Postprint on Synchronous Control of Drive Motors in Radio Telescope Servo Systems

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Abstract

The drive motors of radio telescope servo systems exhibit speed mismatch during operation, which, as telescope aperture increases and precision improves, severely impacts the high-precision pointing and tracking control of large-aperture radio telescopes. To reduce speed deviation during servo system operation and improve the pointing accuracy of radio telescopes, a robust motor synchronization controller is designed based on model predictive control (MPC). A disturbance observer (DOB) is designed based on the system state-space model to calculate the total disturbance from external disturbances and unmodeled errors; a Luenberger observer (LOB) is designed to observe the system states. Based on integration with MPC, a quadratic cost function regulating load angle and motor speed is designed, which achieves motor speed synchronization while ensuring tracking control performance. Simulation and experimental results demonstrate that compared with conventional motor control schemes using proportional-integral (PI) combined with cross-coupled structure (CS), MPC+DOB+LOB endows the servo system with superior dynamic and synchronization performance.

Full Text

Preamble

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Synchronous Control of Drive Motors in Radio Telescope Servo Systems

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Abstract

Radio telescope servo systems exhibit speed mismatch among drive motors during operation. As telescope apertures increase and precision requirements become more stringent, this issue severely impacts high-precision pointing and tracking control of large-aperture radio telescopes. To reduce speed deviations in servo system operation and improve radio telescope pointing accuracy, this paper designs a robust motor synchronization controller based on model predictive control (MPC). A disturbance observer (DOB) is designed based on the system state-space model to calculate the total disturbance from external perturbations and unmodeled errors. A Luenberger observer (LOB) is designed to estimate system states. By integrating these observers with MPC, a quadratic cost function is formulated to regulate both load angle and motor speed, achieving motor speed synchronization while ensuring tracking control performance. Simulation and experimental results demonstrate that compared to conventional proportion-integration (PI) control combined with cross-coupled structure (CS), the MPC+DOB+LOB approach provides superior dynamic performance and synchronization capability for the servo system.

Keywords: radio telescope; synchronized control; model predictive control; disturbance observer; Luenberger observer

1 Introduction

Due to limitations in technical conditions and driving capacity, single-motor drives can no longer meet the requirements for driving power and high-precision control in large-aperture radio telescopes. Multi-motor drive systems have become the prevalent configuration for azimuth and elevation drives. Multi-motor drive represents a strongly coupled nonlinear system where each motor is inevitably affected by external disturbances, internal parameter variations, and torque bias control, leading to speed mismatch among motors. This speed mismatch alters system dynamic response, reduces operational stability, and ultimately degrades the pointing accuracy of radio telescope servo systems. Additionally, speed mismatch increases unnecessary friction and impact between mechanical components, shortening equipment lifespan.

Existing large-aperture high-precision radio telescopes worldwide, such as the Green Bank Telescope in the United States, the Effelsberg Telescope in Germany, and the Shanghai Tianma Telescope in China, achieve pointing accuracy errors within 5 , 10 , and 3 respectively. The Qitai Radio Telescope (QTT) currently under construction at the Xinjiang Astronomical Observatory requires a pointing accuracy better than 5 upon completion. To meet the stringent servo system requirements for QTT pointing accuracy, research on synchronous control of drive motors holds significant practical importance.

Conventional antenna servo drive control primarily employs proportion-integration (PI) controllers with cross-coupled structure (CS). The Nanshan 26 m telescope at Xinjiang Astronomical Observatory uses this basic approach for dual-motor systems in both azimuth and elevation drives. The Shanghai Tianma Telescope utilizes digital controllers to achieve digitization of multi-motor, multi-velocity-loop, and torque-balanced synchronous control, enhancing system flexibility and fault tolerance. The European Svalbard Radar telescope incorporates the average speed of multiple motors as velocity feedback input into the control system. However, these methods remain constrained by the limitation that cross-coupling only works for power-of-two numbers of motors, and they involve filtering of velocity feedback, which affects control performance.

