Research Article

Compound Attitude Maneuver and Collision Avoiding Control for a Novel Noncontact Close-Proximity Formation Satellite Architecture

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In order to achieve the attitude maneuver performance of the noncontact close-proximity formation satellite architecture, this paper presents a compound control strategy with variable-parameter sliding mode control and disturbance observer-based feedforward compensation. Firstly, the variable-parameter sliding mode control is proposed to guarantee the attitude maneuver performance of the payload module. Secondly, the collision avoiding control with disturbance observer-based feedforward compensation is proposed to guarantee the synchronization of the two separated modules within the small air clearance constraint of the noncontact Lorentz actuator. Finally, a physical air-floating platform is established to verify the effectiveness of the proposed approach.

1. Introduction

With the development of the space camera technology, high-resolution imaging under attitude maneuver has been focused on recently [1–3]. However, the imaging results could be declined seriously by the huge flexible solar array and the vibration-generating devices [4–6]. For example, the huge flexible solar array could induce pointing overshoot, the high-frequent vibration could induce the imaging blurring, and the low-frequent vibration could induce the imaging warping [7, 8].

The active, passive, and integral active-passive vibration isolations have been proposed to suppress the transmission of the above-mentioned disturbance. Nevertheless, due to their respective limitations, the impact of the above-mentioned disturbance on the control performance cannot fundamentally be rejected [9–12].

A noncontact close-proximity formation satellite concept has been proposed to separate the conventional integrative-contact satellite into an ultraquiet payload module and a service module by noncontact Lorentz actuator [13]. A ground test system with a single rotation degree of freedom (1R-DOF) and two translation degrees of freedom (2T-DOF) by using planar air-bearing technology has been proposed to conduct several experiments, indicating that the isolation performance is improved by two orders of magnitude and not limited by sensor characteristics [14]. However, it is insufficient to verify the multidynamics coupling problem of the noncontact close-proximity formation satellite architecture. The three-axis coupling dynamic model of the noncontact close-proximity formation satellite has been conducted by Newton-Euler approach, indicating that the current driving accuracy of the noncontact Lorentz actuator plays the most important role in the whole architecture

control [15–17]. The optimization approaches based on multiphysical fields have been proposed to resolve the contradiction between the high power and low ripple, leading to a resolution with ppm within its air clearance [18]. By taking the advantages of the noncontact Lorentz actuator, the advanced control algorithms, such as twistor-based synchronous sliding model control, and model predictive control, have been proposed to guarantee a good performance of the stability control. The development of the noncontact close-proximity formation satellite has been greatly promoted through the above-mentioned researches [19–24]. Also, due to the advantage of the noncontact close-proximity formation satellite, the payload module can be considered the conventional satellite and there are many related researches on controller design [25, 26]. It can be easily found that the recent literatures mainly focus on the theory and simulation analysis to improve the stability control performance of the noncontact close-proximity formation satellite.

In view of the application, the noncontact architecture design demonstrates not only the structure separating but also inertia tensor separating, indicating that the attitude maneuver operation can be realized through two-echelon stratification. However, it is more difficult than stability control due to its close-proximity formation characteristics. The whole attitude maneuver control should be designed carefully within small air clearance of the noncontact Lorentz actuator. Otherwise, the separated payload module and service module could be collided. The collision may damage the actuators and the precision instruments of the noncontact close-proximity formation satellite. Therefore, in order to realize the attitude maneuver performance, it is necessary to study the collision avoidance control.

