International Journal of Multiphysics
Volume 18, No. 2s, 2024
ISSN: 1750-9548

Satellite Multitasking Fuzzy System for Attitude and Sun Tracking

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Abstract— Almost all high-precision pointing satellites use reaction wheels to produce the desired commanded control torque to stabilize their pointing direction. The reaction wheels are good actuators; however, one or two wheels may fail sometimes and could jeopardize the space missions. The solar arrays in low Earth orbiting satellites are typically mounted on the pitch-axis and their rotations are driven by the solar array drive assemblies (SADAs). Although the SADAs generate internal torques due to the rotations, they can potentially be manipulated for the disturbance compensation. In this work, three disturbance rejection control schemes are proposed for the low Earth-orbiting satellite using the combined attitude and sun tracking control system (CASTS). These disturbance compensation schemes are active torque control, linear quadratic integral, and disturbance observer-based control. A multitasking fuzzy fusion framework is introduced to address situations with multiple disturbance rejection control schemes. Numerical treatments of the proposed disturbance compensation strategies are presented. The results show that the disturbance compensation schemes are effective in controlling the attitude and tracking the Sun simultaneously.

Keywords— low Earth orbiting satellites, attitude control, reaction wheels, sun tracking, disturbance compensation

1. INTRODUCTION

To date, three-axis stabilization is still a popular approach in stabilizing low Earth orbit (LEO) satellites that demands relatively accurate positioning and control effort of the reaction wheels. However, if one reaction wheel is malfunctioned, the satellite will be unable to regulate its attitude, which could jeopardize its mission. The Hubble Space telescope, asteroid-sampling Hayabusa, Kepler telescope, and Dawn orbiter are the notable cases in the past 25 years, where their reaction wheels failed and caused mission interruptions. In a recent case, one of six reaction wheels in the Swift Observatory has suffered a failure, caused the observatory to be put in safe mode.

The solar arrays in three-axis stabilized satellites are commonly installed on the pitch-axis to have maximum surface area exposed to sunlight. However, the arrays produce unwanted internal torques as they rotate, that can degrade the performance of the attitude control system [1].

In this paper, it is deemed that the solar arrays' internal torques can be used to compensate for the external disturbance torques without significantly affecting the Sun tracking performance. The proposed method is called the combined attitude and Sun-tracking system (CASTS) and maybe used as a reserve if case of reaction wheel failure [2]. Three disturbance compensation strategies investigated in this work are active torque control, linear quadratic integral, and disturbance observer-based control.

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2. MODELING

A. Pitch Attitude Dynamics

Since the solar arrays are installed on the pitch axis, the work will focus on the control of the pitch angle θ of a three-axis stabilized satellite. The linearized pitch dynamics relative to the inertial frame is given by

$$I_y \ddot{\theta} = \tau_a + \tau_d, \qquad (1)$$

where I_y is the moment of inertia about the pitch axis, τ_a is the torque produced by the actuator, and τ_d is the external disturbance torque.

B. CASTS Architecture

The core component of the CASTS actuator is the Solar Array Drive Assembly (SADA), which is used to rotate the solar array. In fact, it is actually an integrated motor. Thus, a reasonable model for the motor dynamics can be approximated by the first-order system

$$T_m \dot{\tau}_a = -\tau_a + \tau_c, \qquad (2)$$

where T_m is the time constant of the motor, and τ_c is the commanded control torque applied by the actuator. The equivalent transfer function of (1) is given by

$$G_a(s) = \frac{1}{T_m s+1}. \qquad (3)$$

When both SADAs (north and south) are rotated at different angular velocities, with one slightly faster than the orbital velocity and the other slightly slower than the orbital velocity, then a net torque will be generated

$$\tau_a(s) = \tau_n(s) - \tau_s(s) = \frac{1}{T_m s+1}\tau_c, \qquad (4)$$

where the torque produced by the north SADA is

$$\tau_n(s) = \frac{1}{T_m s+1} I_a \left(\omega_o + \frac{\omega_c}{2}\right) s, \qquad (5)$$

and the torque produced by the south SADA is

$$\tau_s(s) = \frac{1}{T_m s+1} I_a \left(\omega_o - \frac{\omega_c}{2}\right) s, \qquad (6)$$

with I_a is the array's moment of inertia about the pitch axis, ω_o is the orbital velocity, and ω_c is the control velocity obtained from the relationship $\tau_c(s) = I_a \omega_c s$. The diagram of the CAST architecture is shown in Fig. 1.

