Design of PID Intelligent Controller Combining Immune Genetic Algorithm

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Abstract. At present, there are many studies on "computer immunology" in the world, and there are many applications of immune genetic algorithm in engineering. The article discusses the immune genetic algorithm in the design of PID intelligent controller. Most objects in the practical industrial process fall in the distributed parameter system (DPS), where the proportional-integral-derivative (PID) control method is used to control the field. In this paper, the PID controller optimization method based on the immune genetic algorithm (IGA) (referred to as the PODM method) is applied to a class of distributed parameter objects to design the optimal controller, which is compared with several controllers based on the conventional tuning formulas. The simulation results suggest that the PID controller designed based on the PODM method can obtain relatively superior control effects in overshoot, tuning time, time integrated time absolute error (ITAE), and other indexes with relatively less control energy. The application of the PODM method to DPS can improve the control level of the PID controller in the industry at present.

Keywords: Proportional-integral-derivative (PID), Distributed Parameter System (DPS), Immune Genetic Algorithm (IGA)

1. Introduction
In the fields of thermal engineering, metallurgy, chemical industry, etc., the control objects generally fall in the distributed parameter system (DPS) [1]. Many advanced control methods for DPSs continue to appear [2-3]. However, they have not been widely used, and proportional-integral-derivative (PID) control has a simple structure, easy to implement, high robustness and easy on-site debugging and other characteristics, are still widely used in industrial process control [3-4].

The transfer function of the distributed parameter model has the form of a transcendental function, which is challenging to apply in system simulation and control design directly. Therefore, the conventional PID controller design [5-6] generally needs to simplify the distributed parameter model of the object into a lumped parameter model. And order reduction, in the process of simplification and order reduction, model errors will inevitably be introduced. To analyze the parameter setting method of PID control more deeply, optimize the PID control system and reduce the failure of the PID...
intelligent controller, it is necessary to study the PID control problem of DPS further.

The optimization design method of PID intelligent controller based on the immune genetic algorithm (IGA) (hereinafter abbreviated as the PODM method) is not restricted by the model form, and can comprehensively consider complex control requirements and constraints, and is suitable for the objects described by general transfer functions; therefore, this paper The PODM method is extended to the design of PID intelligent controller of DPS.

2. Optimized design method of PID intelligent controller based on IGA

The feedback control system studied in this paper is shown in Figure 1.

![Figure 1. Single variable closed loop feedback control system diagram](image)

Where \( r \) represents the set value, \( y \) represents the output value, \( e \) represents the difference between the set value and the output value, \( u \) represents the control amount. \( G_c(s) \) represents the PID controller, as shown in formula (2):

\[
G_c(s) = K_p + \frac{K_i}{s} + K_ds
\]

(1)

Where \( K_p \) represents proportional gain; \( K_i \) and \( K_d \) represent integral coefficient and differential coefficient, respectively.

\( G_p(s) \) represents the controlled object. In this paper, \( G_p(s) \) is a type of distributed parameter object described through a linear heat transfer equation, as shown in equation (2):

\[
G_p(s) = \exp(-ks)
\]

(2)

The design goal of the controller is to determine the appropriate controller parameters \( K_p, K_i \) and \( K_d \), so that the system meets the following 2 requirements:

1) The system's performance indexes such as tuning time, overshoot, ITAE, control energy and anti-disturbance are better.

2) When the object parameter \( k \) is perturbed, the performance of the system is robust.

The design idea of PID controller optimization design method (called PODM method) based on IGA is first to calculate the PID parameter stability domain of the system, then use the genetic algorithm to optimize the parameters within the obtained parameter stability domain, and finally control the system Evaluation of dynamic performance and performance robustness.

