The Sliding Mode Control Algorithm Used in the SONG Tracking Servo System[1※]

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ABSTRACT

China SONG telescope would achieve the goal for long time continuous, uninterrupted, full automatic observation and works in the diffraction limit condition with high tracking precision and reliability, which puts forward a serious challenge to the tracking control system. This paper explores one sliding mode control algorithm to improve the performance of China SONG telescope tracking system. The results show that the algorithm can get higher precision, which has high exploration significance for the telescope tracking system.

Key words:direct drive; torque fluctuations; China SONG Telescope; sliding mode control

1. INSTRUCTION

Generally, the telescope current loop is integrated with a servo amplifier. a pair of motors is involved for dampening the unwanted anti-resonance mode in the drive system, which acts same as a low pass filter. The velocity controller should also include an acceleration limit in its step response. The position controller has a direct impact on telescope pointing accuracy. It is usually a PID one or some type of combination controller with signal feed forward. In a combined controller, when the position error is small, a proportional control is used as it provides rejection on turbulence. A motion profiler is added to feed-forward the future position or/and velocity commands for avoiding resonance in lower frequency ranges. Most domestic and international astronomical telescope tracking system is also widely used, such as the Keck [1], VLT [2] and other large telescope. However, with the demand of larger diameter, higher tracking precision, there is a very huge challenge for the future telescope, The modern large telescope is endowed with advanced imaging systems and active optics, resulting in very high peak angular resolution. The drive systems for the telescope must consequently be able to guarantee a tracking accuracy

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better than the telescope angular resolution, in spite of unbalanced and sudden loads such as wind gusts and in spite of a structure that, because of its size, cannot be infinitely stiff, which puts forward a great challenge to the telescope's drive system. Traditional PID control cannot fundamentally solve the contradiction between static and dynamic performance, tracking data and disturbance, which is more apparent in telescope with such a huge inertia.

In the dynamic running process of many actual systems, there are often discontinuous values such as nonlinear torque fluctuation, the wind disturbance and so on. Former Soviet Union scholars have studied the dynamic characteristics of the controlled system that contains of discrete items and proposed the variable structure control theory. That is, by selecting the switching law, the controlled system is attracted to sliding surface in accordance with the desired designed trajectory and switched on the surface in their movement. What's more the controlled system is not subject to outside influence. It is base idea of sliding mode control [3].Sliding mode control algorithm has been widely used in various precision servo tracking control systems for high-precision in the multi-interference system, strong robust feature and so on [4]. Just because of these excellent characteristics, combined with large telescope tracking control servo system that exists many nonlinear disturbances, such as the nonlinear load torque changes, wind disturbance , one sliding mode controller is designed to meet the tracking control performance requirements. This paper explores sliding mode control algorithm for the large telescope direct drive platform servo system.

2. CHINA SONG TELESCOPE'S TRACKING SYSTEM

China SONG telescope's scientific goals not only require that it would observe the target continuous and uninterrupted in long time, but also must work in the diffraction limit condition, active optical technology and direct drive technology in its tracking system is used in the China SONG standard node telescope. the tracking system is mainly consisted of controllers(UMAC), actuators (direct drive motors), position sensors etc., of which the position, velocity and acceleration has to be controlled. the main hardware is shown in figure 1. Position feedback information is measured by the HEIDENHAIN company's no built-in bearing angle encoder ERA 4282 C, 52000 lines, including ERA 4202 C grating drum and four reading heads ERA 4280. Encoder signals are subdivided into 4096 by ACC-51E of UMAC as position feedback signals. Industrial PC receives telescope observation system (OCS) or remote control system's instructions through the Ethernet and instructs UMAC to control multiple servo motors to implement multi-axial coordinated motion after certain data processing. The control information is outputted by UMAC to servo amplifiers to drive and control servo motor, and form one multi-axes (Azimuth, Altitude) closed loop control system. one PCI GPS card is plugged in the IPC to receive and get accurate UTC time and geographical coordinates. the tracking target 's azimuth Angle and height is calculated by astronomical formula according to the information and the target ascension and declination coordinates, which is feed back to the telescope tracking controlling system to implement target tracking and pointing.

