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Abstract

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Full Text

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Research on Backlash Compensation Strategy for Radio Telescope Based on NLESO-MPC*

Liu Jingyi[1,2] Xu Qian[1,3,4†] Xue Fei[1,2,3] Wang Hui[1,2,3] Cao Xiaoman[1]

(1 Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi 830011)
(2 University of Chinese Academy of Sciences, Beijing 100049)
(3 National Key Laboratory of Radio Astronomy and Technology, Beijing 100101)
(4 Xinjiang Key Laboratory of Radio Astrophysics, Urumqi 830011)

Abstract The continuous increase in high-frequency astronomical observing demand and the enlargement of radio-telescope antenna apertures have imposed higher requirements on pointing accuracy. However, the nonlinear disturbance caused by backlash weakens the synchronization accuracy and stability of multi-motor servo systems for antennas, limiting improvements in the system' s dynamic response performance and pointing accuracy. To address this problem, a composite control strategy based on a NonLinear Extended State Observer (NLESO) and Model Predictive Control (MPC) is proposed, aiming to achieve effective compensation of backlash nonlinear disturbance and high-precision synchronous control simultaneously, and it is verified through joint simulation experiments. The results show that, compared with traditional Proportional Integral Derivative (PID) control and a single MPC control method, the NLESO-MPC control strategy reduces the large-gear dead-zone width from 0.1951 s to 0.0113 s, and reduces the root-mean-square value of the small-gear angular-displacement synchronization error from 0.6884° to 0.3546°, verifying the effectiveness and superiority of this method in suppressing backlash nonlinear disturbance and improving synchronization performance.

Keywords telescope: radio telescope; techniques: multi-motor synchronous control; methods: backlash nonlinear compensation, nonlinear extended state observer, model predictive control

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1 Introduction

Large-aperture radio telescopes play an important role in radio astronomical observations, especially in high-frequency observations, where more stringent requirements are placed on their pointing accuracy. Taking the Green Bank Telescope (GBT) in the United States as an example, during high-frequency observations at 116 GHz, its pointing error is required to be less than 2.5″. To achieve this goal, the azimuth and elevation of the GBT use a multi-motor synchronous drive system, combined with feedback from multiple sensors to correct errors in real time, thereby satisfying the strict pointing-accuracy requirements of high-frequency observations[1]. The 110 m-aperture radio telescope (QiTai Telescope, QTT) being constructed by the Xinjiang Astronomical Observatory of the Chinese Academy of Sciences will extend its operating frequency band to 150 MHz–115 GHz; its initial pointing accuracy is required to be better than 2.5″, and the long-term target is planned to reach 1″[2]. The high pointing-accuracy requirement poses greater challenges to the coordinated optimization of the mechanical structure and servo control system of the telescope.

Large radio telescopes usually adopt multi-motor synchronous drive systems

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† xuqian@xao.ac.cn

system, achieving antenna rotation control through its high-torque output capability. However, in multi-motor transmission systems, backlash nonlinear disturbances can induce torque fluctuations and structural resonance, leading to gear meshing impacts and positioning errors. For large-aperture antennas, the motor transmission chain is long, and such nonlinear disturbances have a more pronounced impact on servo transmission systems, thereby reducing the pointing accuracy and tracking performance of the antenna. To solve the control difficulties of multi-motor servo drive systems, researchers have proposed various control strategies. Although the traditional proportional-integral-derivative (PID) control strategy was widely applied in early radio telescopes, such as deep-space network antennas[^3], its control bandwidth is limited; it can provide stable control only in the low-frequency range and is difficult to apply to high-order nonlinear coupling problems in multi-motor systems. In recent years, active disturbance rejection control (ADRC), which uses an extended state observer (ESO), has been able to estimate and compensate unknown disturbances in large antennas in real time[^4]. However, in multi-motor drive systems it still faces challenges such as complex disturbance coupling and difficulty in tuning observer parameters. Model predictive control (MPC), because of its rolling optimization prediction capability, is often combined with ESO for trajectory-tracking control[^5-^6], thereby achieving effective compensation of external disturbances and high-precision trajectory tracking. In large antenna systems, MPC has been used in modeling and simulation research on the azimuth servo drive control system of the RT-70 large 70 m aperture parabolic radio telescope[^7]. The simulation results show that this method can improve servo tracking performance.