A compound control with variable-parameter sliding mode control and disturbance observer-based feedforward compensation has been proposed to realize both the attitude maneuver performance and the synchronization of the two separated modules in this paper. Meanwhile, a physical air-floating platform with 3R-DOF and 2T-DOF is established to verify the effectiveness of the proposed approach. The main contributions of this paper can be outlined as follows:

- (1) Compared with the previous researches on the noncontact close-proximity formation satellite in [19–24], this paper extends its advantage into the attitude maneuver operation by using compound control strategy
- (2) Compared with the 1R-DOF ground test system established in [14], the physical air-floating platform with full 3R-DOF can effectively verify the overall performance of the noncontact close-proximity formation satellite with multidynamics

The rest of this article is organized as follows. The dynamic modeling of the noncontact close-proximity formation satellite is given in Section 2. And the compound controller design is introduced in Section 3. Section 4 details the physical air-floating platform and the experimental verification results of the proposed approach. Finally, Section 5 exhibits the conclusions of the whole paper.

2. Dynamic Modeling

In this section, the noncontact close-proximity formation satellite architecture is introduced, and the dynamic modeling is established by using Newton-Euler approach.

2.1. Hierarchical Architecture. The noncontact close-proximity formation satellite is divided the structure into an ultraquiet payload module and a service module by noncontact Lorentz actuator, as shown in Figure 1.

The payload module is used to install the ultraquiet devices, such as the star sensor and the coil component of the noncontact Lorentz actuator. Since the huge flexible solar panel and the vibration-generating devices are not equipped within the payload module, it can be regarded as a rigid body. The service module is used to install the control moment gyroscope, thruster, solar panel, and the permanent magnet component of the noncontact Lorentz actuator. Meanwhile, the wireless communication and the power supply is becoming more mature and reliable gradually, suggesting that the wireless technologies can be adopted to avoid the issues due to the cables [27, 28].

The noncontact Lorentz actuator is a magnetic levitation actuator which is driven by the current with linear force output. Compared with the control moment gyroscope, the accuracy of the noncontact Lorentz actuator is more precise without unbalanced vibration [29].

2.2. Payload Module Dynamics. According to the angular momentum theorem, the attitude dynamics of the payload module has the following expression:

$$\mathbf{J}_p \dot{\boldsymbol{\omega}}_p + \boldsymbol{\omega}_p \times (\mathbf{J}_p \boldsymbol{\omega}_p) = \mathbf{T}_{cp} + \mathbf{T}_{dp}, \quad (1)$$

where $\boldsymbol{\omega}_p$ represents the angular velocity vector of the payload module; $\mathbf{J}_p$ represents the inertia tensor of the payload module; $\mathbf{T}_{cp}$ represents the control torque by the noncontact Lorentz actuators; and $\mathbf{T}_{dp}$ represents the sum of the external disturbance torque to the payload module.

The attitude kinematics of the payload module is established based on the quaternion method, as shown in the following expression:

$$\dot{\mathbf{q}} = \begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -\omega_{px} & -\omega_{py} & -\omega_{pz} \\ \omega_{px} & 0 & \omega_{pz} & -\omega_{py} \\ \omega_{py} & -\omega_{pz} & 0 & \omega_{px} \\ \omega_{pz} & \omega_{py} & -\omega_{px} & 0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}. \quad (2)$$

In matrix form,

$$\begin{cases} \dot{q}_0 = -\frac{1}{2} \mathbf{q}^T \boldsymbol{\omega}_p, \\ \dot{\mathbf{q}} = \frac{1}{2} (\mathbf{q}^\times + q_0 \mathbf{I}_{3 \times 3}) \boldsymbol{\omega}_p, \end{cases} \quad (3)$$

FIGURE 1: Hierarchical architecture.

where $\mathbf{q}^\times \in \mathbb{R}^{3 \times 3}$ is the vector cross-product operator of a skew-symmetric matrix:

$$\mathbf{q}^\times = \begin{bmatrix} 0 & -q_3 & q_2 \\ q_3 & 0 & -q_1 \\ -q_2 & q_1 & 0 \end{bmatrix}. \quad (4)$$