Model predictive control (MPC) is a multi-input multi-output optimal control strategy that selects optimal control variables based on a predictive model and current system state according to a cost function. Unlike conventional antenna servo systems that synchronize motors pairwise, MPC directly synchronizes multiple motors simultaneously. Its optimal nature enables higher pointing precision for radio telescope servo systems. In recent years, MPC application in servo control has become a research focus. Phuong et al. applied MPC to servo tracking control simulation for RT-70 (70 Meter Radio Telescope), reducing servo tracking error but without considering external disturbance effects. Zhou et al. incorporated disturbance effects in MPC optimization and designed a disturbance observer (DOB) combined with MPC to improve robust performance. These studies assume known true states of the servo system, but actual radio telescope servo system states are often unmeasurable. Moreover, unmodeled errors accumulate during servo system operation, affecting MPC performance. Direct application to radio telescope servo systems may fail to achieve expected synchronization performance.

This research analyzes the control structure of QTT antenna drive motor servo systems, focusing on dual-motor speed mismatch during operation. MPC is introduced into radio telescope multi-motor control, and an MPC+DOB+LOB control method is proposed. Time-varying disturbances and unmodeled errors affecting different motors in the servo system are aggregated, and a DOB is designed for estimation. Simultaneously, a Luenberger observer (LOB) is designed to estimate the true states of the servo system. Based on integration of these observers with MPC, a cost function is designed to synchronize motor control, with verification through simulation and experiments.

2.1 Control Structure Analysis

The antenna servo control system consists of two independent subsystems for elevation and azimuth. These subsystems operate independently and can employ identical control schemes. This study focuses on the elevation drive system. The PI+CS control approach is illustrated in [Figure 1: see original paper]. The PI controller in the position loop takes the difference between reference angle and controlled object angle feedback as input, calculates velocity commands, and achieves target angle tracking. Simultaneously, proportional gain based on the speed difference between the two motors is applied as cross-feedback to the velocity commands, regulating speed deviation between the two motors to suppress synchronization error.

When tracking specific signal sources with radio telescopes, the reference signal time sequence is deterministic. By minimizing the error between future predicted system output and reference signal, MPC calculates control inputs that can fully utilize future reference information. Consequently, MPC demonstrates superior performance in pointing accuracy compared to PI controllers. To ensure long-term operation of radio telescopes, servo system control inputs are subject to physical, safety, and environmental constraints. MPC addresses the limitations of PI controllers in handling control input constraints, ensuring system stability at all times.

To improve large reflector antenna pointing accuracy and reduce synchronization errors during servo system operation, this study replaces the PI+CS control approach with an MPC controller. As shown in [Figure 2: see original paper], the MPC controller takes reference signals, angle feedback, and speed feedback from Motor 1 and Motor 2 as inputs. Through model prediction and control command constraints, it calculates velocity commands for Motor 1 and Motor 2, achieving target angle tracking while improving speed synchronization performance between the two motors.

2.2 Servo System Mathematical Model

As shown in [Figure 1: see original paper], large reflector antenna servo systems exhibit complex and flexible structures while experiencing various external disturbances. The servo system can be expressed in state-space form as:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) + B_d d(k) \\ y(k) &= Cx(k) \end{aligned}$$

where k represents the time step, $y(k) = [\omega_1(k); \omega_2(k); \theta(k)]^T$ with $\theta(k)$ being the controlled object angle and $\omega_1(k)$ and $\omega_2(k)$ being the angular velocities of Motor 1 and Motor 2 respectively; $x(k)$ is the system state; $u(k) = [u_1(k); u_2(k)]^T$ represents the control inputs for Motor 1 and Motor 2; $d(k) = [d_1(k); d_2(k); d_3(k)]^T$ represents the aggregated unmodeled dynamics and external disturbances from velocity commands to the two motor angular velocities and load; and A, B, C, and B_d are system coefficient matrices.

3 MPC Controller Design Based on DOB and LOB

This section designs DOB and LOB to obtain disturbance and state estimates. Based on ensuring observer stability, the prediction model in the MPC controller is updated and compensated. Simultaneously, constraints on motor velocity command outputs are incorporated into the cost function, and optimal solutions are obtained through rolling optimization to achieve motor speed synchronization. The algorithm process is shown in [Figure 3: see original paper].

