significantly. Finally, numerical simulations are conducted to demonstrate the effectiveness of the proposed control method.

Keywords: Communication burden, Event-triggered, SO(3), Fuzzy logic theory, Spacecraft attitude tracking control.

INTRODUCTION

Spacecraft attitude tracking is a key technology to accomplish a wide range of orbital missions such as pointing and slewing of spacecraft, Earth observation, and spacecraft rendezvous [1-4]. Therefore, the spacecraft attitude tracking control problems have been studied extensively in the past decades by utilizing nonlinear control techniques such as sliding mode control [1-3], proportional-derivative (PD) control [4], $H\infty$ control [5], optimal control [6, 7], and back-stepping control [8], *etc*., where local coordinate representations, the modified Rodriguez parameters (MRPs) or quaternions were utilized to develop the spacecraft attitude model. However, as stated in [9, 10], Euler angles and MRPs suffer from kinematic singularities, and an unwinding problem exists in quaternions. Fortunately, pioneering studies on spacecraft attitude control have been done in [11-13] *via*

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rotation matrix, which can represent a rigid body's attitude globally and uniquely on the Special Orthogonal Group SO(3). Consequently, the problems mentioned above associated with other attitude representations can be avoided. However, SO(3) is a nonlinear non-Euclidean manifold, and the classical control schemes designed on Euclidean space cannot be applied to this model directly. A common way to deal with this problem is to construct a smooth positive-definite function to measure the attitude error and then design an attitude tracking controller with the error function. For example, the attitude control problems were solved in [9, 14, 15]. However, the spacecraft attitude tracking control problem solved in [15] did not take model uncertainties into consideration.

In spacecraft attitude control, the most commonly used method is proportion-integral-derivative (PID) control. But the properties of slow response and poor control performance to model uncertainties and external disturbances make PID control unsuitable for the problem investigated in this paper [16]. An alternative way is to use sliding mode control (SMC), which has been widely applied to guarantee the system robustness against these drawbacks, where model uncertainties and disturbances are regarded as the system total disturbance with an upper bound, and then controllers are designed such as [2, 17, 18]. However, the disturbance upper bound is not easy to obtain in practice. Moreover, the sign function was used in [18] to reject disturbance, which leads to the chattering phenomenon. Chattering is a serious problem for the practical use of sliding mode control. It not only leads to self-oscillations in the system but also increases the consumption of energy [19]. Though the sign function can be replaced by a tanh function, this technique implies deterioration in accuracy and robustness. An effective way to tackle this problem is using the estimation of the system disturbance and applying adaptive control theory to design a continuous robust adaptive controller, where the control gains can be altered and are as small as possible to mitigate chattering effects, but large enough to ensure that sliding can be maintained in the presence of disturbance, and also leads to a reduction of the system energy cost [19-22]. An alternative estimation method is to use a fuzzy logic system (FLS) to approximate the disturbance with high accuracy and then design SMC based on the estimated information. As a result, the limitation on the disturbance upper bound can be released. Moreover, among various fuzzy control methods, researchers have paid more attention to Takagi-Sugeno (T-S) method for its capability of approximating an unknown smooth nonlinear function over a compact set with an arbitrary accuracy [23], and lots of results have been obtained based on this way [24-29]. In addition, the combination of the fuzzy controller with SMC can guarantee assured tracking accuracy even in the presence of high model uncertainties [30]. For instance, an event-triggered adaptive sliding mode controller was designed in [24] to address the control problem of a class of T-S fuzzy systems with actuator failures. Better results were obtained compared with the existing results. For spacecraft attitude tracking control problems in [31-33], FLSs were applied successfully to approximate the disturbance, and then sliding mode controllers were designed, where a better result was obtained compared with the traditional SMC method.

Furthermore, the concepts of spacecraft architectures, such as cellularized spacecraft [32], plug-and-play spacecraft [2], and fractionated spacecraft [34], are becoming more attractive recently with the potential to progress the Technology Readiness Level, in which the functional components of a spacecraft are connected by wireless networks, and data transmission between different modules is achieved through wireless communication. Therefore, for these kinds of spacecraft, it is essential to design an attitude controller with less communication burden, while the control accuracy required for the tracking system should be guaranteed at the same time. An extraordinary choice is an event-triggered control, where signals are transmitted only when a predesigned event-triggering condition is met. Compared with traditional periodic or time-triggered control, where signals are transmitted periodically, and may occupy the onboard communication channel unnecessarily, the transmission time and control performance of event-triggered control can be adjusted by designing the triggering strategy properly. Recently, great progress has been made on event-triggered control for many kinds of nonlinear systems, such as multiagent systems in [35-38], T-S fuzzy systems in [24, 39], and nonlinear dynamic systems in [40, 41]. And the state-of-the-art event-triggered control has been extended to spacecraft attitude control [2, 32, 34]. However, model uncertainties were not considered in these studies and the dynamics were developed based on quaternions. Moreover, the input-to-state stability (ISS) assumption is required for the attitude control system, which is hard to satisfy in practice [41]. Though the ISS assumption on a simple nonlinear system has been released successfully in [41] by designing the triggering strategy based on the control signal measurement error, extending the result to spacecraft attitude control on SO(3) directly is difficult since the nonlinearity of the spacecraft dynamics on SO(3) is high. Therefore, based on the above discussions, the main purposes of this paper are to develop the attitude dynamics on SO(3) in a unique and singular-free way in the presence of model uncertainties and external disturbances and to extend the state-of-the-art in fuzzy controller design with SMC in [31–33] and event-triggered control without ISS assumption in [41] to solve spacecraft attitude tracking control problem, such that the results obtained in this paper will be suitable for the on-orbit application.