For the problem of backlash nonlinear disturbance in servo systems, Zeng et al.[^8] proposed a high-gain compensation method, which suppresses the influence of backlash by increasing the gain of the control loop. However, an excessively high gain may cause system oscillation and significantly increase the computational burden. Another commonly used method is to adaptively compensate backlash disturbances through preload torque[^9-^10]. This method has a low computational cost, but the magnitude of the preload torque is difficult to estimate: if it is too small, it cannot effectively eliminate backlash disturbance; if it is too large, it will cause excessive motor output torque peaks and induce gear meshing impacts. In addition, some studies equivalently regard the dead-zone effect caused by backlash as an input dead zone, and use adaptive neural networks (Neural Network, NN) and dynamic surface control (Dynamic Surface Control, DSC) methods to achieve precise nonlinear disturbance compensation for complex systems[^11]. However, this method requires a large amount of high-quality data during training, and parameter tuning is relatively difficult. In comparison, the design of a load displacement error controller based on smooth switching between contact mode and backlash mode[^12-^13] is relatively simple and easy to implement, and can avoid gear impacts while eliminating backlash.

However, the switching-controller method is highly dependent on accurate identification of parameters such as backlash angle and load inertia. Once the parameter identification is inaccurate, the system control performance will decline significantly and the error will increase accordingly.

Aiming at the backlash nonlinear disturbance problem in multi-motor synchronous drive systems for radio telescope far mirrors, this paper proposes a composite control strategy that integrates model predictive control (MPC) with a nonlinear extended state observer (NonLinear Extended State Observer, NLESO). Taking the meshing structure in which four pinions drive a large gear as the object, a dynamic model of the multi-motor drive system is established, and a hierarchical control architecture is designed. In the outer-loop position control layer, multi-motor synchronization is realized through cross-coupled control (CCC), and NLESO is introduced to estimate and compensate backlash nonlinear disturbances in real time, thereby synthesizing the reference current command. In the inner-loop current layer, MPC is adopted to realize rolling optimization, accurately track the current command synthesized by the outer loop, and realize high-precision torque control. The NLESO-MPC backlash nonlinear compensation control strategy can effectively reduce the influence of backlash nonlinearity on system precision.

2 Electromechanical Coupled System Modeling

The servo system of a radio telescope far-mirror antenna consists of two parts: mechanical transmission and motor drive. It is an electromechanical dynamic system. To accurately describe its dynamic characteristics, this section separately establishes the dynamic model of the gear transmission system and the electromechanical coupling model of the permanent magnet synchronous motor (Permanent Magnet Synchronous Motor, PMSM). Through the joint modeling of mechanical transmission and electrical drive, a theoretical model foundation is provided for subsequent control-strategy design and control-performance analysis.

2.1 Dynamic Modeling of the Gear Transmission System

The system adopts a transmission structure in which four pinions mesh to drive one large gear. The drive model is shown in Fig. 1. This structure has high similarity to the antenna pitch large-gear drive system. In it, the large gear (G_{L}) is the central load gear, and the pinions (G_1-G_4) are four independent drive units, each driven by its own motor. In the figure, α denotes the backlash width parameter.

In this model, the kinematic relationship between gears is described by the mathematical relationship between the transmission ratio i and the angular velocity; its specific form is:

$$i = \frac{z_{\mathrm{L}}}{z_{gk}}, \qquad (1)$$

where i is the transmission ratio; z_{L} and z_{gk} are the numbers of teeth of the large gear and the pinion, respectively; ω_{L} and ω_{gk} are the angular velocities of the large gear and the pinion, respectively; θ_{L} and θ_{gk} are the angular displacements of the large gear and the pinion, respectively; and k denotes the pinion number. (k = 1, 2, 3, 4). Therefore:

$$\omega_{g_k} = i\omega_{\mathrm{L}}, \qquad (2)$$

When four pinions cooperatively drive the large gear, under ideal backlash-free conditions the angular displacement satisfies:

$$\theta_{g_k} = i\theta_{\mathrm{L}}, \qquad (3)$$

Considering the backlash in the actual system, the backlash deviation is defined as:

$$\delta = \theta_{g_k} - i\theta_{\mathrm{L}}. \qquad (4)$$

When $|\delta|$ is within the backlash width range, no meshing force or torque is transmitted; when it exceeds this range, contact force and torque are generated at the instant of contact. This paper adopts the backlash dead-zone model in Ref. [14]:

$$f(\delta) = \begin{cases} \delta - \alpha, & \delta \geq \alpha, \\ 0, & |\delta| < \alpha, \\ \delta + \alpha, & \delta \leq -\alpha, \end{cases} \qquad (5)$$