3.1 Observer Design and Stability Analysis

Through DOB design, we calculate the aggregated unmodeled errors and external disturbances of the servo system. The DOB does not directly compute disturbances but rather calculates an auxiliary variable to indirectly determine disturbance magnitude. Building upon Chen et al., the following DOB is designed:

$$\begin{aligned} z(k+1) &= (I - KB_d)z(k) - KB_d K\hat{x}(k) - K[A\hat{x}(k) + Bu(k)] + K\hat{x}(k) \\ \hat{d}(k) &= z(k) + K\hat{x}(k) \end{aligned}$$

where $\hat{d}(k)$ is the disturbance estimate, $\hat{x}(k)$ is the estimated system state at the current time step, $u(k)$ is the velocity command, $z(k)$ is the estimate of the auxiliary variable for $d(k)$, and K is an adjustable parameter matrix.

Since true states of the radio telescope servo system are unmeasurable during operation, a LOB is designed to estimate the actual system states. The LOB is designed as:

$$\begin{aligned} \hat{x}(k+1) &= A\hat{x}(k) + Bu(k) + B_d\hat{d}(k) + L(y(k) - \hat{y}(k)) \\ \hat{y}(k) &= C\hat{x}(k) \end{aligned}$$

where $y(k)$ and $\hat{y}(k)$ are the actual and theoretical system outputs respectively, and L is an adjustable parameter matrix.

To ensure that both DOB and LOB estimates converge to actual disturbances and states, the coefficient matrices K and L must be properly designed. Subtracting the estimated disturbance $\hat{d}(k+1)$ and state $\hat{x}(k+1)$ from equations (2) and (3) from the actual disturbance $d(k+1)$ and state $x(k+1)$ at time step $k+1$, and combining equations (2) and (3) yields:

$$\begin{aligned} x(k+1) - \hat{x}(k+1) &= (A - LC)(x(k) - \hat{x}(k)) + B_d(d(k) - \hat{d}(k)) \\ d(k+1) - \hat{d}(k+1) &= -KLC(x(k) - \hat{x}(k)) + d(k+1) - \hat{d}(k) \end{aligned}$$

Since unmodeled errors and external disturbances change slowly relative to the servo control system sampling period, we assume $d(k+n) = d(k)$ for $n > 1$, obtaining:

$$\begin{bmatrix} x(k+1) - \hat{x}(k+1) \\ d(k+1) - \hat{d}(k+1) \end{bmatrix} = \begin{bmatrix} A - LC & B_d \\ -KLC & I \end{bmatrix} \begin{bmatrix} x(k) - \hat{x}(k) \\ d(k) - \hat{d}(k) \end{bmatrix}$$

Thus, selecting appropriate K and L to ensure eigenvalues of the matrix on the right side of equation (5) lie within the unit circle satisfies the requirement for observer convergence. While reducing the eigenvalue magnitudes can accelerate disturbance and state convergence, smaller eigenvalues are not always better. In practical operating conditions, actual system outputs typically contain measurement noise, and excessively small eigenvalue magnitudes amplify this noise. Therefore, observer parameters must be reasonably adjusted according to actual operating conditions.

3.2 Controller Design

Establishing the servo system prediction model and substituting the disturbance estimate $\hat{d}(k)$ and state estimate $\hat{x}(k)$ into equation (1) yields:

$$\begin{aligned} x_o(k+1) &= A\hat{x}(k) + Bu(k) + B_d\hat{d}(k) \\ y_o(k) &= Cx_o(k) \end{aligned}$$

where $y_o(k) = [\omega_{1o}(k); \omega_{2o}(k); \theta_o(k)]^T$, with $\omega_{1o}(k)$ and $\omega_{2o}(k)$ representing the predicted outputs for Motor 1 and Motor 2 respectively, and $\theta_o(k)$ representing the predicted load angle output.