CHAPTER 4

Robust Finite-time Adaptive Control Algorithm for Satellite Attitude Maneuver

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Abstract: A robust adaptive finite-time controller for satellite fast attitude maneuver is proposed in this paper. The standard sliding mode is robust to some typical disturbances, but the convergence speed is slow and often could not meet the system requirements. The finite-time sliding mode not only has the robustness of the classical sliding mode, but also could greatly improve the terminal convergence speed. In order to deal with inertia matrix uncertainty, a finite-time adaptive law for inertia matrix estimation variables is proposed. A new method to deal with the singularity problem is proposed,based on the properties of Euler rotations. Considering that the variable estimation system has no direct feedback, an auxiliary state that converges slower than the system is designed to achieve finite-time stability. The Lyapunov method is used to demonstrate the global finite-time stability of the ensemble, and the numerical simulation results demonstrate the performance of the controller.

Keywords: Adaptive control, Fast attitude maneuver, Finite-time control, Robust control

INTRODUCTION

As a mature control method, sliding mode control has been widely used in satellite attitude control issues. The standard sliding mode has a clearl physical meaning that angular velocity is reversed to attitude quaternion, and this property could suppress some typical perturbations caused by disturbance, model uncertainty, actuator error and so on; hence standard sliding mode has its inherent robustness. However, the convergence rate of the system near the equilibrium point is relatively low, and the system control capability is not fully utilized. Therefore, it is necessary

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to improve the convergence speed when dealing with fast attitude maneuvering problems for the classical sliding mode.

In order to improve the convergence speed of the system, many people have done a lot of research on this. Refs. [1-4] pointed out that the key to improving the convergence speed of the system is to design the angular velocity trajectory reasonably, so they designed a constant angular velocity maneuvering stage, which could maintain the convergence speed. However, most of the work does not solve the exponential convergence problem, and the terminal convergence speed needs to be improved [5,6], Ref. [7] designed the angular velocity "braking curve" of satellite attitude maneuver, optimized the angular velocity trajectory, and designed the deceleration process trajectory. However, the problem of exponential convergence speed still exists.

The finite-time control method is also an effective method to improve the convergence rate of the system, so this method is suitable for the fast maneuvering of satellites. The improvement of the convergence speed near the equilibrium point and the improvement of the torque control efficiency make the system performance near the equilibrium point the main focus of this method, so many researchers have done a lot of research on time-finite controllers for satellite attitude control. Ye, Refs. [8,9] focused on the control torque distribution algorithm and fault-tolerant algorithm, and designed a finite-time controller for satellite control. Refs. [10,11] proposed finite-time stabilization methods such as the Lyapunov and terminal sliding mode methods based on the finite-time controller structure and terminal sliding-mode standard structure of classical nonlinear systems. Refs. [12-14] designed a finite-time controller for satellite formation attitude control and analyzed the finite-time stability using the Lyapunov method. Existing approaches to deal with finite-time stability could be generalized as designing fractional state feedback and singularities near equilibrium points. Furthermore, existing finite-time control methods often require some special modifications to deal with unknown disturbance torque and model uncertainty.

Since the precise inertia matrix and some other unknown disturbances could not be known in the satellite attitude control problem, many researchers will design a controller with a symbolic function to suppress the disturbance for the problem uncertainty mentioned above. Refs. [15-17] designed a fault-tolerant controller to estimate the uncertainty of the system. Although this method is suitable for several typical uncertainty models, it is not suitable for random noise models, so there are still some shortcomings. Refs. [18-20] designed some robust controllers for system uncertainty and added symbolic function items to the controller, but the symbolic function items would bring high-frequency vibration and cause damage to actuators and physical systems. To deal with uncertainty without causing high-frequency vibrations, some researchers have delved into adaptive control. Ref. [21] designed an output feedback attitude stabilization controller for the control problem of rigid body satellites. Ref. [22] proposed a disturbance observer-based attitude controller for spacecraft based on a time-varying inertial matrix model. Ref. [23] designed a sliding mode controller for coupled orbit-attitude tracking of spacecraft electromagnetic docking. Ref. [24] and Ref. [25] designed an adaptive law for the quadrotor UAV control problem, taking into account the problems of fuzzy sensor data and model uncertainty. Ref. [26] designed a space exploration law that accommodates the uncertainty of the gravity gradient model. Ref. [27] designed a synchronous input and state estimation algorithm for integrated motor drive systems in a controller area network environment via an adaptive unscented Kalman filter. Ref. [28] designed a warp-based finite-time consensus for Euler-Lagrangian systems with an event-triggered strategy. Researchers have done other work focusing on adaptive and finite-time controllers [29-35], and the main idea of designing an adaptive law is to use system state feedback. Since the error state of the model is difficult to get feedback directly, this paper proposes another method to design the adaptive law and design the auxiliary state to achieve the purpose of finite time stabilization. This paper proposes a finite-time controller based on a standard sliding mode for the satellite control problem. This method could greatly improve the convergence speed and achieve the purpose of finite-time convergence under the premise of maintaining the advantages of standard sliding mode. Then, the adaptive law of inertia matrix uncertainty is given, and an auxiliary state that converges slower than the system state is designed to overcome the difficulty of estimating the system without direct feedback. The Lyapunov method is used to analyze the overall finite-time stability under the adaptive law, and the controller performance is discussed. The paper is organized as follows: Section 1 introduces the paper, and Section 2 describes the mathematical model used in this paper. Section 3 presents an adaptive finite-time controller for the satellite attitude stabilization problem, and Section 4 discusses the satellite attitude tracking problem. The numerical simulation results will be presented in Section 5, and Section 6 will conclude this paper.