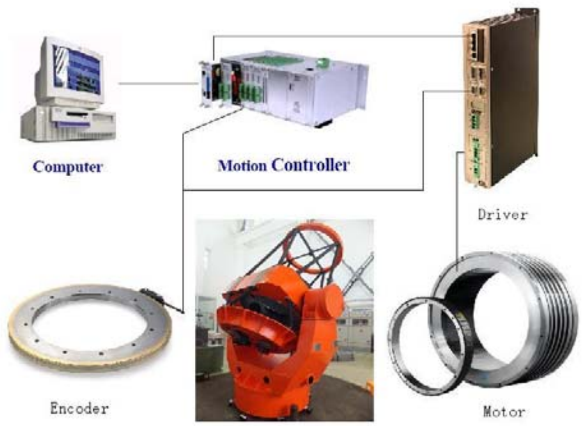


Figure1. the construction of hardware of China SONG Telescope tracking system

3. TRACKING SYSTEM CONTROL MODEL

The mathematical model is simplified to facilitate the realization of the design within the accuracy permissibility of the system. Hysteresis control mode is adopted in current loop, which the direct drive motor and inverter, including current loop can be thought as one generalized controlled object. In addition, the electromagnetic time constant of the system is much smaller than mechanical and the current loop response speed is much faster than the speed and position loop, so, the model simplifies the current loop as one proportional coefficient approximately "1" ($i_q^* / i_q = 1$). After evaluation, three closed-loop position servo system controller of the China SONG Telescope's tracking system is simplified as only two closed-loop system, that is PCR (position controller) and ASR (speed regulator), the equivalent block diagram is shown in figure 2.

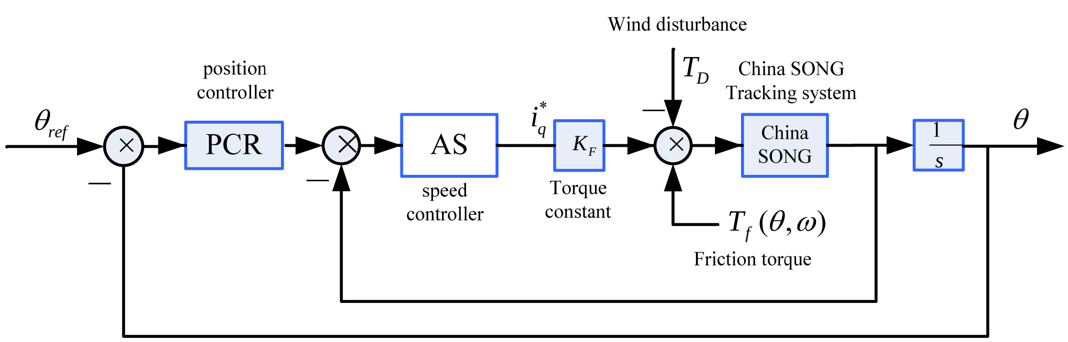


Figure 2. the simplified China SONG Telescope's tracking system servo system

The mathematical model of the China SONG Telescope is firstly established in order to analyze the performance of the direct drive servo tracking system. The mathematical model of the servo system includes mechanical and electrical parts, where the mechanical motion equation can be expressed as:

$$J\frac{d\omega_r}{dt} = T_e - B\omega_r - T_L - T_D - T_f \tag{1}$$

Where:

J—inertia of system converted to the motor rotor shaft;

T_e—Motor electromagnetic torque;

B— Viscous friction coefficient;

ω_r—Rotor mechanical angular velocity;

T_L—Load torque;

T_D—Disturbance torque;

T_f—Friction torque;

Electrical model is founded in the *d-q* coordinate system. The direct drive motor current and voltage equations are expressed as follows:

$$\frac{di_d}{dt} = \frac{1}{L_d}(V_d - R_s i_d + \omega_s L_q i_q) \tag{2}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}(V_q - R_s i_q - \omega_s L_d i_d - \omega_s \lambda_f) \tag{3}$$

$$T_e = \frac{3}{2} p\Psi i_q = K i_q \tag{4}$$

$$\omega_s = p\omega_r \tag{5}$$

$$\frac{d\theta_r}{dt} = \omega_r \tag{6}$$

Where:

ω_s—Electrical motor angular velocity;

p—Rotor pole pairs;

R_s—Stator winding resistance;

Ψ— Rotor flux;

L_q、 L_q —d axis and q axis inductance；

T_e —The motor torque curve;

K— Motor torque coefficient.

4. REACHING LAW BADED SLIDING MODE CONTROL

Some load parameters of the China SONG telescope tracking servo system, such as torque, moment inertia, sharp mutation of motion direction, is changed very much sometime during the tracking and pointing process. What's more, there exists operating point drift and parameter perturbation when the direct drive motor runs. In addition, the system stability is impacted by the strong electromagnetic interference in industrial environments. The magnetic field component of the drive motor is regarded as constant in order to simplify decoupling calculations. One sliding mode control strategy with strong robustness, insensitive to the parameters is discussed in the paper improve the performance although there exits load variation and parameters perturbation in the tracking servo system.