In this paper, the controller design will be based on the state error. Therefore, defining the desired attitude quaternion $\mathbf{q}_t = [q_{t0} \mathbf{q}_t]^T = [q_{t0} \ q_{t1} \ q_{t2} \ q_{t3}]^T$ and the desired attitude angular velocity $\boldsymbol{\omega}_{pt} = [\omega_{ptx} \ \omega_{pty} \ \omega_{ptz}]^T$. The error attitude quaternion $\mathbf{q}_e = [q_{e0} \ \mathbf{q}_e]^T = [q_{e0} \ q_{e1} \ q_{e2} \ q_{e3}]^T$ and the error angular velocity $\boldsymbol{\omega}_{pe} = [\omega_{pex} \ \omega_{pey} \ \omega_{pez}]^T$ can be solved by the following expression:

$$\begin{cases} \mathbf{q}_e = \mathbf{q}_t^* \otimes \mathbf{q}, \\ \boldsymbol{\omega}_{pe} = \boldsymbol{\omega}_p - \boldsymbol{\omega}_{pt}, \end{cases} \quad (5)$$

where $\mathbf{q}_t^* = [q_{t0} - \mathbf{q}_t]^T$ represents the conjugate quaternion and the symbol “ $\otimes$ ” represents the multiplication of quaternions.

2.3. Service Module Dynamics. The control moment gyroscope, flexible solar panel, and other parts with large vibration are installed in the service module; the attitude dynamics of the service module has the following expression:

$$\dot{\mathbf{h}}_s + \boldsymbol{\omega}_s^\times \mathbf{h}_s + \mathbf{C}_{a1} \ddot{\mathbf{q}}_{a1} + \mathbf{C}_{a2} \ddot{\mathbf{q}}_{a2} = \mathbf{T}_{cs} + \mathbf{T}_{ds} + \mathbf{T}_{ps}, \quad (6)$$

where $\mathbf{h}_s = \mathbf{J}_s \boldsymbol{\omega}_s + \mathbf{h}_c$ represents the total angular momentum of the service module; $\mathbf{J}_s$ represents the inertia tensor of the service module; $\boldsymbol{\omega}_s$ represents the angular velocity vector of the service module; $\mathbf{h}_c$ represents the angular momentum of the control moment gyroscopes mounted on the service module; $\boldsymbol{\omega}_s$ represents the angular velocity vector; $\mathbf{C}_{ai}$ and $\mathbf{q}_{ai}$ ($i = 1, 2$) represent the coupling matrix and modes of the solar panels, as shown in Equations (7) and (8); $\mathbf{T}_{cs}$ represents the control torque of the control moment gyroscopes; $\mathbf{T}_{ns}$ represents the sum of the external disturbance torque to the service module; and $\mathbf{T}_{ps}$ represents the reaction torque of the noncon-

tact Lorentz actuators to the service module, as shown in Equation (9).

$$\ddot{\mathbf{q}}_{a1} + 2\zeta \Lambda_a \dot{\mathbf{q}}_{a1} + \Lambda_a^2 \mathbf{q}_{a1} + \mathbf{C}_{a1}^T \dot{\boldsymbol{\omega}}_b = 0, \quad (7)$$

$$\ddot{\mathbf{q}}_{a2} + 2\zeta \Lambda_a \dot{\mathbf{q}}_{a2} + \Lambda_a^2 \mathbf{q}_{a2} + \mathbf{C}_{a2}^T \dot{\boldsymbol{\omega}}_b = 0, \quad (8)$$

where ζ represents the damping coefficient of the solar panels and Λ_a represents the modal frequency of the diagonal matrix.

$$\mathbf{T}_{ps} = -\mathbf{C}_{sp}^T \mathbf{T}_{cp}, \quad (9)$$

where $\mathbf{C}_{sp}$ represents the coordinate transformation matrix of the service module relative to the payload module.

