Disturbance Observer-based Pointing Control of Leighton Chajnantor Telescope Postprint

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Date: 2024-02-01T00:00:00+00:00

Abstract

Leighton Chajnantor Telescope (LCT), i.e., the former Caltech Submillimeter Observatory telescope, will be refurbished at the new site in Chajnantor Plateau, Chile in 2023. The environment of LCT will change significantly after its relocation, and the telescope will be exposed to large wind disturbances directly because its enclosure will be completely open during observation. The wind disturbance is expected to be a challenge for LCT' s pointing control since the existing control method cannot reject this disturbance very well. Therefore, it is very necessary to develop a new pointing control method with good capability of disturbance rejection. In this research, a disturbance observer—based composite position controller (DOB-CPC) is designed, in which an H∞ feedback controller is employed to compress the disturbance, and a feedforward linear quadratic regulator is employed to compensate the disturbance precisely based on the estimated disturbance signal. Moreover, a controller switching policy is adopted, which applies the proportional controller to the transient process to achieve a quick response and applies the DOB-CPC to the steady state to achieve a small position error. Numerical experiments are conducted to verify the good performance of the proposed pointing controller (i.e., DOB-CPC) for rejecting the disturbance acting on LCT.

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:015010 (16pp), 2024 January

https://doi.org/10.1088/1674-4527/ad0826

Disturbance Observer-based Pointing Control of Leighton Chajnantor Telescope

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Received 2023 September 2; revised 2023 October 18; accepted 2023 October 27; published 2023 December 13

Abstract

The Leighton Chajnantor Telescope (LCT), formerly the Caltech Submillimeter Observatory telescope, will be refurbished at its new site on the Chajnantor Plateau, Chile, in 2023. The environment of LCT will change significantly after relocation, and the telescope will be exposed directly to large wind disturbances because its enclosure will be completely open during observation. Wind disturbance is expected to pose a major challenge for LCT’ s pointing control, as the existing control method cannot reject this disturbance effectively. Therefore, developing a new pointing control method with strong disturbance rejection capability is essential. In this research, we design a disturbance observer-based composite position controller (DOB-CPC) that employs an H∞ feedback controller to suppress disturbance and a feedforward linear quadratic regulator to precisely compensate for disturbance based on the estimated disturbance signal. Moreover, a controller switching policy is adopted, which applies a proportional controller during the transient process to achieve quick response and applies the DOB-CPC during steady state to achieve small position error. Numerical experiments verify the excellent performance of the proposed pointing controller (i.e., DOB-CPC) in rejecting disturbances acting on LCT.

Key words: instrumentation: miscellaneous –methods: analytical –methods: numerical –telescopes

1. Introduction

The Caltech Submillimeter Observatory (CSO) telescope was decommissioned in 2015 and will be moved from its old site at Maunakea, Hawaii, to its new site at the Chajnantor Plateau, Chile, in 2023. After relocation, the CSO telescope will be refurbished and renamed as the Leighton Chajnantor Telescope (LCT) (Vial et al. 2020; Chen et al. 2022). However, this relocation and refurbishment will present new challenges for LCT’ s pointing control system, as it must resist strong wind disturbances at the new site, which has an average wind speed of 10 m s^{-1}, a maximum instantaneous wind speed of 30 m s^{-1}, and more frequent wind speed fluctuations (ALMA 2010). Additionally, LCT will operate with its enclosure completely open because it is required to observe a larger area of the sky to achieve new scientific goals (Caltech et al. 2016).

To achieve high pointing accuracy at the new site under strong wind loads, LCT' s pointing control system must maintain the azimuth and elevation angles of LCT' s antenna within sufficiently small deviations from the target source position. As a submillimeter radio telescope with a 10.4 m-diameter antenna receiving radiation at wavelengths from 2 mm to 350 m, LCT requires a pointing error below 3 (i.e., 0.000833°) to achieve its scientific goals, which means the root mean square (rms) of the antenna' s position error must be less than 3 . However, this pointing accuracy is very difficult to achieve under strong wind loads. Testing the existing proportional feedback controller on LCT's simulation model (Chen & Wang 2022) shows that the rms of the azimuth angle error exceeds 3 when wind speeds above 10 m s^{-1} are introduced. Clearly, the existing feedback controller cannot satisfy the pointing accuracy requirement when the telescope is fully exposed to high-speed winds. Therefore, improving LCT' s position controller is necessary to maintain pointing accuracy at the new site.

Few studies have employed advanced control methods for astronomical telescopes' pointing control systems. In practice, the traditional proportional-integral (PI) controller is the most popular choice due to its convenience for implementation (Ravensbergen 1994; Burns 1995; Gawronski 2001; Ranka et al. 2016), although it is sensitive to wind disturbance. Over the past decades, many scientists and engineers have devoted significant effort to improving controller performance to make radio telescopes more accurate and robust against external disturbances. On one hand, model-free control methods have been developed since they have no strict requirements on the accuracy of telescopes' pointing control system models. For example, the active disturbance rejection controller (ADRC) is designed based on the classical feedback control framework. With the help of a tracking differentiator, feedback control law, and extended state observer (ESO), ADRC can handle both internal uncertainty (e.g., system nonlinearity) and external disturbance (e.g., wind disturbance) (Qiu et al. 2014; Ranka et al. 2015; Guo et al. 2016; Feng & Guo 2017; Deng et al. 2018; Li et al. 2019). However, as the core of ADRC, the ESO can only estimate rough disturbance signals and is very sensitive to parameter tuning since it is not designed based on the system model.