DYNAMIC AND KINETIC MODEL

The dynamic model of the rigid satellite could be modeled as follows [1-4]

$$\boldsymbol{J}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega}^{\times}\boldsymbol{J}\boldsymbol{\omega} = \boldsymbol{u} + \boldsymbol{d} \tag{1}$$

CHAPTER 5

Attitude Stabilization of Flexible Spacecraft Using Output Feedback Controller

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Abstract: Spacecraft in space may have some certain non-cooperative characteristics due to the service life limit, fuel exhaustion, component fault, structural fatigue damage, or after performing certain space tasks such as capturing non-cooperative targets. In modeling, these non-cooperative characteristics are often manifested in uncertain and unknown inertia, model parameters uncertainty, actuator faults, etc. In this paper, aiming at the attitude stability control problem of such flexible spacecraft, the attitude dynamics modeling is completed by introducing the nominal inertia to construct the comprehensive disturbance term including external disturbance, inertia uncertainty and actuator failure. Then, a static output feedback (SOF) controller is applied to model the closed-loop attitude control system a stable negative imaginary (NI) system with H_∞ performance constraints according to NI theory. As long as the optimization variables approach zero, the LMI-based iterative algorithm can find such the static output feedback controller to stabilize the flexible spacecraft. It is worth mentioning that an event-trigger mechanism is introduced into the control scheme to reduce communication pressure. Finally, the numerical simulation is carried out in the presence of controller gain perturbations and model parameter uncertainty. The results of the simulation demonstrate the effectiveness, robustness and non-fragility of the control method.

Keywords: Flexible Spacecraft, H_∞ performance, Inertia-free attitude stabilization, Lumped disturbance , Negative imaginary, Static output feedback.

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INTRODUCTION

With the rapid development of human space activities, there are a large number of failure spacecrafts because of the service life limit, fuel exhaustion, component fault, structural fatigue damage and accidental disintegration in the space environment. Malfunctioning spacecraft and space debris cannot provide state information as well as their inertia parameter information actively, which makes them typical non-cooperative targets, and their high-precision on-orbit operation is seriously affected by attitude-orbit coupling [1]. For this kind of spacecraft, the determination of high-precision inertial parameters is costly, moreover, flexible spacecraft usually need to complete pointing accurately, attitude maneuvers rapidly, and stabilization in the case of existing external interference, actuator failure, measurement errors, and input limits which all makes the attitude stabilization more difficult [2]. Therefore, effective, robust methods of control are needed to deal with these problems at the same time.

In recent years, research on attitude control of flexible spacecraft have made a lot of phased progress. For example, as stated in references [3], a fault-tolerant adaptive control scheme developed for attitude tracking of flexible spacecraft with unknown inertia parameters, external disturbance, and actuator faults shows good robustness. The method considering external disturbances and parameter perturbations as uncertainties in Liu's work provides a new idea for dealing with parameter uncertainty [4]. Then, reference [5] proposed a novel finite time control method for spacecraft attitude control and dealt with inertia uncertainty and input constraints. Recently, reference [6] proposed a new fault-tolerant attitude tracking control with specified performance, in which the inertia uncertainty and input constraints were considered. Besides, in order to have better robustness to uncertain dynamics and external disturbances, some other robust sliding mode controllers for satellite attitude stabilization or synchronization are proposed [7, 8].

In addition to the above unfavorable factors, the elastic vibration of spacecraft's flexible appendages may significantly reduce the control performance and even lead to instability of the closed-loop attitude control system, which makes the problem of elastic vibration suppression becomes a research hotspot [9]. Negative imaginary (NI) systems theory is widely used in robust vibration control of flexible structures, such as the control of large space structures and flexible dynamics of aircraft [10]. Especially for the systems with flexible and lightly damped structures using the piezoelectric actuators and sensors for flexible structural control, the system can be modeled as a NI system by choosing system input and output appropriately [11]. However, there is little application example of negative virtual theory in flexible spacecraft in the relevant literature.

Last but not least, it is worth noting that the attitude stability of spacecraft could be handled properly when the full attitude state can be measured. However, in practical applications, due to sensor failure and cost reduction of airborne sensors, state measurement may not be used in controller design [12].

Based on the above discussion, a new static output feedback H_∞ control scheme is proposed in this paper. This scheme does not need the prior knowledge of inertia information, external disturbance and actuator fault to enable the closed loop attitude control system stable negative imaginary and satisfy H_∞ performance constraints simultaneously. Compared to the previous studies, the important contributions in this paper are stated as follows. First of all, introduce the nominal representation of the valid inertia matrix, and the difference between this inertia matrix and the real inertia matrix is treated as one of the sources of the lumped disturbance, so that the controller design will be inertia-free. Secondly, we propose a novel method to decouple controller gain matrix $\boldsymbol{K}$ and Lyapunov matrix by introducing the slack matrix variables, and establishing sufficient conditions for designing a SOF controller. Thirdly, an iterative algorithm is proposed to calculate the SOF controller. Fourth, an event-trigger mechanism is introduced for control input and reduces the communication pressure to some extent.