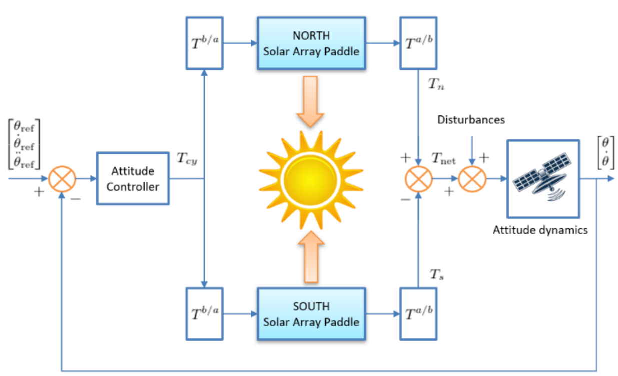

Fig. 1: CASTS architecture.

3. DISTURBANCE COMPENSATION STRATEGIES

Three disturbance compensation strategies are presented in this section and each control design scheme is investigated accordingly. They are active torque control, linear quadratic integral, and disturbance observer-based control.

A. Active Force Control

The active force control (AFC), as implied by its name, actively controls the 'rotational force' to compensate for the external disturbance torque through the active estimation of the disturbance that is acquired from the measured error between the total torque exerted on satellite and the torque produced by the actuator. Technically, this should be active torque control herein. This strategy was initially proposed for the control of robot manipulators [3] and now it has been applied to quadrotor [4] and wheeled mobile robot [5]. It requires an angular accelerometer to perform angular acceleration measurement. Multiplying the measured angular acceleration with the satellite's moment of inertia allows the total torque $\sum \tau = \tilde{I}_y \alpha$ to be calculated. If the satellite's moment of inertia can be accurately estimated, then the total torque can be used to determine the external disturbance torque

$$\tilde{\tau}_d = \sum \tau - \tau_a. \tag{7}$$

However, physically measuring the angular acceleration with the angular accelerometer often introduces a lot of noises. In this work, a first-order lowpass filter is introduced to estimate the pitch angular acceleration from the pitch angle.

$$G_\alpha(s) = \frac{c_2}{c_1 s + 1}. \tag{8}$$

where c_1 and c_2 are the parameters of the lowpass filter to be tuned appropriately.

B. Linear Quadratic Integral

Another way to deal with the external disturbance torque is to introduce the integral compensator so that it produces a measurable reduction in steady-state error. The idea is similar to a proportional-integral-derivative (PID) controller, where the integral action is combined with the full state-feedback controller. To compute an optimal state-feedback control law, the linear quadratic integral algorithm (LQI) can be used [6].

The state-space model of the attitude dynamics

$$\begin{aligned} \dot{\boldsymbol{x}}(t) &= \mathbf{A}\boldsymbol{x}(t) + \mathbf{B}u(t) \\ y(t) &= \mathbf{C}\boldsymbol{x}(t) + Bu(t)' \end{aligned} \tag{9}$$

can be augmented by introducing an extra state variable to denote the integral error ξ between the reference input attitude r and the output signal y

$$\dot{\xi}(t) = r - y(t) = r - \mathbf{C}\boldsymbol{x}(t) \tag{10}$$

to become

$$\begin{bmatrix} \dot{\boldsymbol{x}}(t) \\ \dot{\xi}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ -\mathbf{C} & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{x}(t) \\ \xi(t) \end{bmatrix} + \begin{bmatrix} \mathbf{B} \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} \mathbf{0} \\ 1 \end{bmatrix} r. \tag{11}$$