On the other hand, as more methods have been developed to identify models of telescopes' pointing control systems, it has become feasible to employ model-based control methods to improve robustness. The Linear-Quadratic-Gaussian (LQG) controller is a model-based optimal control method widely applied to many modern radio telescopes, including the Deep Space Network (DSN) (Gawronski et al. 1994; Maneri & Gawronski 2000), the Green Bank Telescope (GBT) (Gawronski & Parvin 1995), the Large Millimeter Telescope (LMT) (Gawronski & Souccar 2005), the Telescope Nazionale Galileo (TNG) (Schipani et al. 2020), and the 110 m QiTai radio Telescope (QTT) (Li et al. 2017). The introduction of the LQG controller effectively restrains vibration in these radio telescopes, reducing position control error under wind disturbance compared to PI controllers. Since the H_2 norm limits the performance of the LQG controller, the H∞ controller was proposed by replacing the H_2 norm with the H∞ norm to further improve optimal controller performance (Gawronski 2001).

Although many model-free or model-based control methods have been applied to telescopes' pointing control systems, disturbance effects can hardly be eliminated since disturbances are not accurately estimated. Chen & Wang (2022) designed an H∞ controller for LCT' s pointing control system to improve wind disturbance rejection. Simulation results showed that although the H∞ controller could significantly compress the antenna' s position error, it still could not precisely eliminate wind disturbance. Therefore, to precisely eliminate wind disturbance, we design a disturbance observer (DOB) to realize accurate estimation of wind disturbance, based on which we propose a new disturbance observer-based controller (DOBC) for LCT to achieve better disturbance rejection performance.

DOBC offers a feasible method for reducing negative influences from external disturbance and internal uncertainty by utilizing the estimated disturbance from the DOB and feeding it forward to the control signal of an electromechanical system (Choi et al. 2003; Chen et al. 2016). DOBC has been applied to many real-world systems, including permanent magnet synchronous motors (PMSM) (Dai et al. 2021), missile seekers (Sadhu & Ghoshal 2011), unmanned aerial vehicles (UAV) (Huang & Chen 2022; Tripathi et al. 2022), overhead cranes (Wu et al. 2020), ship-mounted tower cranes (Qian & Fang 2019), cars with active suspension systems (Pan et al. 2016), and dual-flexible manipulators with telescopic arms (Shang et al. 2022).

To generate a compensation control signal based on the estimated disturbance, most research on DOBC design (Sadhu & Ghoshal 2011; Pan et al. 2016; Qian & Fang 2019; Wu et al. 2020; Huang & Chen 2022; Shang et al. 2022; Tripathi et al. 2022) simply assumes that the control signal (i.e., the controller output rather than the actuator output) and the disturbance signal are of the same type (e.g., both are torques or both are forces). Based on this assumption, the estimated disturbance signal (i.e., the DOB output) is directly utilized as a compensation control signal (by taking its negative value) and simply combined with the feedback control signal. For example, Pan et al. (2016), Qian & Fang (2019), and Wu et al. (2020) ideally consider the feedback control signal to be force, and the disturbance acting on the controlled object is also considered as force, so the estimated disturbance signal can be directly utilized as the compensation control signal.

However, in realistic control systems, the controller output is an electric signal (e.g., voltage) rather than force or torque. The controller output is sent to the actuator, which transforms the control signal into force or torque that directly controls the object. Therefore, to compensate for disturbance, the DOB output, which represents some physical quantity (e.g., force or torque), must be transformed into a compensation control signal that will be sent to the actuator and transformed into the physical quantity (e.g., force or torque) acting on the controlled object.

Some researchers have designed a compensation gain (Chen et al. 2016) or a nonlinear continuous function (Dai et al. 2021) to transform the estimated disturbance signal into a compensation control signal. In this paper, we construct an optimal tracking control model with a linear quadratic regulator to generate a precise compensation control signal that can make the actuator output a physical quantity relatively close to the estimated disturbance, such that the disturbance can be compensated.

The rest of this paper is organized as follows. In Section 2, the model of LCT' s pointing control system is constructed with the vibration modes of the antenna, specifically the first-order and second-order vibration modes. Section 3 presents the design of the DOBC based on the model of LCT' s pointing control system. Section 4 provides simulation results and analysis to verify the performance of the DOBC. Section 5 concludes the paper and outlines future research directions.

2. Model of LCT's Pointing Control System with Structural Vibration Modes

An accurate model of LCT' s pointing control system is very important for the design of the position controller. LCT' s pointing control system model was constructed in our previous work (Chen & Wang 2022), which consists of the position controller, DC motor, reducer box, and antenna.

There are two major vibration modes of the LCT antenna: the low-frequency flexible mode (i.e., the first-order vibration mode of the antenna) and the main structural vibration mode of the main reflector (i.e., the second-order vibration mode of the antenna). In our previous work, the first-order vibration mode was already considered since it is the low-frequency flexible mode resulting from flexible connections between the DC motor and reducer and between the reducer and antenna when the antenna is regarded as a rigid body. Thus, the dynamic equation of the first-order vibration mode can be formulated as shown in Equation (1). For clarity, this paper only considers position control in azimuth, though the developed method can also be applied to elevation control.

$$J_A\ddot{\theta}_1 + D_1\dot{\theta}_1 + K_{RDC}(\theta_1 - \theta_{DCM}) = T_{RDC} \quad (1)$$

where J_A is the moment of inertia of the LCT antenna, D_1 is the damping of the rigid body of the LCT antenna, K_{RDC} is the stiffness of the reducer that accounts for flexible connections among the DC motor, reducer, and antenna, T_{RDC} is the output torque of the reducer, θ_{DCM} is the rotation angle of the DC motor, and θ_1 is the output azimuth angle of the rigid body of the LCT antenna. Equation (1) can be reformulated as:

$$J_A\ddot{\theta}_1 + D_1\dot{\theta}_1 = T_{RDC} - K_{RDC}(\theta_1 - \theta_{DCM}) \quad (2)$$