Defining the angular velocity of the service module relative to the payload module as $\boldsymbol{\omega}_{sp}$, thus, the following relationship has the following expression:

$$\boldsymbol{\omega}_{sp} = \boldsymbol{\omega}_s - \mathbf{C}_{sp}^T \boldsymbol{\omega}_p. \quad (10)$$

According to Equations (1) and (6), the relative attitude dynamics equation of the two modules can be obtained by derivative of the above equation:

$$\begin{aligned} \dot{\boldsymbol{\omega}}_{sp} = & \mathbf{J}_s^{-1} (\mathbf{T}_{cs} + \mathbf{T}_{ds} + \mathbf{T}_{ps} - \mathbf{C}_{a1} \ddot{\mathbf{q}}_{a1} - \mathbf{C}_{a2} \ddot{\mathbf{q}}_{a2}) \\ & - \mathbf{J}_s^{-1} \boldsymbol{\omega}_s^\times (\mathbf{J}_s \boldsymbol{\omega}_s + \mathbf{h}_c) + \boldsymbol{\omega}_{sp} \times (\mathbf{C}_{sp}^T \boldsymbol{\omega}_p) \\ & - \mathbf{C}_{sp}^T \mathbf{J}_p^{-1} (\mathbf{T}_{cp} + \mathbf{T}_{dp} - \boldsymbol{\omega}_p \times (\mathbf{J}_p \boldsymbol{\omega}_p)). \end{aligned} \quad (11)$$

3. Compound Controller Design

In this section, the attitude maneuver operation of the payload module with variable-parameter sliding mode control and the collision avoiding of the service module with disturbance observer-based feedforward compensation is proposed to realize both the attitude maneuver performance and the synchronization of the two separated modules.

3.1. Block Diagram. The block diagram of the compound attitude maneuver and collision avoiding control for non-contact close-proximity formation satellite control system is shown in Figure 2. There are two control loops, including the active control of the payload module and the cooperative

FIGURE 2: Block diagram of noncontact close-proximity formation satellite control system.

FIGURE 3: Schematic diagram of test system.

control of the service module. The variable-parameter sliding mode control algorithm is adopted to guarantee the active attitude maneuver control for payload module, while the disturbance observer-based feedforward compensation is adopted to guarantee the cooperative synchronization for service module within the small air clearance constraint.

3.2. Attitude Maneuver Control of Payload Module. The payload module could be affected by external interference. In order to improve the robustness of the system, the article

adopts the variable-parameter sliding mode control to design the active attitude maneuver control for payload module. And the sliding mode control is based on the exponential reaching law [28–32].

Defining the sliding surface as follows:

$$\mathbf{s} = \mathbf{k}_p \mathbf{q}_e + \boldsymbol{\omega}_{pe}, \quad (12)$$

where $\mathbf{k}_p$ represents the three-dimensional diagonal matrix and its elements are positive real numbers.

FIGURE 4: Physical system of the noncontact close-proximity formation satellite.

TABLE 1: Related parameters of physical system platform.

Parameter	Value
Capacity of air-floating platform	1000-2000 kg
Rotation range of air-floating platform	$\pm 25^\circ$ (X-axis)
Centroid fine adjustment error of air-floating platform	≤ 0.2 kgm
Centroid coarse adjustment error of air-floating platform	≤ 5 gcm
System total interference torque of air-floating platform	≤ 0.1 Nm
Dynamic range of wide-range angle measurement	$\pm 30^\circ$
Accuracy of wide-range angle measurement	1" (3σ)
Angular momentum of control moment gyroscope	≤ 210 Nms
Output torque of control moment gyroscope	≤ 55 Nm
Frame angular velocity stability of control moment gyroscope	$3.9 \times 10^{-3}^\circ/\text{s}$
Output force of noncontact Lorentz actuator	≤ 15 N
Air-gap constraint of noncontact Lorentz actuator	$\pm 0.9^\circ$

According to the exponential approach law, the following equation has the following expression:

$$\dot{\mathbf{s}} = -\boldsymbol{\varepsilon}\mathbf{s} - \boldsymbol{\lambda}\text{sat}(\mathbf{s}). \quad (13)$$

Both $\boldsymbol{\varepsilon}$ and $\boldsymbol{\lambda}$ are the three-dimensional diagonal matrixes, whose elements are positive real numbers.