At steady state, (11) becomes

$$\begin{bmatrix} \dot{\boldsymbol{x}}(\infty) \\ \dot{\xi}(\infty) \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ -\mathbf{C} & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{x}(\infty) \\ \xi(\infty) \end{bmatrix} + \begin{bmatrix} \mathbf{B} \\ 0 \end{bmatrix} u(\infty) + \begin{bmatrix} \mathbf{0} \\ 1 \end{bmatrix} r. \tag{12}$$

When (12) is subtracted from (11), the state error equation is obtained

$$\begin{bmatrix} \dot{\boldsymbol{x}}_\epsilon(t) \\ \dot{\xi}_\epsilon(t) \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ -\mathbf{C} & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{x}_\epsilon(t) \\ \xi_\epsilon(t) \end{bmatrix} + \begin{bmatrix} \mathbf{B} \\ 0 \end{bmatrix} u_\epsilon(t), \tag{13}$$

where $\boldsymbol{x}_\epsilon = \boldsymbol{x}(t) - \boldsymbol{x}(\infty)$, $\xi_\epsilon = \xi(t) - \xi(\infty)$, and $u_\epsilon = u(t) - u(\infty)$. Let the error vector $\boldsymbol{\epsilon}(t) = [\boldsymbol{x}_\epsilon(t) \quad \xi_\epsilon(t)]^T$ is defined, and (13) becomes

$$\dot{\boldsymbol{\epsilon}} = \mathbf{A}_\epsilon \boldsymbol{\epsilon} + \mathbf{B}_\epsilon u_\epsilon. \tag{14}$$

If the feedback control law is

$$u_\epsilon(t) = -\mathbf{K}\boldsymbol{x}_\epsilon(t) + k_I \xi_\epsilon(t) = -\mathbf{K}_\epsilon \boldsymbol{\epsilon}(t), \tag{15}$$

the state equation becomes

$$\dot{\boldsymbol{\epsilon}} = (\mathbf{A}_\epsilon - \mathbf{B}_\epsilon \mathbf{K}_\epsilon)\boldsymbol{\epsilon}. \tag{16}$$

Generally, the pole placement technique can be applied to design the state-feedback gain matrix $\mathbf{K}_\epsilon$ so that the matrix $\mathbf{A}_\epsilon - \mathbf{B}_\epsilon \mathbf{K}_\epsilon$ is Hurwitz. To compute the optimal gain matrix $\mathbf{K}_\epsilon$, the LQI algorithm is applied to minimize the cost function

$$J = \int_0^\infty \{\boldsymbol{\epsilon}^T \mathbf{Q} \boldsymbol{\epsilon} + R u_\epsilon^2\}\, dt. \tag{17}$$

C. Disturbance Observer-based Control

The disturbance observer-based control (DOBC) is somewhat similar to AFC that relies on the estimation of disturbance to compensate for it. Different from AFC that requires the hardware accelerometer to measure the angular acceleration, DOBC is an algorithm that performs the estimation numerically [7]. After estimating the disturbance torque on the satellite pitch dynamics, a feedforward control is used to compensate for it.

The algorithm of the disturbance observer is given by

$$\begin{bmatrix} \dot{z} \\ \hat{\tau}_d \end{bmatrix} = \begin{bmatrix} -\mathbf{LB}(z + \mathbf{L}\boldsymbol{x}) - \mathbf{L}(\mathbf{A}\boldsymbol{x} + \mathbf{B}u) \\ z + \mathbf{L}\boldsymbol{x} \end{bmatrix}, \tag{18}$$

where z is the internal state, $\mathbf{L}$ is the observer gain matrix, and $\hat{\tau}_d$ is the estimated disturbance torque [8].