This article is organized as follows. In the second section, the dynamics model of flexible spacecraft is given, and then it is transformed into state space form, in which actuator failures and input constraints are considered, and the control objectives of this article are formulated. The third section introduces the design method of SOF H_∞ NI controller and stability analysis for the closed-loop control system. In the fourth section, the numerical simulation shows the superior performance of event-triggered controller under the condition of existing controller gain's perturbations and parameter uncertainty. Finally, the fifth section gives the conclusion of this paper.

DYNAMICS MODELING

In this section, the attitude kinematics model and dynamic model of flexible spacecraft will be given.

CHAPTER 6

Vibration Control and Energy Harvesting in Aerospace Engineering Using Nonlinear Energy Sinks

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Abstract: The fact that spacecraft faces a rich and complex dynamic environment makes the development of vibration control and energy harvesting techniques a special concern in space engineering. Nonlinear Energy Sink is such a technique that has developed recently. It generally refers to a lightweight nonlinear device, that is attached to a primary system with essential nonlinear couplings. A special one-way energy transfer called targeted energy transfer (TET) could be observed for passive energy localization into itself. By taking advantage of such essential nonlinearities and the TET phenomenon, NES could be designed as smart and lightweight vibration absorbers or energy harvesters, in a broadband manner, which is especially suitable for the need in aerospace engineering. This chapter is thus devoted to the nonlinear dynamics of vibrational systems with coupled NESs and their applications in the field of passive vibration suppression and vibration energy harvesting.

Keywords: Energy harvesting, Nonlinear energy sink, Targeted energy transfer, Vibration control

INTRODUCTION

Spacecraft faces a complex dynamic environment during the process of launch and on-orbit operation, leading to the vibration of its whole and various components. Such vibrations include the acceleration dynamic load of the engine during launch, aerodynamic noise of high-speed flight, transient vibration during engine ignition shutdown and separation, structural and mechanical vibration during orbit and

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attitude maneuver, impact load during solar sail deployment and locking, friction and thermally induced vibration during reentry and return. On the one hand, the complex dynamic environments greatly threaten the normal use of the whole spacecraft and its components, implying the significance of controlling unwanted vibrations in aerospace engineering. On the other hand, those vibrations also provide a rich external energy source, leading to the development of the vibrational energy harvesting technique, which represents another critical direction for developing smart spacecraft systems in future space missions. The Nonlinear Energy Sink (NES) [1], is one of the recently developed smart technologies that are lightweight and broadband, and have a very broad prospect in both the aforementioned fields of vibration control and energy harvesting.

As depicted in Fig.(**1**), an NES generally refers to a lightweight nonlinear device that is attached to a primary system with essential nonlinear couplings (usually a cubic nonlinear stiffness and linear damping) for passive energy localization into itself. Thanks to the essential nonlinearities, a system coupled with an NES can generate rich dynamical regimes that are not possible in the ones with a traditional linear Tuned Mass Damper (TMD) [2, 3]. Moreover, under certain conditions, a one-way irreversible energy transfer phenomenon, termed as targeted energy transfer (TET) is observed [4, 5], providing a highly efficient mechanism for broadband vibration suppression. Analytical, numerical and experimental investigations concerning such TET phenomenon in coupled NES systems for highly effective broadband vibration suppression, were extensively demonstrated in [4-11].

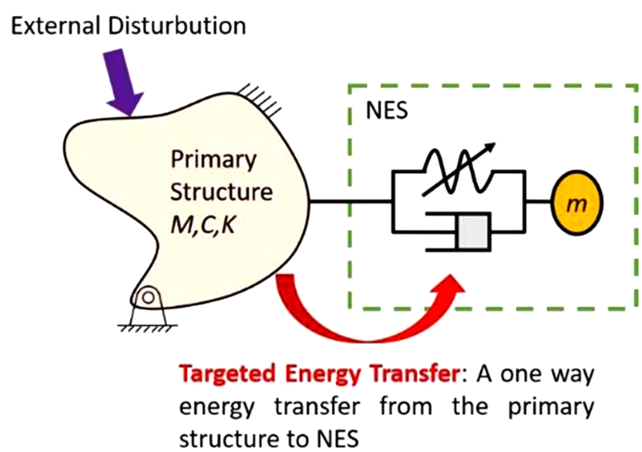

Fig. (1). Schematic of a primary structure coupled to a nonlinear energy sink.

The effectiveness of NES for vibration mitigation could be found in many engineering applications, including beams or plates [12-14], building structures [15], as well as aerospace systems [16, 17]. Especially in the field of aerospace engineering, Yang *et al.* [16] designed conceptually and implemented experimentally a NES to suppress the vibration of whole. Lee *et al.* demonstrated the efficiency of an NES for suppression of aeroelastic instabilities (limit cycle oscillations) in a two-DOF rigid wing model [18, 19]. Recently, NES has also been applied to the flywheel system of a satellite [20]. All of these studies have confirmed the potential of NES for effective vibration suppression in various types of structures in aeronautics and astronautics.