Combining the dynamics and kinematics models of the payload module, the attitude maneuver control law of the payload module has the following expression:

$$\mathbf{T}_{cp} = \frac{1}{2} \mathbf{J}_p \mathbf{k}_p (\mathbf{q}_e^\times + q_{e0} \mathbf{I}) \boldsymbol{\omega}_{pe} + \boldsymbol{\omega}_{pe}^\times (\mathbf{J}_p \boldsymbol{\omega}_{pe}) + \boldsymbol{\varepsilon} \mathbf{s} + \boldsymbol{\lambda} \text{sat}(\mathbf{s}). \quad (14)$$

In order to realize the attitude maneuver control of the payload module, the idea of the variable-parameter control is adopted, and different control parameters $\mathbf{k}_p$ and $\boldsymbol{\varepsilon}$ are selected for the different attitude angle errors. As the attitude angle increases, the parameters will increase accordingly to achieve the purpose of quickly tracking large-angle attitude errors during maneuvering. On the other hand, when the angle error is small, the parameters will decrease accordingly to achieve high precision control of the payload module.

3.3. Collision Avoiding Control of Service Module. According to the function of the noncontact close-proximity formation satellite, the service module should be tracked the payload module within the small air clearance of the noncontact Lorentz actuator to avoid collision. Therefore, the service module needs to track the movement of the payload module synchronously.

FIGURE 5: Attitude angle of payload module with PD controller.

FIGURE 6: Angular velocity of payload module with PD controller.

According to Equation (6), it can be seen that the control torque by noncontact Lorentz actuators act on the payload module produce reaction torques to the service module at the same time. Since the noncontact Lorentz actuator is a magnetic levitation actuator with active current driving, its reaction torque to the service module can be obtained and compensated by the control law through Equation (9).

Meanwhile, the parameters such as the flexible accessory modal matrix of the solar panel and the coupling coefficient matrix can be precalibrated; the control law thus can be designed to compensate the coupling torques of the flexible accessory. Therefore, the control law has the following expression:

$$\mathbf{T}_{cs} = -\mathbf{K}_p \boldsymbol{\Theta}_{sp} - \mathbf{K}_d \boldsymbol{\omega}_{sp} - \mathbf{T}_{ps} + \mathbf{C}_{a1} \ddot{\mathbf{q}}_{a1} + \mathbf{C}_{a2} \ddot{\mathbf{q}}_{a2}, \quad (15)$$

where $\boldsymbol{\Theta}_{sp} = [\varphi_{sp}, \theta_{sp}, \psi_{sp}]^T$ represents the attitude angle error of the service module relative to the three-axis of the payload module.

Substituting Equation (15) into Equation (11), the relative attitude dynamics equation has the following expression:

$$\begin{aligned} \dot{\boldsymbol{\omega}}_{sp} = & \mathbf{J}_s^{-1} (-\mathbf{K}_p \boldsymbol{\Theta}_{sp} - \mathbf{K}_d \boldsymbol{\omega}_{sp} + \mathbf{T}_{ds} - \boldsymbol{\omega}_s^\times (\mathbf{J}_s \boldsymbol{\omega}_s + \mathbf{h}_c)) \\ & + \boldsymbol{\omega}_{sp} \times \left(\mathbf{C}_{sp}^T \boldsymbol{\omega}_p \right) - \mathbf{C}_{sp}^T \mathbf{J}_p^{-1} (\mathbf{T}_{cp} + \mathbf{T}_{dp} - \boldsymbol{\omega}_p \times (\mathbf{B}_p \boldsymbol{\omega}_p)). \end{aligned} \quad (16)$$