If the DOBC control law is designed as

$$u = -\mathbf{K}\boldsymbol{x} - \hat{\tau}_d, \tag{19}$$

then the closed-loop compensated system becomes

$$\begin{bmatrix} \dot{\boldsymbol{x}} \\ \dot{\epsilon}_d \end{bmatrix} = \begin{bmatrix} \mathbf{A} - \mathbf{BK} & \mathbf{B} \\ \mathbf{0} & -\mathbf{LB} \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \epsilon_d \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ 1 \end{bmatrix} \dot{\hat{\tau}}_d, \tag{20}$$

where $\epsilon_d = \hat{\tau}_d - \tau_d$. The observer gain matrix L must be appropriately designed such that both $\mathbf{A} - \mathbf{BK}$ and $-\mathbf{LB}$ are Hurwitz matrices.

D. Fuzzy Fusion Framework

The Fuzzy Fusion Framework (FFF) draws inspiration from Mediative Fuzzy Logic, initially proposed to handle scenarios involving conflicting knowledge from multiple experts in a specific domain [9]. In such situations, a mediative solution offers a more optimal route to handle uncertainties [10]. Inspired by this concept, the multitasking FFF leverages fuzzy control principles to address situations with multiple disturbance rejection control schemes. Each controller is configured to handle specific process operating conditions. When conditions shift, a rule-based supervisor dynamically adjusts the controllers' influence. This mechanism reduces the reliance on the less-relevant controller while progressively increasing the weight assigned to the controller designed for the new operating regime.

While the FFF addresses uncertainties in the controller knowledge, it does not explicitly handle uncertainties inherent in the actual system dynamics. The efficacy of its uncertainty handling capabilities hinges on the individual controllers' robustness features and the fuzzy system's architecture itself. Here, Type-2 and Type-3 fuzzy logic systems could potentially enhance such capabilities. However, this work focuses on exploring the FFF's features within the framework of Type-1 fuzzy logic for clarity and initial investigation. The architecture of FFF is shown in Fig. 2.

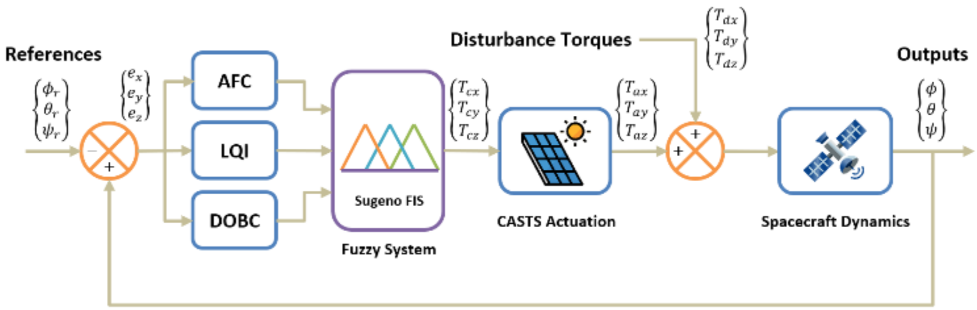

Fig. 2: Architecture of fuzzy fusion framework.

The FFF with three controllers consists of the three rules:

- Rule 1: If input $\bar{\theta}$ is Neg, then output u is AFC.
- Rule 2: If input $\bar{\theta}$ is Zero, then output u is LQI.
- Rule 3: If input $\bar{\theta}$ is Pos, then output u is DOBC.

The symbol $\bar{\theta}$ denotes the normalized attitude displacement, while u denotes the control output. The triangular fuzzy sets adjust rule firing strength based on the input sign association with membership grade, as illustrated in Figure 3.