Up to now, various types of NES have been proposed to optimize the suppression performance, the simplest implementation is a lightweight oscillating mass with cubic nonlinear stiffness and linear damping [1], while other kinds of designs could also be found by using nonlinear damping [21, 22], vibro-impact dynamics [23-25], rotating elements, inerter components [26, 27], bistable or piecewise nonlinearities [13, 28-30]. It is proved that for whatever kind of NES and for whatever kind of applications, their key point of design resides in the same principle, *i.e.*, to highlight the importance of TET condition. More precisely, the present studies reveal that the optimization of NESs in the transient regime is to make the TET activated at the initial time. While in the permanent regime, the objective is reflected in tuning the parameters to generate a strongly modulated response (SMR) [31, 32], which is an equivalent representation of TET in the forced responses.

Besides the fruitful developments in vibration suppression, the potential of NES exploring broadband energy harvesting systems is also investigated in recent studies. One of the representative investigations is by Deniel *et al.* [33, 34], where an electromagnetic energy harvester using NES to achieve efficient TET is designed. Their numerical and experimental results have confirmed that, once TET is activated, the NES can achieve highly effective energy harvesting performance over a wide frequency range and hence outperforms the traditional linear harvesters. Other NES based energy harvesting systems by using piezoelectric transduction methods were also proposed and investigated [35-39]. These studies clearly demonstrated the advantage of NES in developing broadband energy harvesting systems. Despite the abovementioned NES related energy harvesting applications that focus only on smooth essential nonlinearities, it is only recently that the potential of the VINES for energy harvesting was addressed by Li *et al.* [40]. In their study, an electromagnetic VINES consisting of a magnet moving inside the clearance of a coil fixed primary structure was proposed. It is thus demonstrated

CHAPTER 7

Configuration Keeping Technology of Partial Space Elevators

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Abstract: The partial space elevator (PSE) is a space transportation system that consists of one main satellite and one end body connected to a piece of tether. A climber can move along the tether conveying the cargo. This chapter studies a new configure-keeping technology for the stable cargo transportation of the PSE. The new technology contains two control modules. Module I predicts the optimal climber speed as a reference and suppresses the libration motions using the actuators on the climber. The control law of Module I is designed based on an analytical climber speed function, PPC control is used to compensate for system error. Module II further stabilizes the system by eliminating the possible disturbances in real-time acting on the end body. Two control modes are used given to further ensure the system configuration keeping. To test the validity of the proposed technology, two cases are simulated. The numerical results show that the proposed configuration keeping technology is very effective in dealing with the configuration keeping problems for the partial space elevators and other complex nonlinear dynamic systems in the aerospace engineering area.

Keywords: Aerospace engineering, Configuration keeping, Hybrid control scheme, Nonlinear dynamic system, Partial space elevator.

INTRODUCTION

The partial space elevator (PSE) is a candidate cargo transportation technology for the space station and future extra-large space structure [1, 2]. The general structure of a PSE is shown in Fig. (**1**) [3]. In the transportation period, the climber movement leads to libration motions of a PSE like a double pendulum, due to the action of Coriolis force. The libration may lead to instability of the PSE which is adverse to the transportation mission. Thus, it is desired to keep the configuration in a straight

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line with marginal or no libration. However, it is hard to suppress the libration and keep the configuration simultaneously since PSE is underactuated. Furthermore, this estimation of the unknown tether tensions is also an issue in the control process.

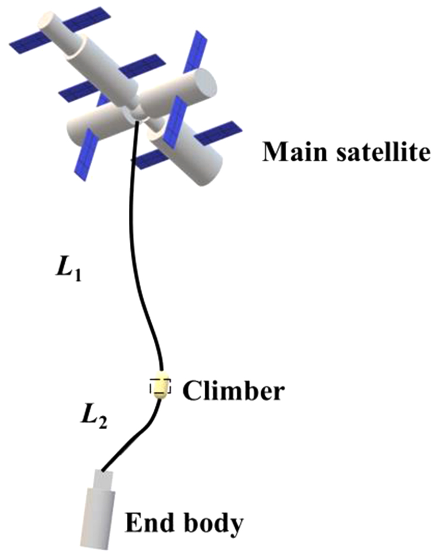

Fig. (1). General scheme of a PSE.

Up to now, many efforts have been devoted to stabilizing the PSE [4, 5]. The concept of PSE was first proposed by Woo and Misra in 2009 [6], the dynamic model matches the earlier studies of Misra [7] and Lorenzini [8]. The dynamic characteristics of a PSE can be analyzed using the classical two-piece dumbbell model (TPDM), which is simple and accurate [9]. In TPDM, the tethers are assumed to light straight rods, ignoring the tether's flexible motion. The flexible motions of the tether can be modeled by multiple nodes and rods [10]. Tang *et al.* [11], Li and Zhu *et al.* [12] proposed high-fidelity PSE models adopting the nodal position finite element method (NPFEM). Such a model is only computationally expensive for concept study. Yamagiwa *et al.* [13] concluded that the tether bend was not significant to a PSE due to the action of tether tension, in the engineering aspect. Using TPDM, Jung [14], Shi and Zhu *et al.* [9] found that the fast-transporting climber leads to significant libration of the PSE, and the libration motion is difficult to be eliminated, even though the libration angles are suppressed. Yu *et al.* [15] analyzed the dynamics of a classical two-body tethered system and found an analytical speed function to ensure a fixed configuration. Shi *et al.* [3] expanded this work and revealed the configuration of PSE is controllable to a fixed angle, relative to the local vertical, by controlling the climber speed and the end body's thrust in the transportation period. The aforementioned investigations also reveal the estimation of uncertain tether tensions is critical to both dynamics and control. One desired way is estimating the unknown tension to enhance the accuracy of the TPDM. The other way is to enhance the robustness of the control method in real-time.