Only when $|\delta| > \alpha$ are the large and small gears considered to be "meshed," with torque transmission. The piecewise backlash dead-zone model shown in Eq. (5) can preserve the true physical characteristic of "zero force–abrupt force" in the gear pair, avoid additional energy storage and dissipation caused by preset contact force within the backlash region, and maintain the physical consistency of force and energy; that is, when the force is in the backlash, the energy remains unchanged, and after contact the abrupt change in force corresponds to an energy jump. The normal contact force F_{n} between the gears is:

$$F_{\mathrm{n}} = k_{\mathrm{m}} f(\delta) + c_{\mathrm{m}} \dot{f}(\delta), \qquad (6)$$

where k_{m} is the gear meshing stiffness and c_{m} is the damping coefficient during gear meshing. When the pinion meshes with the large gear, the reaction torque T_{r_k} generated is:

$$T_{r_k} = rF_{\mathrm{n}}, \qquad (7)$$

where r denotes the pitch-circle radius of the pinion. For this gear system, its dynamic equations can be expressed as:

$$\begin{cases} J_k \dot{\omega}_{g_k} = T_{e_k} - T_{r_k} - b_k \omega_{g_k}, \\ J_{\mathrm{L}} \dot{\omega}_{\mathrm{L}} = \sum_{k=1}^{4} T_{r_k} - b_{\mathrm{L}} \omega_{\mathrm{L}}, \end{cases} \tag{8}$$

where J_k denotes the rotational inertia of the kth pinion, T_{e_k} denotes the driving torque acting on the kth pinion (see Eq. (10)), b_k denotes the friction damping coefficient of the kth pinion, J_{L} denotes the rotational inertia of the large gear, and b_{L} denotes the friction damping coefficient of the large gear. The above constitutes the gear dynamics model of the mechanical part of the four-motor drive system, whose input torque T_{e_k} is determined by the electromagnetic characteristics of the permanent-magnet synchronous motor.

Figure 1 Schematic diagram of the gear-driven model

Fig. 1 Schematic of the gear-driven model

2.2 Modeling of PMSM Electromagnetic-Mechanical Characteristics

This paper uses an interior three-phase permanent magnet synchronous motor (Permanent Magnet Synchronous Motor, PMSM) as the drive unit. Its mathematical model is established based on the rotor reference coordinate system (d-q axis system, where the d axis and q axis represent the direct axis and quadrature axis, respectively). In the d-q axis system, the voltage equations of the PMSM [15] can be expressed as:

$$\begin{cases} \dfrac{\mathrm{d}i_d}{\mathrm{d}t} = \dfrac{1}{L_d} v_d - \dfrac{R}{L_d} i_d + \dfrac{L_q}{L_d} p \omega_{\mathrm{m}} i_q, \\ \dfrac{\mathrm{d}i_q}{\mathrm{d}t} = \dfrac{1}{L_q} v_q - \dfrac{R}{L_q} i_q - \dfrac{L_d}{L_q} p \omega_{\mathrm{m}} i_d - \dfrac{\psi_f p \omega_{\mathrm{m}}}{L_q}, \end{cases} \tag{9}$$

where L_d and L_q are the d-axis and q-axis inductances, respectively; R is the stator resistance; ψ_f is the flux linkage amplitude of the permanent magnet; p is the number of motor pole pairs; ω_{m} is the mechanical angular velocity of the motor; and i_d and i_q are the d-axis and q-axis currents, respectively. The electromagnetic torque T_{e_k} is generated by the joint action of the d-axis and q-axis currents. In vector control, $i_d = 0$ is usually imposed to achieve simplified d-q axis decoupling; at this time, the torque T_{e_k} is determined only by i_q and is expressed as:

$$T_{e_k} = \frac{3}{2} p \psi_f i_q. \tag{10}$$

For a salient-pole rotor, its phase-to-phase inductance L_{ab} varies periodically with the electrical angle θ_{e}:

$$L_{\mathrm{ab}} = L_d + L_q + (L_q - L_d)\cos\left(2\theta_{\mathrm{e}} + \frac{\pi}{3}\right), \qquad (11)$$