Since the unmeasurable terms, complex high-order terms, and other unknown random disturbance moments could affect the control performance, the disturbance observer is designed to guarantee the synchronicity of the service module relative to the payload module within the small air clearance constraint. Therefore, Equation (16) has the following expression:

$$\begin{cases} \dot{\boldsymbol{\Theta}}_{sp} = \boldsymbol{\omega}_{sp}, \\ \dot{\boldsymbol{\omega}}_{sp} = \mathbf{J}_s^{-1} (-\mathbf{K}_p \boldsymbol{\Theta}_{sp} - \mathbf{K}_d \boldsymbol{\omega}_{sp}) + \boldsymbol{\omega}_{sp} \times \left(\mathbf{C}_{sp}^T \boldsymbol{\omega}_p \right) - \mathbf{J}_s^{-1} \boldsymbol{\omega}_s^\times (\mathbf{J}_s \boldsymbol{\omega}_s + \mathbf{h}_c) + \mathbf{J}_s^{-1} \mathbf{T}_{ds}. \end{cases} \quad (17)$$

It can also be written as

$$\begin{cases} \mathbf{J}_s \ddot{\boldsymbol{\Theta}}_{sp} + \mathbf{G}(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp}) + \mathbf{T} = \mathbf{T}_{ds}, \\ \mathbf{G}(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp}) = \mathbf{K}_p \boldsymbol{\Theta}_{sp} + \mathbf{K}_d \dot{\boldsymbol{\Theta}}_{sp} - \mathbf{J}_s (\dot{\boldsymbol{\Theta}}_{sp} \times (\mathbf{C}_{sp}^T \boldsymbol{\omega}_p)), \\ \mathbf{T} = \boldsymbol{\omega}_s^\times (\mathbf{J}_s \boldsymbol{\omega}_s + \mathbf{h}_c). \end{cases} \quad (18)$$

The form of the disturbance observer has the following expression:

$$\begin{cases} \dot{\mathbf{z}} = -\mathbf{L}(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp}) \mathbf{z} + \mathbf{L}(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp}) (\mathbf{G}(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp}) + \mathbf{T} - p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})), \\ \hat{\mathbf{T}}_{ds} = \mathbf{z} + p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp}), \end{cases} \quad (19)$$

where $\mathbf{z}$, $\mathbf{L}(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})$, $p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})$ represents the internal state variable of the disturbance observer and $\mathbf{L}(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})$ has the following relationship with $p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})$:

$$\mathbf{L}(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp}) \mathbf{J}_s \ddot{\boldsymbol{\Theta}}_{sp} = \begin{bmatrix} \frac{\partial p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})}{\partial \boldsymbol{\Theta}_{sp}} & \frac{\partial p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})}{\partial \dot{\boldsymbol{\Theta}}_{sp}} \\ \frac{\partial p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})}{\partial \boldsymbol{\Theta}_{sp}} & \frac{\partial p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})}{\partial \dot{\boldsymbol{\Theta}}_{sp}} \end{bmatrix} \cdot \begin{bmatrix} \dot{\boldsymbol{\Theta}}_{sp} \\ \ddot{\boldsymbol{\Theta}}_{sp} \end{bmatrix}. \quad (20)$$

The internal state variable $p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})$ of the disturbance observer has the following expression:

$$p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp}) = c \begin{bmatrix} \dot{\varphi}_{sp} \\ \dot{\varphi}_{sp} + \dot{\theta}_{sp} \\ \dot{\varphi}_{sp} + \dot{\theta}_{sp} + \dot{\psi}_{sp} \end{bmatrix}, \quad (21)$$

where $c \in R^+$ represents the observer gain.