Applying the Laplace transform to both sides of Equation (2) yields:

$$J_A s^2\theta_1(s) + D_1 s\theta_1(s) = T_{RDC}(s) - K_{RDC}(\theta_1(s) - \theta_{DCM}(s)) \quad (3)$$

Therefore, the transfer function of the first-order mode is:

$$\frac{\theta_1(s)}{T_{RDC}(s)} = \frac{1}{J_A s^2 + D_1 s + K_{RDC}} \quad (4)$$

where $J_A = 160560\,\mathrm{kg}\cdot\mathrm{m}^2$, $D_1 = 1.7827 \times 10^6\,\mathrm{N}\cdot\mathrm{m}\cdot\mathrm{rad}^{-1}\cdot\mathrm{s}$, and $K_{RDC} = 1.07 \times 10^9\,\mathrm{N}\cdot\mathrm{m}\cdot\mathrm{rad}^{-1}$. The natural frequency is $f_1 \approx 3.32\,\mathrm{Hz}$, which is also verified by modal analysis of LCT using Ansys 2022.

Although flexible connections among the DC motor, reducer, and antenna are considered in the first-order mode, the antenna is still assumed to be a rigid body, whereas LCT' s antenna in reality is a flexible body that may experience deformations of the main reflector under wind and gravity. Therefore, to better describe the flexibility of LCT' s antenna, we introduce the structural vibration mode (related to vibration of the main reflector) as the second-order vibration mode to extend the pre-established rigid body antenna model. By analyzing the vibration modes of LCT' s antenna with Ansys 2022, we find that the natural frequency of the main structural vibration mode is 13.004 Hz. Introducing this main structural vibration mode, the extended LCT antenna model can be formulated as:

$$\begin{cases} J_A\ddot{\theta}_1 + D_1\dot{\theta}_1 + K_2(\theta_1 - \theta_2) = T_L \\ J_2\ddot{\theta}_2 + D_2\dot{\theta}_2 + K_2(\theta_2 - \theta_1) = 0 \end{cases} \quad (5)$$

where J_A is the moment of inertia of LCT' s antenna in azimuth, D_1 and D_2 are the damping coefficients of the rigid body and main structural vibration mode respectively, K_2 is the stiffness of the main structural vibration mode, θ_1 and θ_2 are the output azimuth angles of the rigid body and main structural vibration mode respectively, θ_A is the azimuth angle of LCT' s antenna (in $\mathrm{rad}\cdot\mathrm{s}^{-1}$), and T_L is the load torque of LCT' s antenna. Among these parameters, $J_A = 160560\,\mathrm{kg}\cdot\mathrm{m}^2$, $D_1 = 1.7827 \times 10^6\,\mathrm{N}\cdot\mathrm{m}\cdot\mathrm{rad}^{-1}\cdot\mathrm{s}$, and $K_{RDC} = 1.07 \times 10^9\,\mathrm{N}\cdot\mathrm{m}\cdot\mathrm{rad}^{-1}$ are already known (Chen & Wang 2022). D_2 and K_2 can be calculated from the following equations (Gawronski 2008):

$$D_2 = 2\zeta_2\sqrt{K_2 J_A} \quad (6)$$

$$K_2 = J_A \omega_2^2 \quad (7)$$

where $\zeta_2 = 0.01$ is the damping ratio of the main structural vibration mode, and the angular velocity ω_2 of the main structural vibration mode is:

$$\omega_2 = 2\pi f_2 = 81.7065\,\mathrm{rad}\cdot\mathrm{s}^{-1} \quad (8)$$

where $f_2 = 13.004\,\mathrm{Hz}$ is the natural frequency of the structural vibration mode (i.e., the second-order vibration mode of the antenna).

Applying Laplace transforms to Equations (6) and (7), the input-output model of LCT' s antenna can be obtained as:

$$\frac{\theta_A(s)}{T_L(s)} = \frac{1}{J_A s^2 + D_1 s} \cdot \frac{J_2 s^2 + D_2 s + K_2}{K_2} \quad (9)$$

By integrating the model of LCT' s antenna with two major vibration modes into the pre-established LCT pointing control system model (Chen & Wang 2022), we obtain the extended open-loop model of the pointing control system as shown in Figure 1 [Figure 1: see original paper].

Note that $T_L = T_s$ if wind disturbance is not introduced to the system, where T_s is the output torque of the DC motor and reducer. Assuming $x_1 = I_{ARM}$, $x_2 = \omega_{DCM}$, $x_3 = \theta_{DCM}$, $x_4 = \theta_1$, $x_5 = \omega_{A1}$, $x_6 = \theta_2$, $x_7 = \omega_{A2}$, where I_{ARM} is the armature current of the DC motor, ω_{DCM} is the rotating speed of the DC motor, ω_{A1} and ω_{A2} are the rotating speeds of the rigid body and main structural vibration mode of the antenna respectively, and θ_{DCM} is the rotation angle of the DC motor. Then the state-space model of LCT' s pointing control system with the extended antenna model can be written as:

$$\dot{x}_i = A_s x_i + B_s u_c + B_{s,d} T_d \quad (12)$$

$$y = C_s x_i \quad (13)$$

$$T_L = C_{s,l} x_i \quad (14)$$

where x_i ($i = 1 \dots 7$) are the system states, y is the system output (i.e., the antenna position in azimuth, or azimuth angle, in degrees), u_c is the control input (i.e., the command voltage with maximum value U_{COM}), and the parameters of Equations (12)-(14) are listed in Table 1 . Note that T_L in Equations (12) and (14) is the load torque of the reducer, and T_L/N is the load torque of the DC motor.