2.1. Parameter stability field

PID parameter stability domain refers to the set of all PID controller parameters that ensure the closed-loop stability of the control system. In some studies, a graphical method (D-Partitioning method, DP method) is proposed to describe stable boundaries or relatively stable boundaries. The DP method is suitable for distributed parameter objects, and the calculation is simple and easy to program. Its core concept is as follows: assuming that the controlled object has a transfer function description, the value of the stable boundary or relatively stable boundary (amplitude and phase margin) is obtained by analyzing the open-loop frequency characteristics of the system. When the control parameter \( K_d \) is fixed, the area surrounded by the stable boundary or relatively stable boundary on the \( K_p - K_i \) plane is the PI parameter stability domain, and the entire PID parameter stability domain is obtained by traversing \( K_d \).

In this paper, the DP method is used to calculate the parameter stability domain of the system. Parameter optimization in the parameter stability domain can not only ensure the stability of the
closed-loop feedback system but also provide a reasonable constraint for parameter optimization.

2.2. Parameter optimization
The IGA program in this paper is modified on the basis of GAOT, the genetic algorithm toolbox in MATLAB environment. The coding method adopted is real number coding, the initial group \( N = 50 \), and the termination algebra \( T = 80 \).

The optimization model is the control system shown in Fig. 1, which adopts the unit step input of the set value, and the unit quantity disturbance occurs in the control quantity during the control process, i.e., the anti-disturbance performance of the system is considered during the optimization.

The \( W \) function is defined, as shown in equation (3):

\[
W(e) = \begin{cases} 
1, & e > 5\% \\
0, & e \leq 5\% 
\end{cases}
\]  

(3)

Where \( w_1, w_2, w_3 \) represent weights. In this paper \( w_1 = 0.01, w_2 = 0.1, w_3 = 10 \). The weight selection principle is as follows:

1) Make the value of each objective function item the same order of magnitude, i.e., average the impact of each performance index on the objective function.

2) Adjust the weights accordingly according to the results. For example, when the control energy is too large, increase \( w_1 \) to give a higher penalty to the control energy term.

2.3. Robust performance evaluation
Performance robustness means that when the parameters of the controlled object change within a certain range, the dynamic performance of the system changes within the allowed range. It is one of the important indexes to evaluate the performance of the control system. In this paper, the Monte-Carlo principle is used to test and evaluate the performance robustness of the control system. The experimental steps are as follows:

1) Determine the change interval \([k^{-}, k^{+}]\) of the uncertain parameter \( k \) of the research object, and constitute a random sampling model \( G_p(s,k) \);

2) The \( G_p(s,k) \) and controller \( G_c(s) \) designed based on the nominal model form a closed-loop feedback control system to determine the number \( N \) of perturbation experiments, and the two-dimensional performance indexes are overshoot and ITAE indexes \((e, \text{JITAE})\);

3) Repeat the numerical simulation \( N \) times to obtain \( N \) sets of performance index values, i.e., to obtain a two-dimensional performance index set \((e, \text{JITAE})\), which is represented by a graph;

4) Analyze the two-dimensional performance index set. The smaller the range, the better the performance robustness of the control system.

2.4. PID controller design
According to the above method, the specific steps of PID controller optimization design in this paper are as follows:

1) The DP method is used to calculate the PID parameter stability field of the system.

2) Within the obtained parameter stability domain, the objective function is determined according to the design requirements, and the genetic algorithm is used to optimize the parameters.

3) A dynamic simulation is performed on the control system to check the dynamic performance of the system. Monte-Carlo random experiments were used to evaluate performance robustness.

4) If the simulation result meets the requirements, the design ends; otherwise, return to step 2, modify the weights in the objective function, and repeat steps 2 and 3 until a satisfactory result is obtained.

3. Intelligent PID controller tuning method
This paper selects several conventional PID parameter tuning methods to compare with the PODM method. Among them, when the value of the free parameter \( T_f \) in the IMC method tuning formula increases, the response speed of the system will decrease. If the value of \( T_f \) is too small, \( K_p \) will be too large and the system tends to be unstable. Hence, the value of \( T_f \) in this paper is determined based on the test results, and the control effect is relatively good.