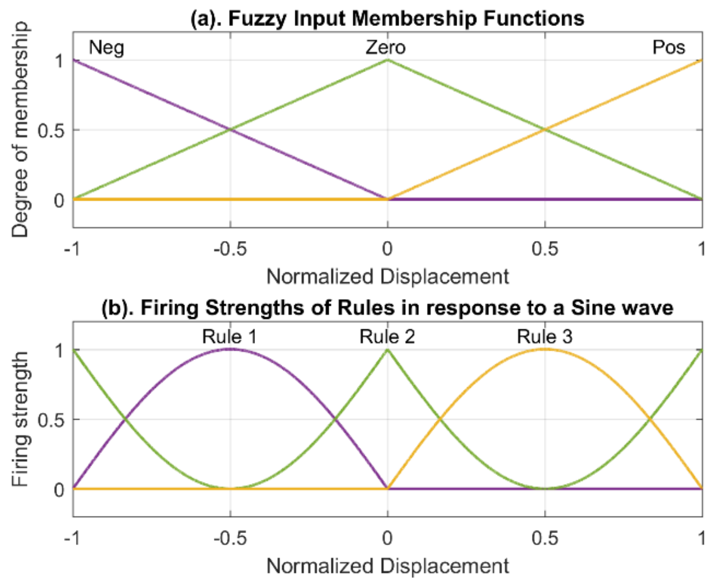

Fig. 3: Membership functions and firing strengths of rules.

4. RESULTS

A. *Case I: Active Force Control*

The control signal, the pitch angle response, and the angle of incidence for both north and south arrays under the AFC control scheme are shown in Figs. 4 to 6, respectively. The attitude accuracy at steady-state is 0.0004°. The angles of incidence are small, making the power loss also small.

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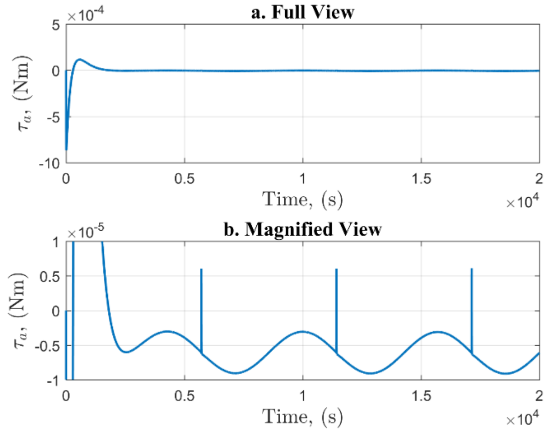

Fig. 4: Control signal under AFC.

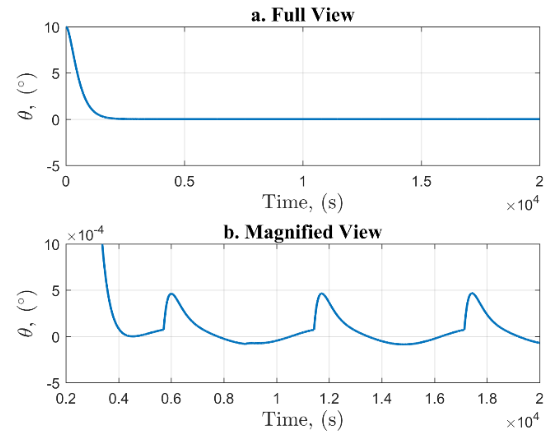

Fig. 5: Pitch angle response under AFC.

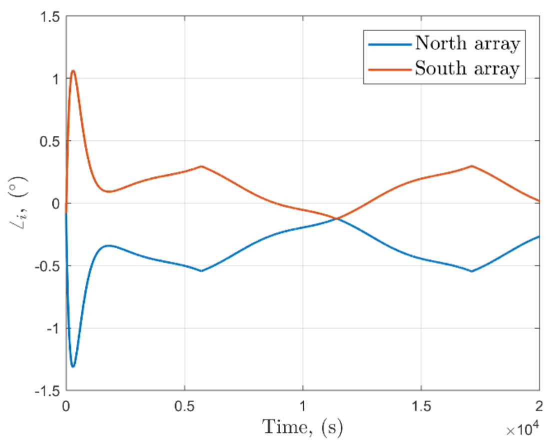

Fig. 6: Angles of incidence under AFC.