It should be noted that the value of K_{DCM} (i.e., the torque coefficient of the DC motor) in Table 1 is twice the value of a single DC motor because there are two DC motors in the azimuth channel of the real-world LCT pointing control system to eliminate backlash in the speed reduction system, and they are equivalent to one DC motor in this model.

From Equations (12)-(14), the state-space model of LCT' s pointing control system with the extended antenna model can be formulated as:

$$\dot{x} = A_s x + B_s u_c + B_{s,d} T_d \quad (15)$$

$$y = C_s x \quad (16)$$

where $x = [x_1, x_2, x_3, x_4, x_5, x_6, x_7]^T$ is the state vector, and A_s, B_s, C_s, D_s are the system parameter matrices formulated as follows:

[The matrices would be shown here with proper formatting]

3. Design of the DOB-Based Position Controller

Two types of disturbances exist in LCT' s pointing control system: external disturbance (i.e., wind load) and internal disturbance (i.e., vibration of the flexible antenna structure). These disturbances are coupled when acting simultaneously. Since the DOB is known for its excellent performance in accurately estimating both external and internal disturbances, the negative impacts can be largely rejected if a well-designed DOB-based position controller (i.e., a position controller composed of a DOB-based feedforward controller and a feedback controller) is employed. Hence, this section focuses on designing the DOB-based controller for LCT' s pointing control system.

First, we design a time-domain DOB to estimate the composite disturbance generated by both external disturbance (wind load) and internal disturbance (structural vibration modes). Second, a suitable linear-quadratic-regulator (LQR)-based feedforward controller is designed to compensate for the disturbance estimated by the DOB. Finally, we design a composite DOB-based position controller by integrating the feedforward controller and feedback controller, along with a controller switching policy to maintain good transient and steady-state performance while rejecting external and internal disturbances.

3.1. The Time Domain DOB (TD-DOB)

Two types of DOB exist: frequency domain DOB (FD-DOB) and time domain DOB (TD-DOB) (Li et al. 2016). Taking the antenna as the controlled object, the key idea of FD-DOB can be explained as follows: If we know the nominal model of the antenna, we can estimate the nominal input torque signal from the inverse of the transfer function of the antenna' s rigid model and the measured output azimuth angle. In the absence of external disturbance (wind disturbance) and internal disturbance (vibration of the flexible structure), this estimated input torque signal should be consistent with the output torque signal of the motor and reducer. However, in practice, the antenna' s input torque is affected by external disturbance torque (such as wind disturbance), and the antenna' s flexible modes cause fluctuations in the output azimuth angle, making the actual input torque differ from the nominal input torque. The input torque disturbances caused by internal and external disturbances can then be obtained by differentiating the actual output torque from the calculated nominal input torque. By estimating and compensating for these input torque disturbances through motor regulation, the negative effects on the pointing control system can be counteracted to some extent.

TD-DOB is another formulation of the DOB. Similar to FD-DOB, TD-DOB uses model information and input/output signals to extract disturbance signals. Therefore, TD-DOB also requires a nominal antenna model, measured output azimuth angle, and output torque signal from the motor and reducer. However, unlike FD-DOB, which directly utilizes the inverse of the transfer function to estimate disturbance in the frequency domain, TD-DOB is constructed in the time domain by augmenting the antenna model in state-space form through introducing a disturbance term, and thus constructing an observer to estimate the augmented state including disturbances.

Considering that TD-DOB is convenient to implement on embedded hardware platforms, we adopt TD-DOB for disturbance estimation. To estimate the composite disturbance generated by both external disturbance (wind load) and internal disturbance (structural vibration modes), we take the rigid body model of LCT' s antenna as the nominal model, which can be obtained from Equation (12) as the following state-space equations:

$$\dot{x}_n = A_n x_n + B_n T_s \quad (17)$$

$$y_n = C_n x_n \quad (18)$$

where $x_n = [\theta_1, \omega_{A1}]^T$ is the state vector of the rigid body model of the antenna, T_d is the torque generated by wind load, and A_n, B_n, C_n are system parameter matrices defined as:

[Matrix definitions would appear here]

To facilitate implementation on embedded hardware platforms, inspired by Yang et al. (2017), the TD-DOB is designed as:

$$\hat{T}_d = z + L x_n \quad (19)$$

$$\dot{z} = -LB_nT_s - LA_nx_n + LB_n\hat{T}_d \quad (20)$$

where $\hat{T}_d$ is the estimated torque of internal and external disturbance, $L > 0$ is the TD-DOB gain matrix to be designed, z is the auxiliary variable of the DOB, and T_s is the nominal load torque of LCT' s antenna without disturbances. It should be noted that T_s can hardly be measured directly and must be calculated from the antenna position $\theta_A = \theta_1 + \theta_2$ and motor speed ω_{DCM} as:

$$T_s = K_{RDC}(\theta_{DCM} - \theta_A) \quad (21)$$

Moreover, a first-order low-pass filter is designed to provide a proper estimated disturbance signal for designing a realizable feedforward controller:

$$\dot{\hat{T}}_{do} = -\lambda\hat{T}_{do} + \lambda\hat{T}_d \quad (23)$$

where $\lambda \in \mathbb{R}^+$ is the parameter of the first-order low-pass filter. Therefore, the ultimate output signal $\hat{T}_{do}$ of the TD-DOB is:

$$\hat{T}_{do} = \frac{\lambda}{s+\lambda}\hat{T}_d \quad (24)$$

By combining Equations (19)-(24), the overall TD-DOB structure is designed as shown in Figure 2 [Figure 2: see original paper]. The designed TD-DOB can estimate composite external and internal disturbances since the output of the whole antenna model, rather than just the rigid body part, is input to the TD-DOB.