The configuration stabilization of the PSE is also important. Tension control [16-19] is widely used to suppress the libration of a PSE. Yet, limited work has been done to keep the system at a desired stable state during the mission, which is critical to the safety of the on-orbit cargo transfer. Yu *et al.* [15] proposed an analytical deployment control law to hold the stabilization of a two-body tethered satellite. Yet for an underactuated three-body PSE, the method in [15] needs further compensation control. To control an underactuated PSE, the optimal control is a reasonable way [20], due to its ability in handling multiple control objectives and constraints [20-24]. Shi and Zhu proposed a parallel optimization method [17] with good computationally efficiency to control the underactuated PSE. These aforementioned works mainly aim to ensure the final state stability without considering the stability held during the mission period. To this goal, it is desired to add thrust controllers on the climber and the end body. Huang *et al*. [25] studied the stable control of the dexterous tethered space robot (DTSR), systematically, with mission design and observer-based controller design. The ground experiment has been used to validate the effectiveness of the proposed control method.

To release the heavy calculation burden of these optimal control schemes, Shi and Zhu [26] proposed a closed-loop velocity control strategy, yet, it cannot keep the configuration stable. Therefore, improvements are needed. To overcome the disadvantages of the optimal control [3] and its alternative [26], a novel prescribed performance control (PPC) is proposed due to its smooth performance subject to boundary constraints [27, 28]. The aforementioned studies give a way to stabilize the PSE free from the optimal control method. Moreover, they also reveal that the configuration can be kept by controlling tether tensions only. This is an advantage to saving fuel for practical missions.

To keep the configuration of a PSE in cargo transportation, the configuration keeping technology for the stable cargo transportation of the PSE is studied. First, a novel tension observing the law is proposed to estimate the tensions in tether so that the system uncertainties can be partly eliminated from the dynamic aspect. Then a two-module control technology is proposed to keep the configuration of the PSE in cargo transportation. The analytical control law in Module I is compensated by a prescribed performance control law. In Module II, two control schemes are

CHAPTER 8

Adaptive Fixed-time 6-DOF Coordinated Control of Spacecraft Formation Flyings

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Abstract: In this paper, the fixed-time coordinated control problem is investigated for multiple spacecraft formation flying (SFF) system based on six-degrees-of-freedom (6-DOF) dynamic model. The system under consideration involves input quantization, external disturbance, and directed communication topology. By utilizing the neighborhood state information, a novel multi-spacecraft nonsingular fixed-time terminal sliding mode function is designed. To reduce the required communication rate, a hysteretic quantizer is employed to quantify the control torque and force. The problem addressed is the design of 6-DOF fixed-time coordinated controller such that, the controlled system is practical fixed-time stable and also ensures the relative attitude and position tracking errors can converge into the regions in fixed time. A numerical example is provided to illustrate the usefulness of the proposed control scheme.

Keywords: Coordinated control, Spacecraft formation flying, Fixed-time control, Input quantization.

INTRODUCTION

As is well known, the spacecraft formation flying (SFF) has been one of the hot research fields owing to its wild applications in various space industry such as deep space exploration, atmosphere monitoring of the Earth, and spacecraft on-orbit maintenance [1-5]. The attitude control and orbit control are arguable two equal vital technologies. For SFF missions, it is important to achieve the required attitude and position at the same time [1]. Due to the dynamic coupling between attitude motion and orbital motion, the two motions can be regarded as a whole six degree of freedom (6-DOF) motion. In recent years, the coordinated control of 6-DOF for SFF has attracted a number of researchers [2, 3]. Nevertheless，the proposed control schemes mentioned above only can ensure the asymptotic stability.

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Fast convergence performance is a crucial requirement for coordinated control problems of SFF [4-7]. Compared with the asymptotic stabilization controller, the finite time stabilization controller has faster response speed and better anti-interference ability. Thus, the finite-time control strategies have been proposed for spacecraft formation control. Although the finite time control approach can guarantee the finite-time stability, the convergence time depends on the initial state information of the system, which brings difficulties to practical application [8]. In order to solve this constraint, the design of finite time controller is studied by using the concept of fixed-time stability, that is, the upper bound of the convergence time can be estimated regardless of the initial state of the controlled system [9, 10]. So far, the fixed-time control strategy has been utilized for a variety of industrial systems [11], but few researchers pay attention to the 6-DOF fixed time coordinated control of SFF, especially for external disturbances with unknown upper bound. Another important problem in multiple SFF missions is that the communication link between spacecraft is not always bidirectional, such as in unidirectional spacecraft laser communication system. However, the coordinated control problem is studied based on the assumption that the communication topology is undirected in some existing results.

On the other hand, networked control systems (NCSs) have received persistent research interest because they have been successfully applied to a variety of modern practical engineering systems [12, 13], such as aerospace engineering systems, nuclear power stations, unmanned vehicles etc. In the modern low-cost small spacecraft formation system, the communication between the different functional modules is connected through wireless network [14-16].