B. Case II: Linear Quadratic Integral

The control signal, the pitch angle response, and the angle of incidence for both north and south arrays under the LQI control scheme are shown in Figs. 7 to 9, respectively. The attitude accuracy at steady-state is 0.0007°, and the initial control torque by LQI is nearly ten times greater than the AFC.

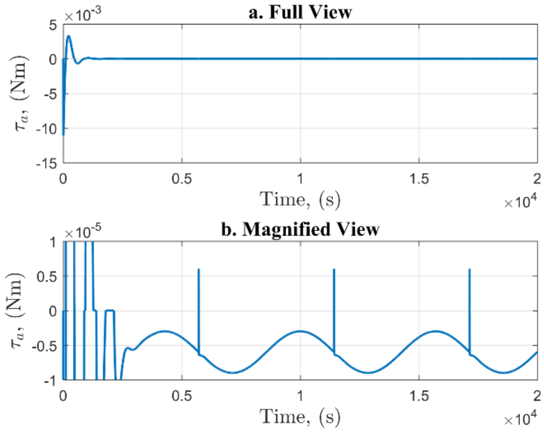

Fig. 7: Control signal under LQI.

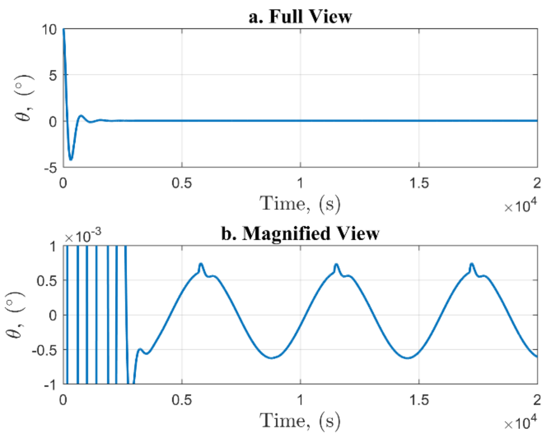

Fig. 8: Pitch angle response under LQI.

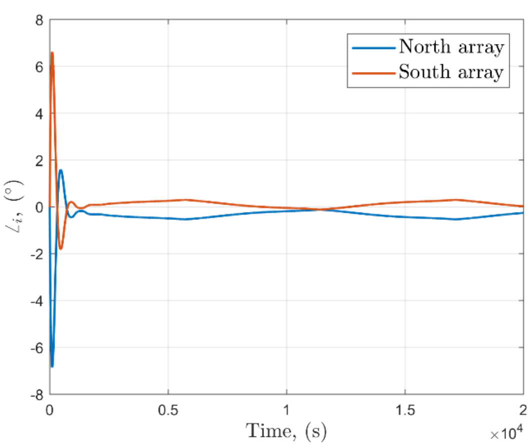

Fig. 9: Angles of incidence under LQI.

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C. Case III: Disturbance Observer-based Control

The control signal, the pitch angle response, and the angle of incidence for both north and south arrays under the DOBC control scheme are shown in Figs. 10 to 12, respectively. The attitude accuracy at steady-state is 0.0005°. The performances are almost the same as the AFC.

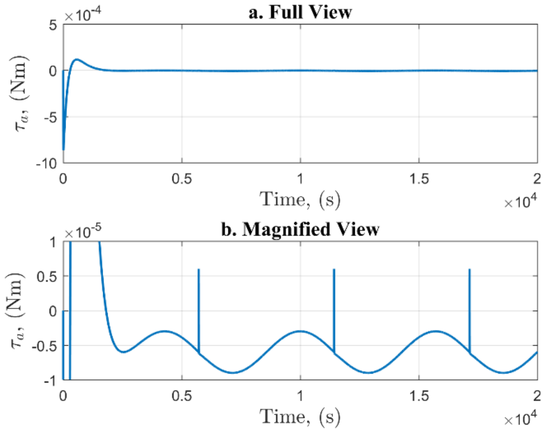

Fig. 10: Control signal under DOBC.