3.2. LQR-Based Feedforward Controller for the DOB (LQR-DOB)

The TD-DOB output (i.e., $\hat{T}_{do}$ in Equation (24)) estimates the torque generated by composite external and internal disturbances, which will be used to design a feedforward controller to compensate for the real disturbance. A straightforward idea is that if we can design a feedforward controller such that the actuator output torque (including driver, DC motors, and reducer) can accurately track $\hat{T}_{do}$, then the disturbance-generated torque will be well compensated.

Based on LCT' s pointing control system captured by Equation (15), we construct a state-space model representing the relationship between the feedforward control signal (denoted by u_d) and the actuator output torque (denoted by $\tilde{T}_d$) as:

$$\dot{x}_g = A_gx_g + B_gu_d \quad (25)$$

$$\tilde{T}_d = C_g x_g \quad (26)$$

where $x_g = [I_{ARM}, \omega_{DCM}, \theta_{DCM}]^T$ is the state vector containing armature current, rotating speed, and rotating angle of the DC motor, and matrices A_g, B_g, C_g are formulated as:

[Matrix definitions would appear here]

To make $\tilde{T}_d$ accurately track the DOB output $\hat{T}_{do}$, a linear quadratic optimal tracking control problem is formulated as:

$$\min_{u_d} J = \int_0^{\infty} \left(e(t)^T Q e(t) + u_d(t)^T R u_d(t) \right) dt \quad (27)$$

subject to:

$$\dot{x}_g = A_g x_g + B_g u_d, \quad x_g(0) = x_{d0} \quad (28)$$

where $e(t)$ is the tracking error, $Q \in \mathbb{R}^{n \times n}$ is the tracking error weight matrix, $R \in \mathbb{R}^{m \times m}$ is the feedforward control signal weight matrix, and x_{d0} is the initial system state.

According to optimal control theory (Lewis et al. 2012), a linear quadratic regulator (LQR) can generate the approximate optimal control signal as:

$$u_d(t) = -R^{-1} B_g^T P x_g(t) + R^{-1} B_g^T \hat{x}_d(t) \quad (30)$$

where $\hat{P}$ is a positive definite matrix satisfying the Algebraic Riccati Equation (ARE):

$$A_g^T P + P A_g - P B_g R^{-1} B_g^T P + C_g^T Q C_g = 0 \quad (31)$$

Define $K_1 = R^{-1} B_g^T P$ and $K_2 = R^{-1} B_g^T$, then the LQR-based feedforward controller for the DOB (LQR-DOB) can be finally designed as shown in Figure 3 [Figure 3: see original paper], where the estimated disturbance is the input and $u_d(t)$ is the output. Note that the amplitude of control signal $u_d(t)$ can be limited by adjusting parameters Q and R.

3.3. DOB-Based Composite Position Controller with Controller Switching Policy (DOB-CPC with CSP)

To reject disturbance from LCT' s pointing control system, the TD-DOB, LQR-based feedforward controller, and feedback controller are combined as the DOB-based composite position controller to replace the existing position controller (which is a proportional controller). Therefore, the control signal u_c generated by DOB-CPC consists of two parts: the feedback control signal u_b and the feedforward control signal u_d.

The first part is the feedback control signal u_b from the feedback controller (i.e., the existing proportional feedback controller or the H∞ feedback controller proposed in our previous work (Chen & Wang 2022)), which calculates the control signal based on LCT' s antenna position error. As LCT' s pointing control system is captured by Equation (15), the H∞ feedback controller can be obtained in many ways. Here, the H∞ loop-shaping technique (Glover & McFarlane 1989; Sefton & Glover 1990; Feyel 2013) is used to design the H∞ feedback controller based on LCT' s pointing control system model because it is easy to implement by designing three loop-shaping weighting filters W_1, W_2, W_3 with the help of MATLAB Robust Control Toolbox. As shown in Figure 4 [Figure 4: see original paper], the error signal e, control signal u, and output signal y are input to loop-shaping weighting filters W_1, W_2, W_3 (which can be set as constant, high-pass, or low-pass filters) respectively to generate robustness measures z_1, z_2, z_3 (which are parts of the infinity norm of the closed-loop transfer function of the augmented model). Since the H∞ feedback controller design aims to minimize the infinity norm of the closed-loop transfer function, the error signal e, control signal u_c, and output signal y can be adjusted by tuning W_1, W_2, W_3 respectively.

The second part is the feedforward control signal u_d from the LQR-based feedforward controller, obtained based on the estimated disturbance signal $\hat{T}_{do}$ from TD-DOB. Hence, DOB-CPC not only utilizes the feedback controller' s characteristics to quickly eliminate position error but also compensates for disturbance to further reduce position fluctuation.

Furthermore, as shown in the step response plots in Figure 5 [Figure 5: see original paper], the H∞ feedback controller and LQR-based feedforward controller negatively impact transient process rapidity, especially under high-speed wind disturbances, although they greatly enhance disturbance rejection capability. Specifically, in the absence of wind disturbances (see Figure 5(a)), the transient process with the H∞ feedback controller is longer compared to the proportional (P) controller, while the LQR-based feedforward controller does not affect the pointing control system' s transient performance. However, this situation changes significantly when facing large wind disturbances (see Figure 5(b)). In addition to the H∞ feedback controller' s negative impact on transient performance, the LQR-based feedforward controller (LQR-DOB) often generates overcompensation during the transient process, leading to significant response delays.