At this time, $L_d = \max(L_{\mathrm{ab}})/2$, $L_q = \min(L_{\mathrm{ab}})/2$, so as to fully utilize the reluctance torque effect. The mechanical motion characteristics of the motor are described by the rotor motion equation, whose expression is:

$$\frac{\mathrm{d}\omega_{\mathrm{m}}}{\mathrm{d}t} = \frac{T_{e_k} - B\omega_{\mathrm{m}} - T_{r_k}}{J_{\mathrm{m}}}, \qquad (12)$$

$$J_k = J_{gk} + J_{\mathrm{m}}, \qquad (13)$$

where B is the friction damping coefficient, J_{m} is the motor rotor moment of inertia, and J_{gk} is the moment of inertia of the k-th pinion itself. The sum of the two constitutes the rotational inertia J_k of the k-th pinion transmission unit, ensuring the dynamic integrity of the motor system. The output torques T_{e1}-T_{e4} of the four PMSMs drive the pinions in the gear system, realizing the conversion of electromechanical energy.

3 NLESO-MPC Controller Design

The composite controller is mainly composed of MPC and NLESO, and is intended to accurately estimate and compensate for nonlinear disturbances caused by backlash. To adapt to the dynamic differences in a multi-motor drive system, each motor is equipped with an independent MPC and NLESO unit. The overall architecture is shown in Fig. 2. This control system adopts a distributed cooperative architecture, mainly including: (a) distributed MPC based on current prediction; (b) CCC for suppressing phase-displacement synchronization errors among multiple motors; and (c) NLESO for real-time estimation of backlash disturbances and feedforward compensation.

In the figure, θ_{ref} is the global expected reference angular displacement, $i_{q,\mathrm{sync},k}$ is the q-axis synchronization compensation current generated by the CCC for the k-th motor, and Δi_{qk} is the q-axis disturbance compensation current generated by the NLESO. After the two are superposed, the final q-axis reference current $i^*_{q,k}$ is obtained; meanwhile, the d-axis reference current is set to $i^*_{d,k} = 0$.

3.1 Distributed Current Model Predictive Control

This paper uses MPC to perform closed-loop predictive control of the d-q axis currents of the PMSM, so as to track the reference currents generated by the various composite controllers. Based on the voltage equation in Eq. (9), discretizing Eq. (9) by the forward Euler method gives:

Fig. 2 Architecture of the multi-motor NLESO–MPC composite controller

Figure 1: Fig. 2 Architecture of the multi-motor NLESO–MPC composite controller

$$\begin{cases} i_d(n+1) = i_d(n) + \dfrac{T_s}{L_d}(v_d(n) - Ri_d(n) + \omega_{\mathrm{m}}(n)L_q i_q(n)), \\ i_q(n+1) = i_q(n) + \dfrac{T_s}{L_q}(v_q(n) - Ri_q(n) - \omega_{\mathrm{m}}(n)[L_d i_d(n) + \psi_f]), \end{cases} \tag{14}$$

where T_s is the sampling period, and n denotes the index of the discrete sampling instant. The inverter output voltage is mapped to the d–q coordinate system as:

$$\begin{bmatrix} v_d(n) \\ v_q(n) \end{bmatrix} = \frac{2}{3}V_{\mathrm{dc}} \begin{bmatrix} \cos\theta_{\mathrm{m}} & \cos\left(\theta_{\mathrm{m}} - \frac{2\pi}{3}\right) & \cos\left(\theta_{\mathrm{m}} + \frac{2\pi}{3}\right) \\ -\sin\theta_{\mathrm{m}} & -\sin\left(\theta_{\mathrm{m}} - \frac{2\pi}{3}\right) & -\sin\left(\theta_{\mathrm{m}} + \frac{2\pi}{3}\right) \end{bmatrix} \left[d(n) - \frac{1}{2}\right], \tag{15}$$

where the three-phase voltage duty-ratio vector is $d(n) = [d_a(n),\, d_b(n),\, d_c(n)]^{\mathrm{T}} \in [0,1]^3$, θ_{m} is the rotor mechanical angular displacement, and V_{dc} is the DC bus voltage.

