Fuzzy-Logic-Based Spacecraft Information Fusion Predictive Attitude Control Postprint

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Abstract

Large flexible spacecraft are equipped with large flexible appendages characterized by large volume and low stiffness, which cause vibrations of these appendages to severely affect spacecraft attitude control. To address this issue, a fuzzy-information-fusion preview attitude controller is designed by integrating fuzzy control with information-fusion preview control. Based on information fusion theory, the optimal preview attitude control law for the spacecraft is derived by fusing information such as the desired trajectory and dynamic equations. This control strategy features a simple design process, low computational complexity, and ease of implementation. To tackle the problem of limited output torque in actuators encountered in practical engineering, fuzzy control is utilized to adjust the relevant parameters of the control law online, thereby ensuring that the control input satisfies the constraint requirements. Simulation results demonstrate that the proposed control strategy enables rapid attenuation of flexible appendage vibrations, allows spacecraft attitude angles to accurately and quickly reach their desired values, exhibits favorable control performance, and can provide a reference for engineering applications of large flexible spacecraft attitude control.

Full Text

Preamble

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Based on Fuzzy Logic Information Fusion Preview Attitude Control for Spacecraft

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Abstract: Large flexible appendages carried by large flexible spacecraft are characterized by large volume and low stiffness, causing their vibrations to severely affect spacecraft attitude control. To address this issue, a fuzzy logic-based information fusion preview attitude controller is designed by combining fuzzy control with information fusion preview control. Based on information fusion theory, the optimal preview attitude control law for spacecraft is derived by fusing information such as desired trajectories and dynamic equations. This control strategy features a simple design process, small computational load, and easy implementation. Considering the practical engineering problem of limited output torque from actuators, fuzzy control is employed to adjust the relevant parameters of the control law online to ensure the control input meets the saturation constraints. Simulation results demonstrate that the proposed control strategy enables rapid attenuation of flexible appendage vibrations and allows spacecraft attitude angles to accurately and quickly reach their desired values, exhibiting favorable control performance and providing a reference for engineering applications of large flexible spacecraft attitude control.

Keywords: large flexible spacecraft; attitude control; information fusion; preview control; fuzzy logic

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Introduction

To enable modern spacecraft to perform various complex space missions, large flexible appendages such as solar panels and antennas are often installed. These appendages exhibit characteristics of large size and low stiffness, making them prone to vibration during attitude maneuvers. This vibration can significantly impact the spacecraft’ s attitude control performance and may even lead to instability. Designing high-precision and robust attitude control strategies for such spacecraft has become a research focus.

In recent years, various advanced control methods have been applied to flexible spacecraft attitude control. However, most existing research targets conventional flexible spacecraft where the central rigid body’ s mass and moment of inertia account for a large proportion of the total system. For large flexible spacecraft, the flexible appendages have substantial mass and inertia, causing their vibrations to significantly influence the spacecraft’ s attitude motion. Information fusion preview control offers an effective approach by utilizing future reference information to improve control performance. According to information fusion estimation theory, this method fuses system state information, desired trajectory information, and ideal control strategy to derive optimal control laws. Compared with traditional optimal control, information fusion preview control can more effectively utilize future information and demonstrates good dynamic characteristics, with broad application prospects.

Fuzzy control is an effective method for handling complex controlled objects. Literature has proposed model predictive control strategies based on fuzzy logic, effectively eliminating controller chattering. Therefore, combining fuzzy control with information fusion preview control can enhance the robustness and adaptability of the control system.

Mathematical Model of Large Flexible Spacecraft

This study investigates a large flexible spacecraft consisting of a central rigid body with large lateral solar panels installed on both sides. The structure and reference coordinate system are shown in [FIGURE:N].

Assuming the spacecraft has reached its desired orbital position and orbital dynamics effects are neglected, the attitude dynamics equation can be expressed as:

$$\dot{x} = Ax + Bu + D\eta \tag{1}$$

where x represents the state vector, u is the control torque vector, and η denotes the flexible vibration modal coordinates.

The control objective is to design a fuzzy logic-based information fusion preview attitude control law that enables rapid attenuation of vibration modes and accurate tracking of desired attitude angles.

Design of Information Fusion Preview Attitude Control Law

For the large flexible spacecraft attitude control problem, we derive the optimal preview attitude control input $u^*(k)$ from an information fusion estimation perspective. Based on information fusion estimation theory:

Lemma 1: Assume the estimated quantity x can be represented by a linear information fusion estimation model. The optimal fusion estimate $\hat{x}$ and its information matrix P^{-1} can be obtained by fusing all available information.

For the attitude control problem, system state information, desired trajectory information, and ideal control strategy are treated as "measurements" of the control input. The performance index function is:

$$J = \sum_{i=0}^{N_p} \left[(x_{k+i} - x_{d,k+i})^T Q (x_{k+i} - x_{d,k+i}) + u_{k+i}^T R u_{k+i} \right] \tag{2}$$

where N_p is the preview step number, Q and R are symmetric positive definite weighting matrices. The first term represents the requirement for tracking the desired state, while the second term represents the requirement for minimizing control effort.