Thus, considering that the existing proportional controller is the fastest (since the control signal is maintained at maximum level), we propose a controller switching policy (CSP) for DOB-CPC. The key idea of CSP is to activate the H∞ feedback controller and LQR-based feedforward controller only when the antenna position is within a certain range around the desired position (e.g., the orange area shown in Figure 6 [Figure 6: see original paper]); otherwise, the existing proportional feedback controller operates.

To utilize different controllers for transient and steady-state stages respectively, CSP has the following form:

$$u_c = \begin{cases} u_p, & |e_r| > \Delta h \\ k_b u_b + k_f u_d, & |e_r| \le \Delta h \end{cases} \quad (34)$$

where e_r is the antenna position error, $\Delta h \in [0, r]$ is the position error threshold for activating H∞ feedback control (which can also be replaced by the existing proportional feedback control) and feedforward control, u_b is the feedback control signal, u_p is the control signal from the existing proportional feedback controller, u_d is the feedforward control signal from the LQR-DOB, k_b is the feedback control weight, and k_f is the feedforward control weight. The equation satisfying $|e_r| > \Delta h$ is for the transient process, while $|e_r| \le \Delta h$ is for the steady-state process. By employing CSP, the DOB-CPC structure is depicted as the blue block in Figure 7 [Figure 7: see original paper].

4. Simulation Results and Analysis

4.1. Experiment Design

The experiment is divided into two parts: (1) **Mathematical Simulation Experiment**: MATLAB/Simulink is used to test the proposed composite DOB-based position controller based on the mathematical model of LCT' s pointing control system (whose antenna model includes rigid body and main structural mode). This experiment tests and compares the performance of four position controllers (listed in Table 2) under wind disturbance. (2) **Collaborative Simulation Experiment**: Due to LCT' s unavailability during relocation, we developed a collaborative simulation testbed (Yao et al. 2023) to verify the proposed DOB-CPC (H∞+LQR-DOB) by introducing a pre-constructed multibody dynamic model of the antenna.

The collaborative simulation testbed reflects the complex multimodal characteristics of the antenna and their impacts on the entire pointing control system dynamics. (Without Adams, the complex multimodal characteristics can only be analyzed statically in Ansys, which cannot analyze their influence on system dynamics.)

As described in our previous research (Yao et al. 2023), the Adams model is constructed based on LCT' s Ansys model. Specifically, as shown in Figure 8 [Figure 8: see original paper], we first constructed LCT' s mechanical structure using SpaceClaim (a 3D modeling tool within Ansys). The mechanical structure has two categories: rigid bodies and flexible bodies. Rigid bodies are well supported by Adams and can be imported directly. Flexible bodies are difficult to import directly since Adams is not adept at building complex structural bodies. Therefore, we use Ansys to transform LCT' s mechanical structure model into a finite element model and perform modal analysis to obtain the modal neutral file of flexible bodies. Finally, with Adams, rigid bodies (imported directly) and flexible bodies (imported via modal neutral file) are integrated by applying fixed joints to contact surfaces.

With the established Adams model, the simulation testbed can reflect the complex multimodal characteristics of the antenna in Simulink and their impacts on system dynamics. Based on the existing pointing control system model, we replace the state-space formulation of the antenna with its multibody dynamics model constructed using Adams (Yao et al. 2023) to reduce the gap between simulation and reality. The multibody dynamics model has the same properties (material, dimensions, structures, density, and stiffness) as the real antenna based on on-site measurements and the Ansys model provided by Chilean colleagues (see Acknowledgments), ensuring model accuracy. Then, through collaborative simulation combining MATLAB/Simulink and Adams, we further verify the proposed DOB-CPC (H∞+LQR-DOB) on the collaborative simulation testbed (integrating mathematical and multibody dynamics models, as shown in Figure 9 [Figure 9: see original paper]).

Wind disturbance consists of wind gust (captured by wind speed fluctuation Δv_w) and steady wind (captured by average wind speed v_w), where wind gust is the main factor causing position error increase. Therefore, constructing a good wind gust model is important. A Davenport filter is introduced, designed following the instructions in Section 3 of Chen & Wang (2022). The white noise power (source of Davenport filter) and average wind speed are adjustable to generate wind disturbances of different average speeds and fluctuation amplitudes.

According to climate conditions at the new Chajnantor Plateau site, wind speed changes slowly during a day, with maximum wind speed fluctuation amplitude of 5 m s^{-1} (i.e., wind speed fluctuates from 6 to 11 m s^{-1} during winter days) (ALMA 2010). Additionally, the average wind speed is 10 m s^{-1}, and maximum wind speed is 30 m s^{-1} (ALMA 2010). Based on this information, we test and compare position control performance of four controllers under different average wind speeds (10, 15, and 20 m s^{-1}) and wind gust fluctuation amplitudes (2, 6, and 10 m s^{-1}). For convenience, wind gust fluctuation amplitude is measured by (see Figure 10 [Figure 10: see original paper]):

$$\Delta A_{vw} = \frac{\Delta v_{w,\max} - \Delta v_{w,\min}}{2} \quad (35)$$

where ΔA_{vw} is wind gust fluctuation amplitude, $\Delta v_{w,\max}$ is maximum wind gust fluctuation, and $\Delta v_{w,\min}$ is minimum wind gust fluctuation.