Fig. 2 Architecture of the multi-motor NLESO–MPC composite controller

To achieve accurate tracking control of the d-q axis currents, a cost function J is designed within the prediction horizon N_p and the control horizon N_c to coordinate the current tracking accuracy:

$$J = \sum_{j=1}^{N_p} \left(\mu \left\|i_q(n+j) - i_q^*(n+j)\right\|^2 + \nu \left\|i_d(n+j) - i_d^*(n+j)\right\|^2\right) + \lambda \sum_{j=1}^{N_c} \left\|d(n+j) - d(n+j-1)\right\|^2, \tag{16}$$

where μ and ν are the weighting coefficients for the q-axis and d-axis current tracking errors, respectively, and λ is the penalty weighting coefficient for the duty-ratio variation rate. The value of λ is used to balance the current tracking performance and the smoothness of the control input: a smaller λ emphasizes reducing the current tracking error, which helps improve current tracking accuracy, but leads to larger duty-ratio variations and a higher inverter switching frequency, thereby reducing the smoothness of the control input; a larger λ can suppress duty-ratio variations and obtain a smoother PWM modulation signal, but reduces the current tracking performance. In each sampling period, the following constrained optimization problem is solved to generate the optimal duty-ratio sequence:

$$D^*(n) = \arg \min_{D(n)\in[0,1]^{3\times N_c}} JD(n), \qquad (17)$$

where $D(n) = [d(n+1), d(n+2), \cdots, d(n+N_c)]$ is the duty-ratio sequence over the future N_c steps. A receding optimization strategy is adopted, and the first element $d^*(n+1)$ of the optimal sequence $D^*(n)$ is applied to PWM modulation to drive the inverter to generate the required voltage vector, thereby realizing closed-loop predictive control of the current.

3.2 Cross-coupled synchronization of multiple motors

To suppress the synchronization errors caused by differences in transmission chains such as loads and gear clearances in multi-motor control systems, this paper adopts CCC to realize multi-motor synchronous control. The position error of the pinion is defined as:

$$e_{\theta,gk} = \theta_{\text{ref}} - \theta_{gk}. \qquad (18)$$

The synchronous tracking torque is synthesized according to the position error:

$$T_k = K_p e_{\theta,gk} + K_c e_{c,k}, \qquad (19)$$

where K_p is the proportional gain of the position loop, K_c is the cross-coupling gain, and $e_{c,k}$ is the deviation of the angular displacement of the k-th motor relative to the average angular displacement θ_{avg} of the four motors, expressed as:

$$e_{c,k} = \theta_{\text{avg}} - \theta_{gk}, \qquad \theta_{\text{avg}} = \frac{1}{4}\sum_{k=1}^{4}\theta_{gk}. \qquad (20)$$

Finally, the synchronous torque is converted into the q-axis compensation current used to correct the synchronization deviation:

$$i_{q,\text{sync},k} = \frac{T_k}{K_t}, \qquad (21)$$

where K_t is the torque constant. This compensation current is superimposed together with the disturbance compensation current output by NLESO, and is used as the q-axis current command input of the MPC module.

3.3 Nonlinear extended state observer

With reference to a nonlinear second-order continuous ESO [16], a third-order NLESO suitable for this system is designed. Considering that the gear-meshing reaction torque acts on the system in the form of T_{rk}/J_k in the dynamic equation, it is incorporated into the total disturbance term, and the estimated value of this total disturbance term is taken as the third-order extended state variable of the system. The state vector of the observer is defined as:

$$z_k = \begin{bmatrix} z_{k1} \\ z_{k2} \\ z_{k3} \end{bmatrix} = \begin{bmatrix} \hat{\theta}_{gk} \\ \hat{\omega}_{gk} \\ \dfrac{\hat{T}_{rk}}{J_k} \end{bmatrix}, \qquad (22)$$

where z_{k1} and z_{k2} correspond respectively to the estimated values $\hat{\theta}_{gk}$ and $\hat{\omega}_{gk}$ of the angular displacement and angular velocity of the pinion, and z_{k3} is the estimated value of the total disturbance term T_{rk}/J_k, mainly representing the nonlinear disturbance caused by the tooth clearance, whose specific form is $\hat{T}_{rk}/J_k$. In addition, the angular observation error is defined as

$$e_k = \hat{\theta}_{gk} - \theta_{gk}. \qquad (23)$$

To account for both fast convergence under large errors and non-oscillatory characteristics under small errors [16], the nonlinear function fal$(\cdot)$ is introduced, whose expression is

$$\mathrm{fal}(e, a, \delta) = \begin{cases} |e|^a \,\mathrm{sign}(e), & |e| > \delta, \\ \dfrac{e}{\delta^{1-a}}, & |e| \le \delta, \end{cases} \qquad (24)$$