It's common knowledge that the quantization error induced by signal quantization behavior may exist in modern SFF systems, which will reduce control performance and even lead to instability [17-20]. Therefore, it is necessary to design the new control scheme for SFF, in which signal quantization is considered. Although some researches focus on the quantized control of SFF, there are no results considering the 6-DOF coordinated control of multi spacecraft formation with quantized input control signals. The complexity of the multiple spacecraft formation coordinated control task make the quantized fixed-time coordinated control a serious challenge.

In the present paper, we consider the fixed-time 6-DOF adaptive coordinated control problem for SFF involving input quantization and directed communication topology. The main contributions lie in three aspects: (1) For the coordinated controller design, the directed communication graph will bring more challenges than the undirected communication graph. (2) Based on 6-DOF dynamic model, a new multi-spacecraft nonsingular FTTSM is constructed, on which each spacecraft converges to their desired states while keeping synchronization with other formation spacecraft. (3) A fixed-time adaptive coordinate controller is designed to eliminate the effects of external disturbances and hysteretic quantizer on the control performance and ensure the practical fixed-time stability of the closed-loop system.

MODELLING AND PRELIMINARIES

6-DOF Dynamic Model

The 6-DOF dynamic model of spacecraft formation is represented as follows:

$$\begin{cases} \dot{\boldsymbol{x}}_{1i} = \boldsymbol{\Lambda}(\dot{\boldsymbol{x}}_{1i})\boldsymbol{x}_{2i} \\ \boldsymbol{G}_{fi}\dot{x}_{2i} + \boldsymbol{C}(\boldsymbol{x}_{2i}) + \boldsymbol{N}(\boldsymbol{x}_{1i}) + \boldsymbol{\tau}_i = \boldsymbol{u}_i, \quad i = 1, 2, \ldots, n \end{cases} \tag{1}$$

Where

$$\boldsymbol{x}_{1i} = \begin{bmatrix} \boldsymbol{\rho}_i \\ \boldsymbol{q}_i \end{bmatrix}$$

$$\boldsymbol{x}_{2i} = \begin{bmatrix} \dot{\boldsymbol{\rho}}_i \\ \boldsymbol{\omega}_i \end{bmatrix}, \quad \boldsymbol{\Lambda}(\dot{\boldsymbol{x}}_{1i}) = \begin{bmatrix} \boldsymbol{I}_{3\times3} & \boldsymbol{0}_{3\times3} \\ \boldsymbol{0}_{3\times3} & \dfrac{\boldsymbol{T}(\boldsymbol{q}_i)}{2} \end{bmatrix}, \quad \boldsymbol{G}_{fi} = \begin{bmatrix} m_{fi}\boldsymbol{I}_{3\times3} & \boldsymbol{0}_{3\times3} \\ \boldsymbol{0}_{3\times3} & \boldsymbol{J}_{fi} \end{bmatrix}$$

$$, \boldsymbol{C}(\boldsymbol{x}_{2i}) = \begin{bmatrix} \boldsymbol{C}(\boldsymbol{n}_0)\dot{\boldsymbol{\rho}}_i \\ \boldsymbol{\omega}_i^{\times}\boldsymbol{J}_{fi}\boldsymbol{\omega}_i \end{bmatrix}, \quad \boldsymbol{N}(\boldsymbol{x}_{1i}) = \begin{bmatrix} \boldsymbol{N}(\boldsymbol{\rho}_i, \boldsymbol{n}_0, \boldsymbol{R}) \\ \boldsymbol{0}_{3\times1} \end{bmatrix}, \quad \boldsymbol{\tau}_i = \begin{bmatrix} \boldsymbol{F}_{di} \\ \boldsymbol{z}_i \end{bmatrix}, \quad \boldsymbol{u}_i = \begin{bmatrix} \boldsymbol{u}_{fi} \\ \boldsymbol{u}_{ti} \end{bmatrix}$$

$$\boldsymbol{T}(\boldsymbol{q}_i) = \begin{bmatrix} -\boldsymbol{q}_{vi}^T \\ \boldsymbol{q}_{0i}\boldsymbol{I}_{3\times3} + \boldsymbol{q}_{vi}^{\times} \end{bmatrix}, \quad \boldsymbol{C}(n_0) = 2n_0\begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \boldsymbol{N}(\boldsymbol{\rho}_i, n_0, R) = \begin{bmatrix} -\dot{n}_0 y_i - n_0^2 \boldsymbol{x}_i - 2\dfrac{\mu}{R^3}x_i \\ \dot{n}_0 x_i - n_0^2 y_i + \dfrac{\mu}{R^3}y_i \\ \dfrac{\mu}{R^3}z_i \end{bmatrix}$$

where superscript *i* stands for the *i*th follower spacecraft; $\boldsymbol{\rho}_i = [x_i \ y_i \ z_i]^T$ represents the relative position vector from the *i*th follower spacecraft to the leader spacecraft; $\boldsymbol{\omega}_i \in \mathbb{R}^3$ denotes the angular velocity; $\boldsymbol{q}_i \in \mathbb{R}^4$ is the quaternion defined as

CHAPTER 9

FTCESO-based Prescribed Time Control for Satellite Cluster Reconstruction

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Abstract: In this paper, a prescribed time control strategy for satellite cluster formation reconstruction with multiple environmental disturbances and thruster constraints is proposed. Firstly, a finite time convergent extended state observer (FTCESO) is used to eliminate the effects of external disturbances. And it has been proved to be able to accurately estimate the total disturbances of the satellite cluster in a short time. Secondly, based on the sliding mode, a prescribed time controller with piecewise control law is designed for satellite cluster reconstruction which can ensure that the satellites move to the specified configuration at a prescribed time. Then, the convergence of the controller is proved by Lyapunov stability theory. Finally, compared with a sliding mode controller, a numerical simulation is performed to demonstrate the effectiveness of the proposed method.