From Equations (20) and (21), we can get

$$\mathbf{L}(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp}) \mathbf{J}_s \ddot{\boldsymbol{\Theta}}_{sp} = \begin{bmatrix} \frac{\partial p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})}{\partial \boldsymbol{\Theta}_{sp}} & \frac{\partial p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})}{\partial \dot{\boldsymbol{\Theta}}_{sp}} \\ \frac{\partial p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})}{\partial \boldsymbol{\Theta}_{sp}} & \frac{\partial p(\boldsymbol{\Theta}_{sp}, \dot{\boldsymbol{\Theta}}_{sp})}{\partial \dot{\boldsymbol{\Theta}}_{sp}} \end{bmatrix} \cdot \begin{bmatrix} \dot{\boldsymbol{\Theta}}_{sp} \\ \ddot{\boldsymbol{\Theta}}_{sp} \end{bmatrix} = c \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \ddot{\boldsymbol{\Theta}}_{sp}. \quad (22)$$

4. Experimental Verification

In this section, the experimental verification by using the physical air-floating platform is introduced as first. Meanwhile, a PD controller is conducted to demonstrate that the collision avoiding control has to be considered while attitude maneuver operating. Finally, the feasibility and effectiveness

FIGURE 7: Relative attitude angle between two modules with PD controller.

FIGURE 8: Relative angular velocity between two modules with PD controller.

of the proposed compound control are successfully verified to guarantee both attitude maneuver performance and collision avoiding performance for noncontact close-proximity formation satellite architecture.

4.1. Experimental System. In order to verify the proposed compound attitude maneuver and collision avoiding control of the noncontact close-proximity formation satellite, the schematic diagram of the physical air-floating platform with 3R-DOF and 2T-DOF is shown in Figure 3. The system is composed of two air-floating platforms, in which the left air-floating platform is used to simulate the service module, the right air-floating platform is used to simulate the payload

FIGURE 9: Attitude angle of payload module with compound controller.

FIGURE 10: Angular velocity of payload module with compound controller.

module, and eight noncontact Lorentz actuators are installed between the two modules.

The payload module is equipped with the batteries, DC-DC, industrial computer, fiber optic gyros, camera, etc., and the service module is equipped with the batteries, DC-DC, industrial control computer, eddy current sensors, magnetic suspension control moment gyroscopes, and flexible solar panel.

The control system is adopted as the MATLAB/Simulink XPC system. The wide-range angle measurement system

and fiber optic gyros are adopted to obtain the current attitude information of the payload module. The relative attitude and position between the service module and payload module are measured and calculated by eight eddy current sensors fixed with the noncontact Lorentz actuators. The attitude information of the experimental system is sent to the industrial computer through RS422 communication. The industrial computer is used to calculate the command input through the attitude control algorithm according to the difference between the current attitude information

FIGURE 11: Relative attitude between two modules with compound controller.

FIGURE 12: Relative angular velocity between two modules with compound controller.

and the expected attitude and to drive the noncontact Lorentz actuators and control moment gyroscopes to output the command input. The under-stage computer and the on-stage industrial computer are used to upload the control program and to download the telemetry information through the wireless network.

According to the above-mentioned design, the physical air-floating platform of the noncontact close-proximity formation satellite is shown in Figure 4, in which the related parameters are shown in Table 1. Combining with the placement position in the laboratory, the reference coordinate system is established in the east-north-sky direction. Taking the center of mass of the service module as the coordinate origin, the body coordinate system $O_s X_s Y_s Z_s$ of the service

module is established along the three directions of the inertia axis. In the same way, the payload module body coordinate system $O_p X_p Y_p Z_p$ of the payload module is established along the three directions of the inertia axis with the center of mass as the coordinate origin.