Accordingly, the continuous-time state equation of the NLESO can be written as

$$\begin{cases} \dot{z}_{k1} = z_{k2} - \beta_1 \mathrm{fal}(e_k, a_1, \delta), \\ \dot{z}_{k2} = \dfrac{K_t}{J_k} i_{q,k} - z_{k3} - \beta_2 \mathrm{fal}(e_k, a_2, \delta), \\ \dot{z}_{k3} = -\beta_3 \mathrm{fal}(e_k, a_3, \delta), \end{cases} \qquad (25)$$

where β_1, β_2, and β_3 are the coefficients for adjusting the angle, velocity, and disturbance states, respectively. Increasing these coefficients can improve the response of the observer.

response speed, enabling it to track changes in system state more rapidly and compensate for disturbances; however, an excessively large value will cause system oscillation. a_1, a_2, and a_3 are the nonlinear exponential parameters of the fal function, used respectively for convergence adjustment of angle, speed, and disturbance observation errors. When these exponents take relatively small values, the system has higher gain under small errors, thereby accelerating convergence, but may cause excessive response under large errors and even induce oscillation; when these exponents take relatively large values, the fal function tends more toward linearity and the system dynamic characteristics are smoother, but the advantage of nonlinear accelerated convergence is lost.

Considering the implementation of the digital control system, the forward Euler method is used to transform the above continuous-time state equation $\dot{z}_k = f(z_k, i_{q,k})$ into the discrete form:

$$\begin{cases} z_{k1}(n+1) = z_{k1}(n) + [z_{k2}(n) - \beta_1 \operatorname{fal}(e_k(n), a_1, \delta)]\, T_s, \\ z_{k2}(n+1) = z_{k2}(n) + \left[\dfrac{K_t}{J_k} i_{q,k}(n) - z_{k3}(n) - \beta_2 \operatorname{fal}(e_k(n), a_2, \delta)\right] T_s, \\ z_{k3}(n+1) = z_{k3}(n) + [-\beta_3 \operatorname{fal}(e_k(n), a_3, \delta)]\, T_s. \end{cases} \tag{26}$$

Finally, the third state variable $z_{k3}(n)$ output in real time by the observer is converted through the torque–current conversion relationship to obtain the current compensation value:

$$\Delta i_{qk} = \frac{J_k z_{k3}(n)}{K_t}. \tag{27}$$

This value, together with the synchronous compensation current output by the CCC in Section 3.2, is superimposed onto the q-axis current reference value of the MPC, realizing feedforward elimination of tooth-gap disturbance and forming a multilevel coordinated control of "centralized coordination–distributed execution."

4 Simulation Verification and Result Analysis

To verify the synchronization and backlash-elimination performance of the proposed NLESO-MPC control strategy, this paper builds co-simulation models of three control strategies (PID, MPC, and NLESO-MPC), respectively. Under the same step-signal input and cross-coupled control structure, comparative performance analysis is conducted for the four-motor servo system of gear transmission. In the system, four motors respectively drive pinions with 62 teeth, which jointly drive a large gear with 242 teeth as the load; the transmission ratio is approximately 3.9. In the MPC controller, after simulation tuning, the penalty weight coefficient for the duty-cycle change rate is set as $\lambda = 0.25$. This value mainly aims to improve current-tracking accuracy while also accounting for the smoothness of the control input. This paper focuses on comparing the performance differences of various control strategies in backlash elimination and synchronous control from aspects such as angular-position response, torque fluctuation, and synchronization error. The key performance metrics are shown in Table 1.