Basic idea of sliding mode control is that the dynamic performance of controlled system is always has been designed to be constrained to the defined sliding surface by switching back and forth through sliding surface and the controlled system will automatically dynamic slide along the sliding surface to the origin. Advantages of sliding mode control is mainly reflected that once the controlled system reaches the sliding surface phase point, then the system operating mode depends only on the sliding surface equation and has nothing to do with the system's original parameters. Even though the system parameters have a greater change, as long as the sliding surface is reachable, the sliding mode control can be achieved. Therefore, sliding mode control method is not only robust to interference but also can be achieved to track any continuous change of the input signal. Because of these characteristics, combined with a China SONG telescope tracking servo system where there exists much nonlinear interference, one sliding mode controller is designed to improve the tracking performance of China SONG telescope tracking and pointing servo system.

Mathematical model of China SONG telescope tracking and pointing servo system could be described by the state space, and set the system state variables as:

$$x_1(t) = \theta_{ref} - \theta_r \tag{7}$$

$$x_2(t) = \frac{dx_1(t)}{dt} = -\omega_r \tag{8}$$

According to China SONG Telescope mechanical equations of motion and the electromagnetic torque equation ($i_d = 0$), the state-space equation can be evaluated as:

$$\begin{cases} \dfrac{dx_1(t)}{dt} = x_2(t) = -\omega_r \\ \dfrac{dx_2(t)}{dt} = \dfrac{1}{J}[Ki_q^* - Bx_2(t) - (T_L + T_D + \mathrm{T_f})] \end{cases} \tag{9}$$

Namely:

$$\begin{bmatrix} \dfrac{dx_1(t)}{dt} \\ \dfrac{dx_2(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -B/J \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ -K/J \end{bmatrix} i_q^* + \begin{bmatrix} 0 \\ -1/J \end{bmatrix} (T_L + T_D + T_f) \tag{10}$$

Define:

$$U(t) = i_q^*, A = \begin{bmatrix} 0 & 1 \\ 0 & -B/J \end{bmatrix}, H = \begin{bmatrix} 0 \\ -K/J \end{bmatrix}, D = \begin{bmatrix} 0 \\ -1/J \end{bmatrix}, \frac{dX}{dt} = \begin{bmatrix} \dfrac{dx_1(t)}{dt} \\ \dfrac{dx_2(t)}{dt} \end{bmatrix}, X = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}$$

And there is:

$$\frac{dX(t)}{dt} = AX(t) + HU(t) + D(T_L + T_D + \mathrm{T_f}) \tag{11}$$

Sliding mode control approach rate is designed for China SONG telescope tracking and pointing servo system, and the switching function is expressed as:

$$s = ce + \dot{e} \tag{12}$$

Exponential reaching rate function is selected in le sliding mode controller:

$$\dot{s} = -\varepsilon \operatorname{sgn}(s) - ks \tag{13}$$

Where $\varepsilon > 0, k > 0$, and considering the nonlinear interference effects on the controlled system the sliding mode surface function can be obtained:

$$\dot{s} = c\dot{e} + \ddot{e} = c\dot{e} + \ddot{r} - \ddot{x} = c\dot{e} + \ddot{r} - [-\frac{B}{J}x + \frac{K}{J}u - \frac{1}{J}(T_L + T_D + T_f)] \tag{14}$$

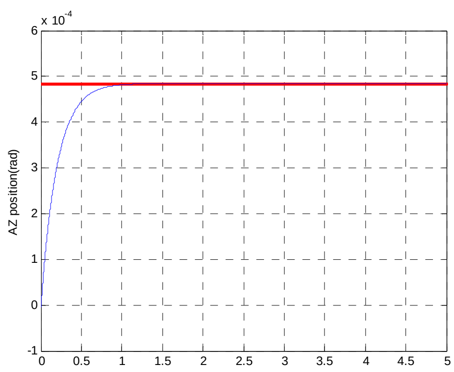
Thus the amount of available control value u can be evaluated as:

$$u = \frac{J}{K}[c\dot{e} + \ddot{r} + \varepsilon \operatorname{sgn}(s) + ks + \frac{B}{J}x + \frac{1}{J}(T_L + T_D + T_f)] \tag{15}$$

5. SIMULATION AND ANALYIS

the rotary moment of inertia of AZ axis reach the max value for $J = 1451 kg \cdot m^2$ when the tube is horizontal, AZ axis damping coefficient B is 0.033, the confounding factors has not been more precise estimated and the simulation process does not take into account the actual non-linear disturbances, but only with random noise to simulate. When the exponential reaching rate parameters are determined as $\varepsilon = 1.5$, $k = 25$ and the system tracks one 4.85×10^{-6}rad step signal, the simulation results are shown in figure 4,figure 5.

