

DLADRC Controller Parameter Tuning Based on IPSO Algorithm for Quadrotor

Yao Boyu

Department of UAV Engineering
Army Engineering University, