Parameter Tuning of PID-I Controller for Optoelectronic Tracking System Based on NSGA-II Multi-Objective Optimization

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Abstract. In order to solve the delay in the optoelectronic tracking system, some scholars have proposed the PID-I controller based on the traditional PID controller. PID-I controller is formed by connecting an integrator in series to improve the system performance of the CCD position closed loop. But how to choose controller parameters is a key factor in determining system performance. The open-loop gain and bandwidth of the system are two important indicators for selecting the controller parameters, but these two indicators are coupled and cannot achieve the optimal performance at the same time. Meanwhile, the multidimensionality of the controller parameters also makes it difficult to set the parameters. In view of the above problems, traditional numerical methods and artificial experience methods cannot obtain good controller parameters. Therefore, this paper uses the NSGA-II multi-objective optimization algorithm to optimize the open-loop gain and bandwidth of the system at the same time by a non-inferior ranking method to achieve the purpose of optimizing the controller parameters. The theory and simulation show that the performance of the optoelectronic tracking system using this multi-objective optimized PID-I controller is better than that of the PID-I controller optimized by numerical methods in closed-loop bandwidth and step response indicators.

1. Introduction
In the optoelectronic tracking system, it has been widely used in space optical communication, adaptive optics, precision measurement, aerospace and other fields [1]. Charge-coupled device is a high-sensitivity, small-capacity imaging element used in the closed-loop position of an optoelectronic tracking system to detect position deviation. The feedback position deviation is used as the input signal of the system. This forms a closed loop system. In closed loop systems, time delay is the biggest factor limiting control performance [2][3]. How to improve the closed-loop performance in the delay system has always been a technical problem that researchers concerned. Reducing the time delay by improving hardware and software performance is a preferred method for researchers [4][5]. However, if the CCD integration time is too short, its detection performance will be greatly affected. Some scholars have proposed a method of using predictive control to compensate for time delay, but predictive control will bring system instability, and in the case of large measurement noise, the performance of the system will be greatly limited[3]. Therefore, the PID-I controller used in this paper adds an integral action to the traditional PID controller to form a controller with two integrals. The tuning of the controller parameters...
has an important impact on the performance of the system. Bandwidth and open-loop gain are two important metrics for measuring system performance. Some scholars have proposed numerical analysis methods to set the parameters [6], but this method only considers the open-loop gain method. The parameters are not balanced by the bandwidth and open-loop gain, and there is a hypothesis between the parameters decided by engineers. In this paper, an NSGA-II multi-objective optimization algorithm based on pareto sorting is adopted. The bandwidth and open-loop gain are used as two objective functions to optimize the controller parameters. The simulation analysis shows that the controller parameters obtained by multi-objective optimization have better improvement in the step response index such as bandwidth, overshoot and adjustment time.

2. The establishment of control model

2.1 Optoelectronic tracking system controlled object model

The optoelectronic tracking system using CCD sensor is shown in Figure 1:

![Figure 1. Optoelectronic tracking system control block diagram.](image)

Where: $D(s)$ indicates the time delay, $G_c(s)$ indicates the controller, $G_p(s)$ indicates the controlled object. Since the bandwidth of the inner ring of the photoelectric tracking system is very high, the controlled object can be described as follows:

$$F(s) \approx 1$$ (1)

The control system using CCD closed loop has approximately three times the sampling time delay. These delays mainly come from the integration of CCD, image processing and data transmission, sample and hold, etc. The time delay can be described as follows:

$$D(s) = e^{-\tau s}$$ (2)

2.2 PID-I controller model

The PID-I controller is based on the traditional PID controller to connect an integrator to improve the performance of the system. The form is as follows:

$$G_c(s) = \frac{K_p(T_s + 1)(T_a s + 1)}{s^2}$$ (3)

The system open loop transfer function can be expressed as follows:

$$G(s) = G_p(s)G_c(s) = \frac{K_p(T_s + 1)(T_a s + 1)}{s^2}e^{-\tau s}$$ (4)

Combining equations (1) and (2) (3), the parameter optimization problem for PID-I controllers is essentially the optimization of three parameters $K_p, T_s, T_a$.

3. Multi-objective parameter optimization of PID-I system

3.1 PID-I controller model
The NSGA algorithm proposed by Indian researchers Srinivas and Deb in the 1990s is a way to simplify the multi-objective optimization problem into a fitness function using non-dominated sorting ideas [7]. On this basis, Deb proposed the improved NSGA-II in 2002 [8]. Compared with the previous multi-objective genetic optimization algorithm, it reduces the computational complexity and introduces the congestion degree and congestion comparison operator. In the process of evolution, the parent population is combined with the progeny population obtained from it to ensure that the outstanding individuals in the father are not lost, so as to improve the population level. Figure 2 shows the algorithm flow chart of NSGA-II [9].

