Design of the Robust Controller of the APT Fine Tracking System Based on the Structured Singular Value Theory

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Abstract

APT (Acquisition, Pointing, Tracing) system is the important component of the space laser communication system, and its tracing accuracy is mainly determined by the fine tracing subsystem. To enhance the tracing accuracy and robustness of the APT system, the robust control technology based on the structured singular value theory (μ integration) is adopted in the design of the controller of the APT fine tracing subsystem, and the mathematical model of the augmented object of the fine tracing subsystem based on μ integration is established, and the robust H_∞ controller is designed by the D-K iterative method in this article, and the bandwidth of the fine tracing subsystem could achieve 318 Hz, which could satisfy the requirements of the APT system to the bandwidth of the fine tracing subsystem. The equivalent sine simulation of the system indicates that the system tracing accuracy is better than 0.6 µrad.

Keywords: Laser communication, Compound axis system, Fine tracing subsystem, Robust control, μ integration

1. Components of the APT system

The components of the compound axis APT system are seen in Figure 1, and the coarse tracing subsystem includes the gimbal servo turntable and the coarse-tracing CCD, with the characteristics such as wide dynamic range, narrow control bandwidth, lower resonance frequency, and it could accomplish the initial orientation of the laser axis and realize the capture and coarse tracing. The main components of the fine tracing subsystem are the fast steering mirror and the fine tracing detector, and the fine tracing subsystem could further correct the residual error which could not be compensated by the coarse tracing loop, to satisfy the aiming and tracing accuracy required by the system (Toyoda Masahiro, 2006, P.4-12 & Tzung-Hsien Ho, 2005, P.81-92 & T. Tolker-nielsen, 2002, P.6-20 & Liu, 2006, P.103-103).

2. Mathematical model of the fine tracing subsystem

The executive component of the fine tracing subsystem is the two-dimensional fast steering mirror, and its mathematical model is

$$G_F(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{8.2 \times 10^7}{s^2 + 1.3 \times 10^4 \times s + 8.2 \times 10^7}$$

The fine tracing imaging system is the CCD camera with the frame frequency of 1600 Hz, and its mathematical model could equal a delay factor, and the delay time is determined by the frame frequency of the fine tracing CCD camera.

3. Design of the robust controller based on the structured singular value theory (μ integration)

3.1 Establishment of the fine tracing system augmented object model based on μ integration

The robust control structure of the fine tracing subsystem is seen in Figure 2, and $K(s)$ is the transfer function of the system controller, and θ_i is the target visual axis, and θ_o is the visual axis of fine tracing. d_1 is the main disturbance acting on the visual axis of fine tracing, d_2 and z_2 are evaluation signals of the system to the multiplicative perturbing robustness, z_3 is the evaluation signal to the control signal of system, z_1 is the evaluation signal to the response of the system to the disturbance, W_1 is the weighted function to measure the disturbance performance of the system, W_2, W_3 and W_4 respectively are the weighted functions of multiplicative perturbing, disturbance perturbing, and control signal. $\Delta(s)$ is multiplicative perturbing, and $\|\Delta\|_\infty < 1$. The augmented object model of the fine tracing system based on μ integration obtained from Figure

2 is seen in Figure 3.

3.2 Selection of the weighted function

The selection of the weighted function is the core approach of the robust controller design based on μ integration, and the weighted function determines the robust stability and the robust tracing performance of the system, and through repeated adjustment, the weighted function is

$$\omega_1(s) = \frac{0.782s + 100}{s + 0.00009}$$

$$\omega_2(s) = \frac{33.3s^3 + 3.567 \times 10^5 s^2 + 1.9 \times 10^9 s + 5.417 \times 10^{12}}{s^3 + 3.967 \times 10^4 s^2 + 4.042 \times 10^8 s + 6.708 \times 10^{12}}$$

$$\omega_3(s) = 0.24$$

$$\omega_4(s) = \frac{9.98s + 1.412 \times 10^4}{s + 1.298 \times 10^5}$$

3.3 The μ integration of controller

The design target of the robust controller based on μ integration is to design the robust H_∞ controller $K(s)$ by the μ theory, and minimize the μ value of the closed-loop transfer function $F(G,K)$ from d to z, i.e. minimize $\mu_\Lambda(M(j\omega))$, and $M(s) = F(G,K)$ (Mei, 2008, P.96-100).

When designing the controller of the APT fine tracing subsystem by the D-K iterative method, the value of μ obtained through three times of iteration equals the norm of H_∞, and the iterative process ends. The order of controller and the μ values of the corresponding controllers are seen in Table 1.

From Table 1, the values of μ of the third iteration and the second iteration are very close with the norm of H_∞, because the order of the controller obtained in the third iteration is higher. So the result of the second iteration is the final controller, and the relationship between the structured singular value and the frequency is seen in Figure 4, and the peak value of μ is 0.413, and the mathematical model of the 13-order controller after two iterations is

$$K(s) = \frac{914.669\,(s + 6e6)\,(s + 1.35e5)\,(s + 3.36e4)^{\wedge}2\,(s + 724.6)\,(s + 347.2)}{(s + 6.001e006)\,(s + 3.458e004)\,(s + 3.264e004)\,(s + 6152)\,(s + 1868)\,(s + 638.8)} \quad \cdots$$

$$\cdot \frac{(s + 309.6)\,(s + 289.5)\,(s^{\wedge}2\, + 6087s + 1.998e008)^{\wedge}2}{(s + 309.5)^{\wedge}2\,(s + 0.0001)\,(s^{\wedge}2\, + 5760s + 1.939e008)\,(s^{\wedge}2\, + 6475s + 2.056e008)}$$

3.4 Analysis of the simulation of the APT fine tracing system based on robust H_∞ controller

Through designing the robust controller by the μ theory, the step response and the closed-loop frequency characteristic curve of the fine tracing system respectively are seen in Figure 5 and Figure 6, and the bandwidth of the fine tracing subsystem is 2000 rad/s (318.3 Hz), and the adjustment time is 0.0045s, and the overshoot is zero, which all could satisfy various index requirements of the system.

4. Simulation of the tracing performance of the compound axis APT system

The simulation analysis of the tracing performance of the APT system is implemented by adding equivalent sin signal to the APT signal. According to the maxim work speed and the accelerated speed required by the system, the amplitude of the equivalent sin signal is 0.0262 rad, and the frequency is 2 rad/s (Hu, 2005, P.7-9 & Fu, 1998, P.5-10 & Wu, 2008, P.41-47).

From the simulation result, the responses of the APT system based on the robust control and the system based on the routine compensation respectively are the curve 1 and the curve 2 in Figure 7. The part error enlargement figure of the APT system based on the robust control is Figure 8. The result shows that the robust control based on μ integration could enhance the tracing accuracy of the system, and the tracing accuracy of the system is better than 0.6 μrad.

5. Conclusions

In this article, the μ integration method is used to design the robust H_∞ controller of the APT fine tracing subsystem, which could make the system bandwidth achieve 318 Hz. By the equivalent sin simulation of the APT system, the result shows that robust control technology based on μ integration could make the tracing accuracy of the fine tracing system exceed 0.6 μrad.

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Tzung-Hsien Ho, Stuart D. Milner, Christopher C Davis. (2005). Fully optical real-time pointing, acquisition and tracking system for free space optical link. *Proc.SPIE.* Vol.5712. P.81-92.

Table 1. D-K iterative result

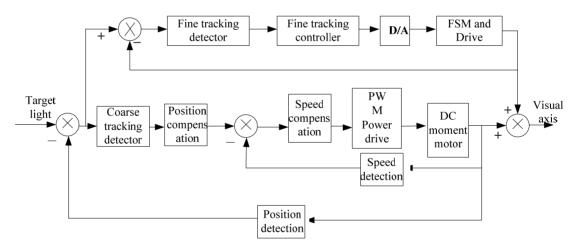| Iterative times	Orders of controller	μ	H_∞ Norm
1	10	0.488	1.598
2	13	0.409	0.413
3	16	0.396	0.396

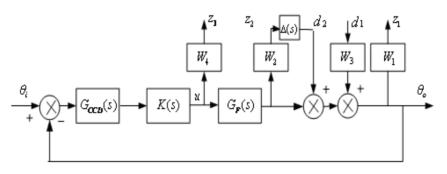Figure 1. Block Diagram of the APT System

Figure 2. Robust Control Structure of the Fine Tracking Subsystem
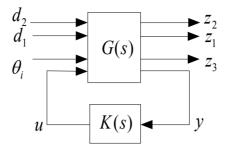
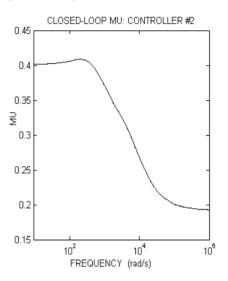Figure 3. Augmented Object Model of the Fine Tracking System

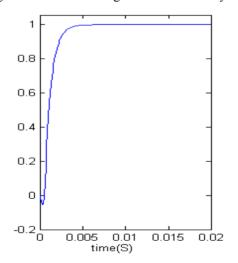Figure 4. Structured Singular Value of the System

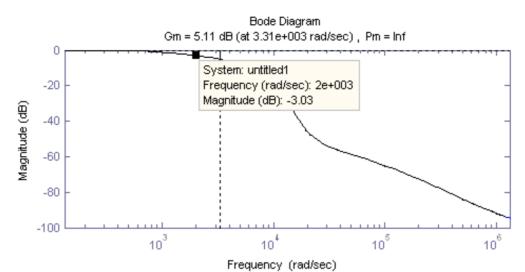
Figure 5. Step Response of the Fine Tracking System

Figure 6. Closed-loop Magnitude-frequency Characteristic of the After-compensation Fine Tracking Subsystem
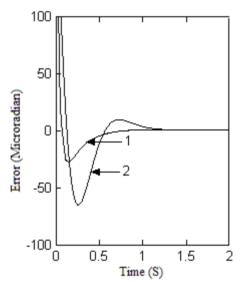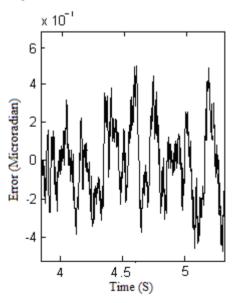
Figure 7. Equivalent Sine Simulation Result of APT System

Figure 8. Part Enlargement of Error