Most tuning formulas above are established based on the first-order inertia of the object plus a pure delay model, so before tuning the PID parameters, the first-order system model must be fitted to the object to obtain the first-order system parameters \( K, T, f \), and then The PID controller parameters can be obtained by substituting these parameters into the set formula.

4. Design results

4.1. PODM method
The genetic algorithm is used to identify the controller parameters designed under the optimal ITAE index in the parameter stability domain. The calculation results are shown in Table 1.

| \( K_p \) | \( K_i \) | \( K_d \) |
|------|------|------|
| 8.91 | 18.56 | 0.37 |

4.2. Normal method
Using the drawing method, the first-order system parameters \( K = 1, f = 0.06, T = 1.2 \) can be obtained, i.e., the first-order fitting model of the object is shown in equation (4):

\[
G_p^r(s) = \frac{1}{1+1.2s} e^{-0.06s}
\] (4)

The results show that the first-order system fits poorly with the distributed parameter model. This is because for the first-order system, where \( \Delta = 5\% \), the transition time is \( t_s \approx 3T \), and for the model in this paper, \( t_s \approx 100T \).

4.3. Analysis of simulation results
The control system designed by different methods is used for dynamic simulation. At 4s, the control quantity has a unit step disturbance. Assuming that the practical parameters have a perturbation of \( \pm 10\% \) near the nominal parameters, i.e., \( k = 0.9 \sim 1.1 \), subject to a uniform distribution, 300 samples are randomly selected, and the Monte-Carlo test is performed.

The system dynamic performance indexes show that in the conventional methods, the performance indexes of CHR, IMC, and Opt methods are larger. In contrast, the Z-N method and C-C method cannot even obtain the closed-loop stability of the system. In contrast, the PODM method shows greater advantages in adjusting time, overshoot, and ITAE indexes. The reason is that the tuning formula of the conventional method is based on the first-order system model of the object, and in this case the first-order system cannot fit the practical object well. The PODM method does not require first-order approximation of objects, and there is no model error problem so that it can obtain better control effects.
Figure 2. Distribution of control performance points of different control methods

It is worth emphasizing that the controller designed based on the PODM method has achieved excellent control performance without the cost of a large amount of control energy. On the contrary, the control capability required in the PODM method is minimal. The reason is that the PODM method punishes control energy during the optimization process.

The output response of the control quantity step disturbance shows that the conventional method takes a long time to make the system output value return to the set value. In contrast, the PODM method adds the control quantity disturbance to the optimization model, and the designed controller can quickly restore to stability, with strong disturbance rejection performance.

Monte-Carlo experimental results show that the controllers designed by the PODM method and the CHR, IMC, and Opt methods can make the object stable within the given parameter perturbation range. However, from the perspective of control performance point distribution, for the model in this paper, the performance robustness of the PODM method has no advantage. The reason is that the PODM method does not give feedback on the robustness information to the optimization model. In contrast, the distribution of control performance points of IMC and CHR methods is relatively concentrated. Hence, if the dynamic performance and performance robustness are taken into thorough consideration, IMC and CHR methods are also optional for the control problem of the model in this paper.

5. Conclusion

Based on the PODM method, multi-objective optimization problems can be considered flexibly without performing lower order approximation of the distributed parameter model, i.e., no model error issue. In this paper, a class of PID controllers based on the distributed parameter model is designed by the PODM method and compared with conventional PID tuning methods such as CHR, IMC, and Opt. The simulation results suggest that the PID controller designed based on the PODM method can achieve better control results with less control energy.

The PODM method cannot obtain highly satisfactory performance robustness in this model. How to give feedback on robustness information to the optimization model so that the control system can have excellent dynamic performance and relatively good performance robustness requires further study.

The simulation results also suggest that the controllers designed based on the Z-N and C-C methods cannot control the distributed parameter objects in this paper effectively. Hence, it is necessary to verify the applicability of designing controllers for distributed parameter objects using
traditional methods first.

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