Table 1 Comparison of key performance metrics under different control strategies

Metric	PID	MPC	NLESO-MPC
$t_{\mathrm{resp},\theta_L}/\mathrm{s}$	0.8524	0.8195	0.7443
$\alpha_{\theta_L}/\mathrm{s}$	0.1951	0.1608	0.0113
$\hat{T}_{rk}/(\mathrm{N}\cdot\mathrm{m})$	19.014/-19.062	18.122/-18.074	14.99/-15.131
$e_{\theta_L,\infty}/(^\circ)$	0.211	0.039	0.002
$\Delta\theta_{\mathrm{RMS}}/(^\circ)$	0.6884	0.4437	0.3546
$e_{\omega_{gk},ss}/[(^\circ)\cdot \mathrm{s}^{-1}]$	0.5503	0.3337	0.3193
$\sigma_{\omega_{gk}}/[(^\circ)\cdot \mathrm{s}^{-1}]$	0.6056	0.5238	0.4941

Notes: Symbol definitions: $t_{\mathrm{resp},\theta_L}$—start response time of the large gear angle; α_{θ_L}—dead-zone width of the large gear angle; $\hat{T}_{rk}$—peak reaction torque (positive/negative); $e_{\theta_L,\infty}$—final error of the large gear angle; $\Delta\theta_{\mathrm{RMS}}$—RMS synchronous position error of pinions; $e_{\omega_{gk},ss}$—steady-state speed error of pinions; $\sigma_{\omega_{gk}}$—standard deviation of pinion angular speed. Units are indicated in each row.

From the large-gear angular-position response curve (Fig. 3), it can be observed that, under PID (Fig. 3(a)) and MPC (Fig. 3(b)) control, there is an obvious dead-zone phenomenon during the reversal stage; that is, the motor output has already reversed, but the pinion has not yet meshed with the large gear in time, resulting in a brief stagnation of the system response. After introducing NLESO, under NLESO-MPC (Fig. 3(c)) control, the response time of the large gear angular position decreases from 0.8524 s to 0.7443 s, the dead-zone width is significantly reduced from 0.1951 s to 0.0113 s, and the final error is also reduced from 0.211° to 0.002°. This indicates that, while eliminating the backlash, the position-tracking accuracy is significantly improved. In addition, as can be seen from the output torque curves of the pinions shown in Fig. 4, under PID and MPC control, both ⋯

there are obvious torque peaks, reaching about $\pm 19\ \mathrm{N}\cdot\mathrm{m}$, and the impact is relatively large. Under NLESO-MPC control, however, the torque peak is reduced to below $\pm 15\ \mathrm{N}\cdot\mathrm{m}$, indicating that, while suppressing backlash disturbance, this control strategy can effectively alleviate gear impact and improve the smoothness of system operation.

Fig. 3 Large-gear angular displacement under PID (a), MPC (b), and NLESO-MPC (c)

Fig. 3 Large-gear angular displacement under PID (a), MPC (b), and NLESO-MPC (c)

Figure 2: Fig. 3 Large-gear angular displacement under PID (a), MPC (b), and NLESO-MPC (c)

Fig. 4 Reaction torque of the four pinions under PID (a), MPC (b), and NLESO-MPC (c)

Figure 3: Fig. 4 Reaction torque of the four pinions under PID (a), MPC (b), and NLESO-MPC (c)

Fig. 4 Reaction torque of the four pinions under PID (a), MPC (b), and NLESO-MPC (c)

In terms of synchronization performance, Fig. 5 and Fig. 6 give the angular-velocity and angular-displacement response curves of the pinions, respectively. Combined with the data in Table 1, it can be seen that, compared with PID, MPC control reduces the root-mean-square value of the synchronization error of the pinion angular displacement from 0.6884° to 0.4437°. The four pinions can share the load more uniformly, thereby reducing meshing impact. Meanwhile, the steady-state error and standard deviation of the pinion angular velocity also decrease, the speed fluctuation during operation becomes smaller, and the control output is smoother and more stable. After introducing NLESO, the synchronization performance of NLESO-MPC is further improved: the root-mean-square value of the pinion angular-displacement synchronization error decreases to 0.3546°, and the steady-state error and standard deviation of the pinion angular velocity decrease to 0.3193 $(^\circ)\cdot s^{-1}$ and 0.4941 $(^\circ)\cdot s^{-1}$, respectively, giving the best overall synchronization effect. It can also be observed from the figures that, under NLESO-MPC control, the pinion speeds converge faster, the oscillation amplitude is smaller, and the angular-displacement trajectories are more consistent. This indicates that, while improving backlash elimination performance, this control strategy enables the system to exhibit higher synchronization stability.