Define the predicted output vector $\hat{Y}(k)$ and control input vector $\hat{U}(k)$:

$$\begin{aligned} \hat{Y}(k) &= [y_o(k+1); y_o(k+2); \cdots; y_o(k+N_p)]^T \\ \hat{U}(k) &= [u(k); u(k+1); \cdots; u(k+N_c-1)]^T \end{aligned}$$

where N_p and N_c are the prediction horizon and control horizon respectively, satisfying $N_p > N_c$. After N_c steps of prediction, the control variables remain constant, and the disturbance $\hat{d}(k)$ is assumed unchanged within the prediction horizon:

$$\begin{aligned} u(k+i) &= u(k+N_c-1), \quad i = N_c, N_c+1, \cdots, N_p \\ \hat{d}(k+i) &= \hat{d}(k), \quad i = 1, 2, \cdots, N_p \end{aligned}$$

Compared to the actual system model, the prediction model contains unmodeled errors. Although DOB can compensate for these errors in the prediction model and equation (8) assumes a disturbance form, identical solutions cannot be obtained for the disturbance, resulting in error between predicted and actual outputs. For the dual-motor case, the error is:

$$e(k) = [e_{\omega 1}(k); e_{\omega 2}(k); e_\theta(k)]^T = y(k) - y_o(k)$$

where $e_\theta(k)$ is the deviation between measured and estimated load angle, and $e_{\omega 1}(k)$ and $e_{\omega 2}(k)$ are deviations between measured and estimated angular velocities for Motor 1 and Motor 2 respectively.

Prediction errors exist for all future N_p steps, and future actual outputs cannot be measured. Assuming future N_p step prediction errors equal the current prediction error $e(k)$:

$$e(k + N_p) = e(k + N_p - 1) = \cdots = e(k)$$

Using the current actual output $y(k)$ and predicted output $\hat{y}(k)$, MPC calculates $\hat{Y}(k)$ and $e(k)$ and substitutes them into the cost function to minimize it, thereby obtaining $U(k)$. Considering the time-varying nature of the system, only the first calculated control input is applied to the system, enabling rolling optimization. In practical systems, control inputs $U(k)$ have upper and lower limits, requiring constraints in the cost function. The cost function adopts a quadratic form:

$$J = \sum_{i=1}^{N_p} (q_1[\theta_o(k+i) + e_\theta(k+i) - \theta_r(k+i)]^2 + q_2[\omega_{1o}(k+i) + e_{\omega 1}(k+i) - \omega_{2o}(k+i) - e_{\omega 2}(k+i)]^2) + \sum_{j=1}^{N_c} u(k$$

where $\theta_r(k)$ is the reference trajectory, q_1 and q_2 are output weighting coefficients (positive real numbers), R is the control weighting coefficient matrix (generally diagonal with positive elements), and the control input $u(k+i)$ is constrained by $u_{\min}(i)$ and $u_{\max}(i)$, i.e., $u_{\min}(i) \le u(k+i) \le u_{\max}(i)$ for $0 \le i \le N_c - 1$.

4 Simulation Analysis

We designed simulation tests with a 90° step command and a periodic command signal of $10\sin(0.5t)^\circ$ in dual-motor synchronization configuration to evaluate the proposed method and compare it with PI+CS. presents the servo system simulation parameters. Since traditional mechanism modeling cannot easily obtain these parameter values, they were obtained through system identification of the experimental platform described below. The MPC+DOB+LOB cost function parameters are: $N_p = 10$, $N_c = 10$, $q_1 = 100$, $q_2 = 100$, $R = [1, 0; 0, 1]$. Control input constraints in this study are time-invariant with fixed limits: $u_{\min} = -10$ V, $u_{\max} = 10$ V. The PI+CS controller parameters are: $P = 0.54$, $I = 0.007$, $A = 0.0018$. To investigate controller robustness, parameters in the coefficient matrices for the two motors were modified, and different step disturbances were applied to Motor 1 and Motor 2 at system startup.

As shown in [Figure 4: see original paper], with proper controller parameter tuning, both methods achieve 0° overshoot for step signal tracking. However, the PI+CS approach exhibits longer settling time compared to the proposed method, and adjusting the proportional term parameter P requires trade-offs between overshoot and settling time. [Figure 5: see original paper] and [Figure 6: see original paper] demonstrate that MPC+DOB+LOB achieves faster synchronization adjustment for dual-motor speed control, with a maximum synchronization error of 21 rad · min^{1}, maintaining good synchronization during both dynamic response and steady-state processes. Compared to PI+CS, the proposed method only reduces velocity command gain during the initial dynamic stage while ensuring excellent control performance and speed synchronization throughout the entire motion process. Furthermore, PI+CS exhibits a maximum synchronization error of 77 rad · min^{1} during dynamic response and cannot completely eliminate error in steady state, which is related to using only proportional terms in the cross-coupled structure.