Due to the gravity constraint, the physical system of the noncontact close-proximity formation satellite is carried out along X-axis to verify the attitude maneuver control of the payload module and cooperative control of the service module. Setting the initial attitude angle of the two modules as -15° , the desired attitude angle as $+15^\circ$, and attitude maneuver control as $30^\circ/10s$ in a sinusoidal manner; therefore, the maneuver angle, angular velocity, and angular acceleration planning command curve can be obtained as follows:

$$\begin{cases} \varphi = 3t - \frac{15}{\pi} \sin\left(\frac{\pi}{5}\right)t, \\ \omega_x = 3 - 3 \cos\left(\frac{\pi}{5}\right)t, & t \in [t_0, t_0 + 10], \\ \dot{\omega}_x = \frac{3}{5}\pi \sin\left(\frac{\pi}{5}\right)t. \end{cases} \quad (23)$$

4.2. Test Results with PD Controller. In order to validate the feasibility of the proposed compound controller, the PD controller is carried out firstly in this paper. The control results are shown in Figures 5–8.

Figures 5 and 6 show the attitude angle and angular velocity curves of the payload module while the PD controller is adopted. It can be seen that the attitude angle and angular velocity curves are deformed and the whole attitude maneuver process is not completed.

Figures 7 and 8 show the attitude angle and angular velocity curves of the service module relative to the payload module. It can be seen that the relative attitude angle of the two modules has exceeded the air clearance constraint of the noncontact Lorentz actuator and the relative attitude angular velocity curve of the two modules is greater than $0.5^\circ/s$, indicating that the service module could not track the payload module well, and the two modules are colliding in the attitude maneuver process.

4.3. Test Results with Compound Controller. The control results of the proposed compound controller are shown in Figures 9–12. Figures 9 and 10 show the attitude angle and angular velocity curves of the payload module while the compound attitude maneuver and collision avoiding control proposed in this paper are adopted. It can be seen that the X-axis can realize the maneuver control with $30^\circ/10s$. Meanwhile, the angular runout is less than 0.15° , and the angular velocity runout is less than $0.1^\circ/s$ in the attitude maneuver process.

As shown in Figures 11 and 12, the relative attitude angle between the two modules is less than 0.3° , which is in the range of the small air clearance constraint of the noncontact Lorentz actuator. Meanwhile, the relative attitude angular velocity is less than $0.25^\circ/s$. Obviously, the cooperative control of the service module is convergent, suggesting that

TABLE 2: Controller performance comparison.

Indexes	PD method	Proposed method
Attitude maneuverability	Failed	30°/10s
Collision avoidance ability	Failed	Success
Convergence rate		
Attitude angle of payload module	25 s	10s
Angular velocity of payload module	25 s	10s
Relative attitude	≥ 35 s	30s
Relative angular velocity	≥ 35 s	30s
Runout of the other two axes		
Attitude angle of payload module	$\geq 0.7^\circ$	$\leq 0.15^\circ$
Angular velocity of payload module	$\geq 1^\circ$	$\leq 0.1^\circ/\text{s}$
Relative attitude	$\geq 0.5^\circ$	$\leq 0.4^\circ$
Relative angular velocity	$\geq 0.5^\circ/\text{s}$	$\leq 0.35^\circ/\text{s}$

the service module tracked the payload module very well in the attitude maneuver process without collision.

The above-mentioned experimental results clearly demonstrate that the compound controller with the variable-parameter sliding model control for payload module and disturbance observer-based feedforward compensation for service module can well realize attitude maneuver without collision within the small air clearance constraint of the non-contact Lorentz actuator. The comparison of the control performance of the two methods is shown in Table 2.

5. Conclusion

The noncontact close-proximity formation satellite has been successfully demonstrated for stability control. This paper extends its advantage into the attitude maneuver operation by using a compound control strategy with variable-parameter sliding mode control and disturbance observer-based feedforward compensation. The experimental verification results with the established physical air-floating platform show that the PD controller cannot be used to deform the attitude angle and angular velocity and the collision of the two modules would be occurred. The proposed compound control not only can be used to guarantee the attitude maneuver performance of the payload module but also can be used to guarantee the synchronization of the two separated modules within the small air clearance constraint of the noncontact Lorentz actuator.

Data Availability

No data files are available.

Conflicts of Interest

The author(s) declare(s) that they have no conflicts of interest.

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