Wind speed is converted to equivalent wind disturbance torque (T_d) applied to the antenna' s azimuth axis by multiplying a conversion factor (calculated based on antenna wind area, static air density, and wind direction) according to the method in Chen & Wang (2022).

For fair comparison, all controllers are well-tuned and tested under identical conditions (same target antenna position, same pointing control system model, and same wind disturbance). We observe the output of LCT' s pointing control system model (i.e., antenna position) with different controllers (existing proportional feedback controller, H∞ feedback controller, DOB-CPC with existing proportional feedback controller, and DOB-CPC with H∞ feedback controller) when the target azimuth angle is set to 10°.

Controllers are pre-configured as follows: First, the existing proportional feedback controller formulation and parameters are kept as given in the original technical report (Leighton 1977). Second, the H∞ feedback controller is redesigned based on the state-space model of the pointing control system with vibration modes (see Equations (12)–(14)) using the following loop-shaping weighting filters W_1, W_2, W_3: (1) W_1 is a low-pass filter with low-frequency gain (LFG) of 5000 (i.e., 74 dB), 0 dB magnitude frequency of 5 rad $\cdot$ s^{-1}, and high-frequency gain (HFG) of 0.1 (i.e., -20 dB); (2) W_2 is a constant equivalent to 0.000001; (3) W_3 is a high-pass filter with LFG of 0.1 (i.e., -20 dB), 0 dB magnitude frequency of 6 rad $\cdot$ s^{-1}, and HFG of 5000 (i.e., 74 dB). The Bode diagram of W_1 and W_3 is illustrated in Figure 11 [Figure 11: see original paper]. Third, parameters of proportional and H∞ feedback controllers used in DOB-CPC are the same as above, and other undeclared DOB-CPC parameters are tuned case by case.

4.2. Simulation Results and Discussions

A. Mathematical Simulation Experiment To conduct mathematical simulation experiments, controller parameters are first well-tuned, including: (1) TD-DOB parameters L, λ (gain matrix and first-order low-pass filter parameter, see Equations (21) and (23)); (2) LQR-DOB parameters Q, R (weights for tracking error and feedforward control signal, see Equation (29)); (3) CSP parameters k_b, k_f, Δh (weights for feedback control signal u_b from proportional or H∞ controller, weight for feedforward control signal u_d from LQR-DOB, and position error threshold for activating H∞ feedback control and feedforward control, see Equation (34)). Some controller parameters are configured as shown in Table 3 , with other unlisted parameters set as: $Q = 15$, $k_b = 1$, $k_f = 1$, and $\Delta h = 0.1$ for all simulation cases.

Figures 12–14 present LCT' s antenna position error using different controllers under different average wind speeds and fluctuation amplitudes of 2, 6, and 10 m s^{-1} respectively. To quantify disturbance rejection performance, the root mean square (rms) of position error is measured during the interval from 10 s to 20 s. Table 4 summarizes the RMS position errors for different controllers under various wind conditions.

From Figures 12–14, transient performances under the four controllers are almost identical due to CSP effectiveness—proportional control is adopted before entering steady state. When position error enters the range for activating H∞ control or feedforward control, controller switching demonstrates its strength in wind disturbance rejection. Figures 12–14 and Table 4 show that employing DOB-CPC (especially H∞+LQR-DOB) significantly reduces the rms of position error. Additionally, they depict a clear trend: position error increases with rising average wind speed and wind fluctuation amplitude. However, even under high wind speed of 20 m s^{-1} and large fluctuation of 10 m s^{-1}, the rms of position error can be reduced by over 90%. For lower wind speed of 10 m s^{-1} and smaller fluctuation of 2 m s^{-1}, the rms reduction exceeds 92%.

Comparing position errors under the existing proportional controller, H∞ feedback controller, and DOB-CPC (P+LQR-DOB), the H∞ feedback controller yields much smaller position error than the existing proportional controller. Moreover, when DOB-CPC (P+LQR-DOB) is employed, position error is dramatically reduced compared to both H∞ and proportional controllers. Obviously, replacing the existing proportional controller with the H∞ controller or combining the proportional controller with LQR-DOB feedforward control helps reduce antenna position error under wind disturbance. The LQR-DOB feedforward controller contributes more to eliminating wind disturbance effects than the H∞ controller. This can be explained as: (1) The H∞ controller compresses the position error range globally by improving system robustness; (2) The LQR-DOB (integrated with feedback controller as DOB-CPC) provides precise elimination of external and internal disturbance effects by estimating disturbance signals, achieving better performance.

Comparing DOB-CPC (P+LQR-DOB) and DOB-CPC (H∞+LQR-DOB) results shows that position error is further reduced when the feedback controller changes from proportional to H∞. This occurs because the combination of H∞ controller and LQR-DOB feedforward controller combines both strengths: rough disturbance rejection (error range compression) from H∞ feedback and refined disturbance rejection from LQR-DOB feedforward.

LCT' s pointing accuracy requirement is 3 arcseconds (3) (rms), requiring the pointing control system' s position error rms to be less than 3 . However, Table 4 shows that RMS position errors exceed 3 in all cases using the existing proportional feedback controller. After applying the proposed DOB-CPC (H∞+LQR-DOB), RMS position errors are greatly reduced by over 90% in all cases, with most achieving less than 3 . Nevertheless, the proposed DOB-CPC may have performance limitations for extreme cases: (1) wind disturbances with average speed of 15 m s^{-1} and fluctuation of 10 m s^{-1}, and (2) wind disturbances with average speed of 20 m s^{-1} and fluctuation above 6 m s^{-1}. These results provide guidance for proper DOB-CPC application. If high pointing accuracy (e.g., 3) is required during LCT operation, employing DOB-CPC can achieve this when wind disturbance is not very large (e.g., relatively low average speed of 10 m s^{-1} or small fluctuation of 2 m s^{-1}). If wind disturbance is relatively large (e.g., average speed of 20 m s^{-1} or medium fluctuation of 6 m s^{-1}) but pointing accuracy requirements are less stringent (e.g., above 3 but below 10), DOB-CPC still works well.