Figure3. China SONG Telescope



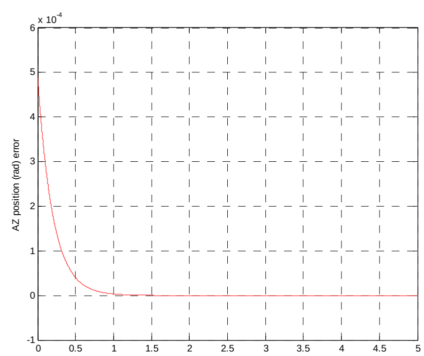
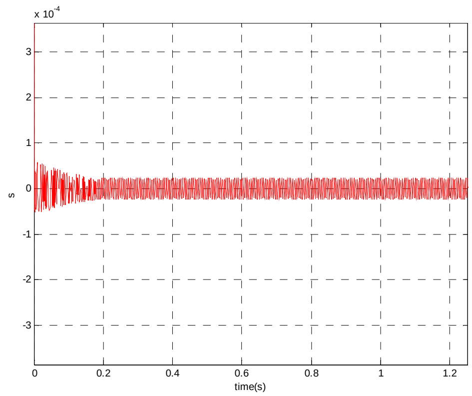


Figure 4. Reaching rate based sliding mode control position for the 4.85×10^{-6} rad system response curve.Figure 4. Reaching law based sliding mode control position is 4.85×10^{-6}rad system error curve.



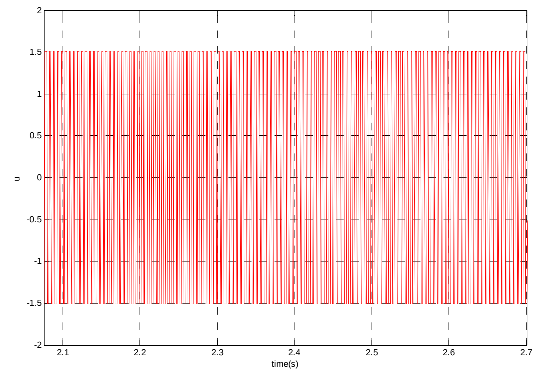


Figure 5. Reaching rate based sliding mode control position is 4.85 $\times 10^{-6}$ rad curve Figure 6. Reaching law based sliding mode control position for the 4.85 $\times 10^{-6}$ rad u curve the amount of system control

From the simulation results, it can be proofed that China SONG telescope tracking and pointing servo system can be achieved high accuracy by sliding mode control approach control based on exponential reaching rate function. However, from the results of the controller control value and switching function, there exists high frequency jitter, which is closely interrelated to high-speed switching inverter of the servo motor. Therefore, in the actual system, the impact of high frequency jitter in the sliding mode controller on the switching frequency of the inverter must be considered and make deeper research.

6. CONCLUSION

China SONG telescope's scientific goals demand it works in the diffraction limit condition, which make it must realize 0.3 arc second or even better tracking precision without guide star. direct drive technology is used in the China SONG standard node telescope. Simulation results show that the sliding mode control approach based on exponential reaching rate function can achieve high accuracy in the China SONG telescope tracking and point system. However, there exists high frequency jitter, which is closely interrelated to high-speed switching inverter of the servo motor. Therefore, the real control effect should be verified in future test in the actual system.

7. REFERENCES

[1]. Martin Ravensbergen, "Main axes servo systems of VLT", proc. Of SPIE vol. 2199, 1994, 997-1005,

[2]. Mark J. Sirota, Peter M. Thompson. "Azimuth/elevation servo performance of the W.M. Keck telescope", proc. of SPIE vol. 2199,1994,126-141

[3]. Zinober, A., O. Ei-Ghezawi, and S. Billings. "Multivariable-structure adaptive model-following control systems" , Proc. of IEEE, 1982,129 , 6-12

[4]. Xian, B., M. S. Queiroz, D. M. Dawson, and M. L. McIntyre., "A discontinuous output feedback controller and velocity observer for nonlinear mechanical systems", Automatica[J], 2004,40 :695-700

[5]. Davila, J., L. Fridman, and A. Levant,"Second-order sliding-mode observer for mechanical systems", IEEE Transactions on Automatic Control[J] , 2005,50:1785-1789,.

[6]. Fridman, L. "Chattering analysis in sliding mode systems with inertial sensors", International Journal of Control[J], 2003,76 , 906-912

[7]. RenChangzhi, XuJin,etc. "China SONG Telescope Tracking System Based on Direct Drive Technology", Proc. of SPIE Vol. 8449,2012