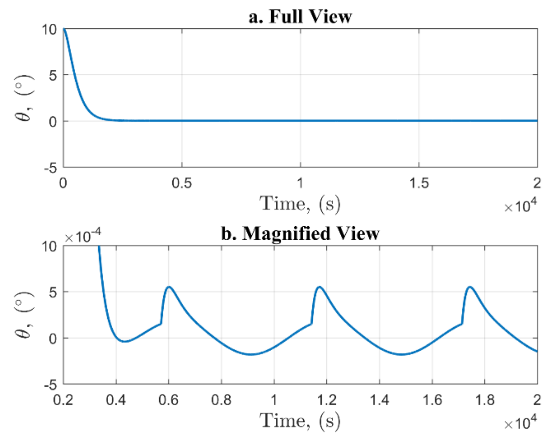

Fig. 11: Pitch angle response under DOBC.

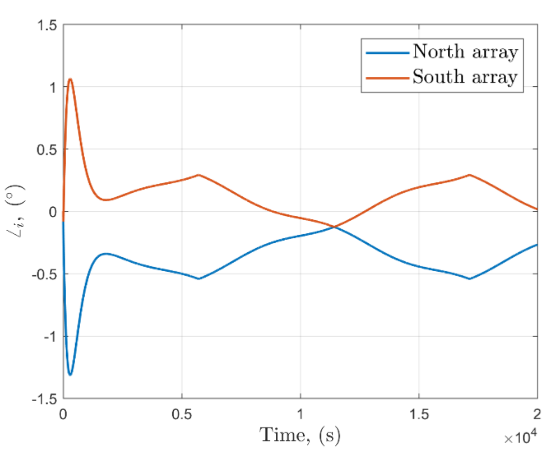

Fig. 12: Angles of incidence under DOBC.

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Volume 18, No. 2s, 2024
ISSN: 1750-9548

D. Case IV: Fuzzy Fusion Framework

The control signal, the pitch angle response, and the angle of incidence for both north and south arrays under the FFF control scheme are shown in Figs. 13 to 15, respectively. The attitude accuracy at steady-state is 0.0012°. The performances of the tri-mode control is quite oscillatory.

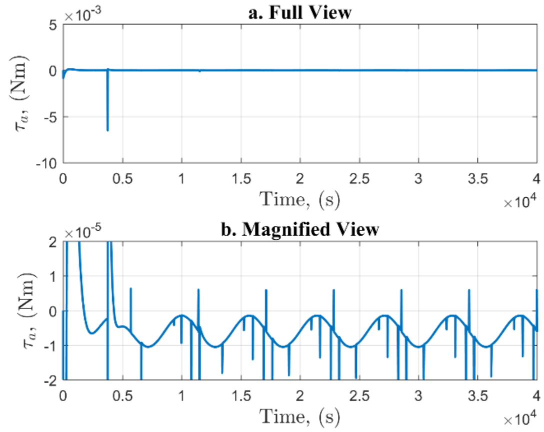

Fig. 13: Control signal under FFF.

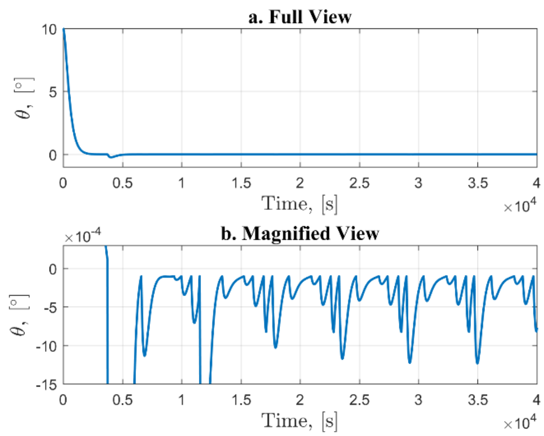

Fig. 14: Pitch angle response under FFF.