In general, these tests demonstrate that the proposed DOB-CPC helps LCT' s pointing control system handle different wind disturbances and achieves significant performance improvement compared to single feedback controllers (proportional or H∞). Accurate disturbance estimation by TD-DOB and precise feedforward control signal generation by LQR together eliminate negative effects from wind load and antenna structural flexibility.

B. Collaborative Simulation Experiment By integrating LCT' s pointing control system model with the multibody dynamics model of LCT' s antenna, we conduct collaborative simulation experiments to further verify the proposed DOB-CPC (H∞+LQR-DOB) in more realistic conditions. This experiment is conducted under three typical wind disturbances: (a) $v_w = 10$ m s^{-1}, $\Delta A_{vw} = 2$ m s^{-1}; (b) $v_w = 15$ m s^{-1}, $\Delta A_{vw} = 6$ m s^{-1}; (c) $v_w = 20$ m s^{-1}, $\Delta A_{vw} = 10$ m s^{-1}. Considering that antenna dynamics in the state-space formulation differ from those in the Adams model (which contains more vibration modes and nonlinear characteristics not captured by state-space), the previously well-tuned controller parameters need adjustment for the Adams model: (1) change λ from 0.001 to 0.006 for the case of $v_w = 10$ m s^{-1}, $\Delta A_{vw} = 2$ m s^{-1}; (2) change λ from 0.002 to 0.01 for $v_w = 15$ m s^{-1}, $\Delta A_{vw} = 6$ m s^{-1}; (3) change λ from 0.003 to 0.02 for $v_w = 20$ m s^{-1}, $\Delta A_{vw} = 10$ m s^{-1}.

Figure 15 [Figure 15: see original paper] shows LCT antenna position error under DOB-CPC (H∞+LQR-DOB) for both the mathematical model and collaborative simulation testbed under different wind disturbances, with RMS position errors calculated and shown in Table 5 . Figure 15 and Table 5 indicate that the proposed DOB-CPC (H∞+LQR-DOB) performance on the collaborative simulation testbed is almost the same as on the mathematical model under the most common wind disturbance ($v_w = 10$ m s^{-1}, $\Delta A_{vw} = 2$ m s^{-1}). However, for stronger wind disturbances, performance degrades relatively on the collaborative simulation testbed: position error increases from 1.9860 to 4.0290 for $v_w = 15$ m s^{-1}, $\Delta A_{vw} = 6$ m s^{-1}, and from 7.8560 to 18.3300 for $v_w = 20$ m s^{-1}, $\Delta A_{vw} = 10$ m s^{-1}. Despite this degradation, the position error of 4.0290 is still acceptable under average wind speed of 15 m s^{-1} and fluctuation of 6 m s^{-1}. At LCT' s new site on Chajnantor Plateau, the first two wind load cases are much more common than the third. Therefore, this experiment verifies the feasibility of applying the proposed DOB-CPC (H∞+LQR-DOB) to LCT' s pointing control system after relocation and refurbishment in Chile.

5. Conclusions

This paper proposes a disturbance observer-based composite position controller (DOB-CPC) for LCT' s pointing control system to achieve better disturbance rejection performance under high wind loads. Since the key issue in implementing disturbance observer-based control is generating proper compensation control signals when control and disturbance signals are of different types, an optimal control model with linear quadratic regulator (LQR-DOB) is constructed to precisely generate compensation control signals that make the actuator output physical quantities close to the estimated disturbance, thereby compensating disturbance as much as possible. Finally, to maintain transient process rapidity while acquiring disturbance rejection performance from both LQR-DOB feedforward and H∞ feedback controllers, a controller switching policy is designed to integrate LQR-DOB feedforward, H∞ feedback, and existing proportional controllers as a composite DOB-based position controller (DOB-CPC).

To verify DOB-CPC (H∞+LQR-DOB) performance, we conduct simulation experiments including mathematical simulation and collaborative simulation for LCT' s pointing control system. Mathematical simulation results indicate that the proposed DOB-CPC (H∞+LQR-DOB) performs much better than other controllers for all wind disturbance types. Meanwhile, collaborative simulation testbed results, which integrate the Adams-constructed multibody dynamics antenna model, further ensure that the proposed DOB-CPC (H∞+LQR-DOB) is applicable in practice.

Once LCT relocation and refurbishment are completed in 2024, the proposed DOB-CPC (H∞+LQR-DOB) will be physically verified during astronomical observation to further evaluate its capability for achieving high-precision pointing accuracy under large wind loads. Based on this, future work will focus on enhancing integration between the proposed pointing control method (DOB-CPC) and pointing correction techniques to further improve LCT pointing accuracy.

Acknowledgments

We thank Nicolás Lastra Inzunza, Brian Andler Prendergast, and David Arroyo Reyes from the University of Concepción, Chile, for providing the Ansys model of LCT as a basis for our modal analysis. We also thank Mr. Yiwei Yao from Southeast University, China, for his efforts on LCT vibration modal analysis.

References

[The references would be listed here with proper formatting]

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