The costate fusion estimate λ_k satisfies:

$$\lambda_k = P_k^{-1}[A^T\lambda_{k+1} + Qx_k] \tag{3}$$

with the terminal condition $\lambda_N = 0$. The optimal control law is:

$$u_k^* = -R^{-1}B^T\lambda_{k+1} \tag{4}$$

All costates λ_k and their information matrices P_k can be obtained by solving the Riccati equation:

$$P_k = Q + A^T P_{k+1}A - A^T P_{k+1}B(R + B^T P_{k+1}B)^{-1}B^T P_{k+1}A \tag{5}$$

Since the information fusion preview control has the same feedback control term as traditional optimal control, the closed-loop system matrix $(A - BR^{-1}B^T P)$ can be designed to have eigenvalues within the unit circle, ensuring asymptotic stability of the designed information fusion preview control system.

Fuzzy Logic-Based Information Fusion Preview Attitude Controller Design

In practical engineering, actuators such as reaction wheels have limited output torque. Considering that the weighting matrices Q and R directly affect the magnitude of the control input, fuzzy control is employed to adjust these parameters online to satisfy the torque constraints.

A Takagi-Sugeno (T-S) fuzzy model is adopted due to its simple structure and ease of system analysis and controller design. When the control output magnitude is too large, the fuzzy controller increases R to suppress the control input; when the control input is within acceptable limits, the fuzzy controller decreases R to improve response speed.

Let $u_{max}(k)$ denote the maximum absolute value of control torque components at time k. The fuzzy system inputs are defined as $e_u = u_{max}(k)$ and $\Delta e_u = u_{max}(k) - u_{max}(k-1)$. The fuzzy output is the weight adjustment factor $\alpha(k)$ for matrix R.

The i-th fuzzy rule can be expressed as:

Rule i: IF e_u is M_i AND Δe_u is N_i, THEN $\alpha_i = c_i$

where M_i and N_i are fuzzy subsets, and c_i are constant parameters. Using center-average defuzzification, the final adjusted weight matrix becomes:

$$R(k) = \alpha(k)R_0 \tag{6}$$

where R_0 is the baseline weighting matrix.

The complete control algorithm proceeds as follows: First, compute the fuzzy system inputs from the control magnitude and its increment, then calculate the adjusted weight matrix $R(k)$ using the fuzzy inference. Next, solve the Riccati equation backward to obtain the costate sequence. Finally, compute the current control input using the optimal control law.

Simulation Results

To verify the effectiveness of the proposed control algorithm, simulations are conducted with the following parameters: spacecraft mass 1000 kg, solar panel length 10 m, width 2 m. Other parameters are detailed in the literature. Initial attitude angles are set as $\phi_0 = 5^\circ$, $\theta_0 = 0^\circ$, $\psi_0 = 0^\circ$, with initial vibration modal values.

The fuzzy sets for e_u and Δe_u are defined as {NB, NM, NS, ZO, PS, PM, PB} with Gaussian membership functions. Simulation results compare the proposed fuzzy preview control strategy with traditional preview control.

Traditional Preview Control: The maximum control torque reaches 15 N · m. Vibration modes have not fully attenuated even after 40 s under non-fuzzy information fusion preview control. Attitude angles converge at 3.5 s to reach the desired values.

Fuzzy Preview Control: The maximum control torque is limited to 10 N · m. Vibration modes converge after 25 s under fuzzy preview control based on information fusion. Attitude angles reach their desired values at 1.2 s and 0.8 s respectively, demonstrating superior control performance.

[Figure 1: see original paper] shows the attitude angles, [Figure 2: see original paper] shows the flexible vibration modes, and [Figure 3: see original paper] shows the control torque profiles.

When the moment of inertia increases by 10%, simulation results are shown in [Figure 3: see original paper]. Under traditional preview control, attitude angles stabilize at 3.5 s, 1.5 s, and 1.8 s, with maximum torque reaching 12 N · m. Vibration modes converge after 35 s. Under the proposed fuzzy preview strategy, attitude angles stabilize at 0.8 s and 0.5 s, with maximum torque limited to 8 N · m, showing better control performance.

Similar results are obtained when the moment of inertia decreases by 10%. The simulation demonstrates that parameter variations have minimal impact on the proposed control algorithm, which maintains good performance through online fuzzy adjustment of control parameters.

Conclusion

For spacecraft with large flexible appendages, an information fusion preview attitude control strategy is designed by fusing desired trajectory information and ideal control strategies. This approach improves system control performance. Considering the practical limitation of actuator torque saturation, fuzzy logic is employed to adjust control law parameters online, ensuring control inputs remain within constraints. Simulation results show that the proposed control strategy enables rapid attitude convergence and effective vibration suppression, providing a viable solution for engineering applications of large flexible spacecraft attitude control.

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