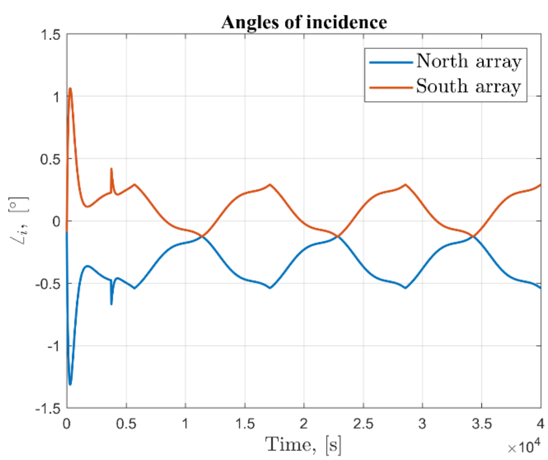

Fig. 15: Angles of incidence under FFF.

https://doi.org/10.52710/ijm.v18.i2s.952

The control performances for the disturbance compensation strategies are summarized in Table I.

TABLE I. PERFORMANCE COMPARISON OF CONTROLLERS

Type of Controller	Attitude Accuracy (max at steady-state)	Angle of Incidence (max at steady-state)
AFC	0.0004°	0.5486°
LQI	0.0007°	0.5438°
DOBC	0.0005°	0.5439°
FFF	0.0012°	0.5415°

This numerical test setup introduced a sinusoidal signal to simulate external disturbance torques perturbing the pitch dynamics. All three disturbance compensation schemes aimed to regulate the attitude angle within a strict threshold of 0.001 degrees. While the Active Force Control (AFC) achieved superior attitude accuracy compared to the Disturbance Observer-Based Control (DOBC), its reliance on angular accelerometer measurements may introduce unwanted noise in the control loop under practical conditions. Conversely, the DOBC, as a disturbance determination algorithm, estimates the unknown disturbance torque solely based on the pitch angle measurements provided by the attitude sensor.

The pitch angle response under the Fuzzy Fusion Framework (FFF) exhibits a distinctly oscillatory behavior, characterized by a frequency twice that of the individual disturbance compensation schemes. This higher frequency can be attributed to the continuous activation of both control modes, each employing different rule strengths. When the normalized attitude displacement falls below zero, the AFC-LQI mode assumes control. Conversely, a positive attitude displacement triggers the LQI-DOBC mode. While these specific combinations provide adequate disturbance rejection, potential for further optimization exists through exploration of alternative configurations of different control schemes. Notably, conventional disturbance compensation control laws effectively regulate the process under stable and near-nominal operating conditions. However, in the event of sudden perturbations or abnormal states within the satellite attitude control process, the FFF configuration emerges as a promising strategy to expedite the stabilization process's return to normal operation.

5. CONCLUSIONS

This work successfully demonstrated the design of disturbance compensation control laws for an accurate satellite attitude regulation under the external disturbance torques while simultaneously enabling Sun tracking via the CASTS actuator. Such disturbance compensation strategies are well-suited for satellite applications, with the specific choice depending on the mission requirements. Moreover, the multitasking Fuzzy Fusion Framework exhibits versatility as a precursor to an event-triggered smart switching hybrid disturbance rejection controller incorporating AFC, LQI, and DOBC, effectively maintaining attitude pointing accuracy under uncertain disturbances. Future work will focus on enriching the rule base to guarantee seamless transitions between the three operating control modes and implement deep learning algorithms to identify the optimal tri-mode configuration for specific uncertainty scenarios.

ACKNOWLEDGMENT

This work has been supported by the UPM Research University (RU) Grant.

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