The angular displacement response curves in [Figure 7: see original paper] show that PI+CS exhibits significant lag when tracking periodic signals, which cannot be effectively eliminated even after adjusting proportional and integral parameters. [Figure 8: see original paper] and [Figure 9: see original paper] present dual-motor speed synchronization results for both methods, with maximum synchronization errors of 12 rad · min^{1} and 24 rad · min^{1} for MPC+DOB+LOB and PI+CS respectively. This improvement occurs because the proposed method utilizes model prediction, multi-step control prediction of command signal time series, and observer error compensation to achieve better tracking precision and smaller synchronization error.

5.1 Experimental Platform Setup

We constructed a hardware-in-the-loop experimental platform simulating antenna elevation motion, consisting of a drive control unit and hardware platform. The drive control unit includes a host computer, motion controller, and drivers, with communication time of 10 ms between host computer and motion controller. The hardware platform comprises servo motors, an 81:1 reduction gear, load, and angle encoder. Motor speed is limited to ±500 rad · min^{1}, and angle encoder sampling frequency is 200 Hz. The experimental control structure is shown in [Figure 10: see original paper], where the host computer reads speeds of Motor 1 and Motor 2 and the load angle, then outputs velocity commands for both motors after computation.

5.2 Experiments and Analysis

To verify the proposed control method’ s effectiveness under actual operating conditions, we compared MPC+DOB+LOB with PI+CS for step and periodic signal tracking performance, analyzing dual-motor speed synchronization during tracking. The simulation experiments in this study were designed to mimic actual operating conditions, with parameters tuned in simulation then applied to practical conditions. Therefore, experimental conditions are similar to simulation: step command of 90° and periodic command of $10\sin(0.5t)^{\circ}$. Results are shown in [Figure 11: see original paper]–[Figure 16: see original paper].

As shown in [Figure 11: see original paper], both MPC+DOB+LOB and PI+CS exhibit identical overshoot, but the proposed method achieves a rise time of 1.45 s, shorter than the 1.51 s rise time of PI+CS, thus providing faster response. Regarding speed synchronization, [Figure 12: see original paper] and [Figure 13: see original paper] present dual-motor speed responses and synchronization errors during step signal tracking for both methods. Through observer compensation of model errors and disturbances, the proposed method achieves a maximum synchronization error of 41 rad · min^{1}, compared to 140 rad · min^{1} for PI+CS. This demonstrates superior tracking and synchronization performance for step signals, consistent with simulation results.

As shown in [Figure 14: see original paper], both methods exhibit periodic errors when tracking periodic signals, but MPC+DOB+LOB demonstrates smaller tracking error than PI+CS. [Figure 15: see original paper] and [Figure 16: see original paper] show that during tracking of low-amplitude periodic commands with slowly varying motor speeds, both methods maintain small speed synchronization errors, but MPC+DOB+LOB achieves a maximum synchronization deviation of 4 rad · min^{1} versus 6 rad · min^{1} for PI+CS. Consistent with simulation results, MPC+DOB+LOB provides superior load angle response and smaller maximum motor speed synchronization error compared to PI+CS when tracking periodic signals.

6 Summary and Outlook

This paper investigates synchronous control of drive motors in radio telescope servo systems, proposing an MPC+DOB+LOB control method verified through simulation and experiments. Results demonstrate that this method reduces speed synchronization errors during motor operation in radio telescope servo systems while ensuring target signal tracking. Compared to conventional PI+CS, the controller exhibits better dynamic performance, steady-state performance, and robustness. The method can more simply and conveniently achieve synchronization control for three or more motors by increasing input variables and modifying the cost function, without the power-of-two limitation on motor count. This provides a reference method for improving synchronous drive performance of QTT antenna servo systems and enhancing QTT antenna pointing accuracy.

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Note: Figure translations are in progress. See original paper for figures.