In summary, the backlash-elimination control strategy based on NLESO-MPC not only effectively suppresses the response delay and dead-zone effect caused by gear backlash, but also reduces torque impact during the direction-reversal process and improves angular-displacement positioning accuracy. While eliminating backlash, this control strategy also reduces the pinion ···

the steady-state error and synchronization error of the pinion angular velocities, improving the synchronization performance of the system.

Fig. 5 Angular velocities of the four pinions under PID (a), MPC (b), and NLESO-MPC (c)

Fig. 6 Angular displacements of the four pinions under PID (a), MPC (b), and

Fig. 5 Angular velocities of the four pinions under PID (a), MPC (b), and NLESO-MPC (c)

Figure 4: Fig. 5 Angular velocities of the four pinions under PID (a), MPC (b), and NLESO-MPC (c)

Fig. 6 Angular displacements of the four pinions under PID (a), MPC (b), and NLESO-MPC (c)

Figure 5: Fig. 6 Angular displacements of the four pinions under PID (a), MPC (b), and NLESO-MPC (c)

NLESO-MPC (c)

5 Conclusion

Focusing on the servo-control requirements of an antenna system under high-precision motion conditions, and addressing the problems of response lag and synchronization error caused by backlash during multi-motor drive, this paper proposes an NLESO-MPC-based coordinated control strategy and conducts simulation comparisons. Compared with traditional PID control and MPC control, this control strategy can significantly reduce the dead-zone width of the bull-gear angular displacement during the meshing process (from 0.1951 s to 0.0113 s), reduce the commutation lag caused by backlash, and improve the response continuity and stability of the system during the commutation process. At the same time, this strategy effectively reduces the steady-state error of the pinion angular velocities, and decreases the root-mean-square value of the angular-displacement synchronization error from 0.6884° to 0.3546°, making the motion of the gears during the driving process more consistent, thereby significantly improving the synchronization control accuracy of the system. The NLESO-MPC control strategy is superior to PID control and MPC control in terms of backlash nonlinear-disturbance compensation, dynamic response speed of the multi-motor system, and synchronization performance improvement.

In future work, the dynamic compensation capability under variable-speed tracking conditions will be further improved, dynamic load-disturbance problems will be addressed, adaptive parameter-adjustment mechanisms under multiple operating conditions will be studied, and the performance will be verified through platform experiments or antenna experiments.

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NLESO-MPC-Based Compensation Strategy for Gear Backlash in Radio Telescopes

DENG Jing-yi[1,2] XU Qian[1,3,4] XUE Fei[1,2,3] WANG Hui[1,2,3] CAO Xiao-man[1]

(1 Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi 830011)
(2 University of Chinese Academy of Sciences, Beijing 100049)
(3 State Key Laboratory of Radio Astronomy and Technology, Beijing 100101)
(4 Xinjiang Key Laboratory of Radio Astrophysics, Urumqi 830011)

ABSTRACT With the growing demand for high-frequency astronomical observations and the increasing aperture of radio telescopes, more stringent requirements are imposed on pointing accuracy. However, backlash-induced nonlinear disturbances degrade the synchronization accuracy and stability of antenna multi-motor servo systems, thereby limiting improvements in dynamic response and pointing precision. To address this issue, we propose a composite control strategy based on a NonLinear Extended State Observer (NLESO) and Model Predictive Control (MPC) to simultaneously compensate backlash-induced nonlinear disturbances and achieve high-precision synchronization control. Cosimulation experiments were conducted for validation. The results show that, compared with conventional Proportional Integral Derivative (PID) control and standalone MPC, the NLESO-MPC strategy reduced the large-gear dead-zone width from 0.1951 s to 0.0113 s and decreased the Root Mean Square (RMS) pinion angular-displacement synchronization error from 0.6884° to 0.3546°, demonstrating the effectiveness and clear advantages of the proposed method in suppressing backlash nonlinear disturbances and improving synchronization performance.

Key words telescopes: radio telescope, techniques: multi-motor synchronization control, methods: backlash nonlinear compensation, nonlinear extended state observer, model predictive control