Keywords: Extended state observer, Formation reconstruction, Multiple disturbances, Piecewise control law, Prescribed time control, Satellite cluster.

INTRODUCTION

With the rapid development of computer, new energy and new materials technology, countries all over the world seize the opportunity to design and develop satellites with different functions. Thanks to the continuous development of aerospace industry technology, space systems are becoming more and more powerful, especially distributed satellite system [1, 2]. Compared with the traditional single large satellite, the distributed satellite system has significant

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application advantages, such as the large spatial distribution, low development and maintenance costs, high system reliability and strong flexibility [3]. Satellite formation and satellite cluster are two typical systems in distributed satellite systems. Where, satellite formation generally maintains a specific spatial configuration and the satellite cluster spends most of its operating time in a loose configuration to reduce fuel consumption [4, 5]. At the same time, satellite cluster can be reconstructed into specific spatial configurations to meet mission requirements.

When the satellite cluster orbits the earth, the disturbance force may come from the uneven distribution of the mass of earth, the gravitational attraction of other planetary bodies, the solar radiation pressure and other perturbations [6, 7]. Especially, Satellites are mainly affected by J_2 perturbation and atmospheric drag in low earth orbit. The persistent effect of the multiple disturbances causes the orbit of the satellite to change and deviate from the orbit of the two-body model [8, 9].

Disturbance observer is a very practical method for external disturbance and uncertainty which has captured considerable attention [10]. Compared with general nonlinear observer, extended state observer has the advantage of requiring less state information and faster observation speed [11]. ESO is able to estimate uncertainties, external disturbances and any unmodeled parts of the system as the so-called total disturbance [12]. Therefore, ESO is widely used in engineering applications [13-15]. Liu P constructed linear ESO with high-gain which can estimate the uncertainty items in a large spacecraft system without velocity information [16]. To deal with the problem of peaking value, a nonlinear ESO constructed from piece-wise smooth functions is investigated by Zhao Z [17]. A sliding mode controller based on ESO is designed for the attitude tracking of large flexible spacecraft by Zhang Z [18]. Li B proposed a novel continuous finite-time extended state observer which can estimate the attitude angular velocity and extended state observation errors of the satellite in a finite time [19].

On the other hand, sliding mode variable structure control is a robust control method for satellite cluster reconstruction whose main advantages are high control precision, and insensitive to parameter variation and disturbance [20-22]. Shahid K designed a sliding mode control law based on C-W equation to realize the satellite formation reconstruction which considered the effects of initial state deviation, target eccentricity and J_2 perturbation [23]. To ensue each satellite convergence to their desired state in finite time, terminal sliding mode control (TSMC) was used to solve the problem of relative motion control for spacecraft formation [24]. A nonsingular fast terminal sliding mode controller (NFTSMC) to realize the synchronization control of spacecraft formation is proposed by Liu R [25]. Although the terminal sliding mode can stabilize in finite time, the time of convergence is determined by the initial state of the system. To fix this problem, fixed time sliding mode control had been proposed whose convergence time is independent of the initial selection of the system [26-28]. On the basis of these theories, scholars have proposed prescribed time control strategy that can stabilize the system at a predetermined time [29-30]. Fixed-time control and preset-time control have been widely used in multi-agent systems [31-34], but seldom used in satellite cluster control.

However, in a space mission, satellites in cluster may be required to transform to a new specified configuration in a prescribed time. Considering the multiple disturbances, the control strategy combined with FTESO and prescribed time controller is very suitable for the requirement of satellite cluster reconstruction. To our knowledge, little research has explicitly focused on the aforementioned issues. This paper documents several key contributions as follows. Firstly, in the case of multiple environmental disturbances, a FTCESO is designed to estimate perturbations and uncertainties in a finite time. Secondly, a prescribed time control strategy is designed to ensure that the error state can converge to the equilibrium point within the user-defined time. Finally, based on a piecewise control law, we proposed a control strategy which can ensure that the satellites move to the specified configuration at a prescribed time.

The rest of this paper is organized as follows. Section 2 describes the dynamics model of the relative motion of satellite cluster and the influence of J_2 perturbation and atmospheric drag. In Section 3, a prescribed time controller based on FTCESO is developed for the satellites reconstruction and corresponding stability analysis is performed *via* a Lyapunov approach. A set of numerical simulations for comparison with normal sliding mode controller is presented in Section 4. Finally, some conclusions are drawn.

DYNAMICS MODELING

For the relative motion of satellite cluster, Earth-centered inertial (ECI) and local-vertical local-horizontal (LVLH) are the widely used coordinate systems which are shown in Fig. (**1**). Then a real or virtual satellite is regarded as the origin of the LVLH coordinate system which is called leader satellite. And the other satellites in satellite cluster are called the follower satellites. Let $\boldsymbol{r}_l$ and $\boldsymbol{r}_f$ are the position vectors of the leader and follower satellites in the ECI coordinate system, we can get that,

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