3.2 Constraints on system stability
The stability of the closed-loop system can be determined by the phase margin $Pm$ and amplitude margin $Gm$ of the open-loop system. For a stable control system, it is generally necessary to achieve $Pm \geq \frac{\pi}{4}$, $Gm \geq 6dB$. Therefore, the two constraints of the multi-objective problem can be expressed as follows:
4. System multi-objective optimization simulation

4.1 Numerical analysis method optimization results
The sampling frequency of the system CCD is 2000Hz, and the delay of the control loop of the controlled object \( \tau = 0.0015 \text{s} \).

According to the numerical optimization method in [6], the amplitude phase of the system is specified as \( P_m = \frac{\pi}{4} \). The parameter optimization of the PID-I controller can be expressed as:

\[
K_p = \frac{\pi^2}{40\tau^2} = 109551
\]

\[
T_i = \frac{8\tau}{\pi} = 0.00382
\]

\[
T_d = \frac{2\tau}{\pi} = 0.0009554
\]

However, the multiple relationship between \( T_i \) and \( T_d \) of this method is determined by engineering experience, so that it has certain limitations.

4.2 Multi-objective optimization simulation
According to the objective function and constraint requirements in 3.0, the NSGA-II method was used to write a simulation program in matlab. Set the population size to 100, and the result after 1000 iterations is shown as fig 3:
Figure 3. NSGA-II algorithm iteration results.

Among them, the abscissa is the objective function value representing the open-loop gain, and the ordinate is the objective function value representing the bandwidth. The smaller the ordinate and the abscissa, the better the performance of the corresponding controller. The controller parameter values obtained by iteration are:

\[ K_p = 206 \]  \hspace{1cm} (10)

\[ T_i = 0.000732 \]  \hspace{1cm} (11)

\[ T_d = 2.53 \]  \hspace{1cm} (12)

4.3 Simulation analysis and comparison of results

Compare the closed-loop bode diagram of the system using the numerical method to optimize the controller and the system of the NSGA-II multi-objective optimization controller, as shown in Figure 4:
Figure 4. Comparison of closed loop bode diagrams of the system.

Table 1. Comparison of closed-loop indicators of two controllers.

|                        | Numerically optimized PID-I | Multi-objective optimization PID-I | Optimization percentage |
|------------------------|-----------------------------|-----------------------------------|-------------------------|
| Bandwidth              | 324.2105Hz                  | 328.8980Hz                        | 1.44%                   |
| Maximum tracking error | 3.44dB                      | 0.443dB                           | 87%                     |

As can be seen from Figure 4 and Table 1, the closed-loop tracking bandwidth and maximum tracking error of the multi-objective optimized controller are significantly better than the numerically optimized controller.
Figure 5. Comparison of two controllers for sine signal tracking.

Compared with the tracking of a 20Hz sin signal in Figure 5 (a), the error of the multi-objective optimized controller is 13.4%, and the error of the numerically optimized controller is 0.52%.

Compared with the tracking of a 50Hz sin signal in Figure 5 (b), the error of the multi-objective optimized controller is 47.7%, and the error of the numerically optimized controller is 4.17%.

A comparison of the step response curves of the two controllers is shown in Figure 6:

Table 2. Comparison of closed-loop indicators of two controllers.

|               | Numerically optimized PID-I | Multi-objective optimization PID-I |
|---------------|----------------------------|------------------------------------|
| Overshoot    | 6%                         | 30%                                | 80%                               |
From the simulation results and the data in Table 2, it can be seen that the overshoot of the numerically optimized controller is 30%, and the adjustment time is 0.0173s. The overshoot of the multi-objective optimization controller is 6%, and the adjustment time is 0.0173s. Compared with a numerically optimized controller, the overshoot is reduced by 80% and the adjustment time is reduced by 48%.

5. Conclusion
Based on the coupling relationship between the bandwidth and the open-loop gain of the optoelectronic tracking system, which cannot achieve the optimal performance at the same time, a new frequency domain objective function and constraints are designed. The PID-I controller in the photoelectric tracking system was optimized by using the NSGA-II algorithm, and the obtained control parameters were simulated and verified. The closed-loop tracking performance and step response curve were tested. The simulation results show that compared with the numerically optimized controller effect, the multi-objective optimized controller is better than the numerically optimized PID-I controller in closed-loop bandwidth, overshoot, and adjustment time.

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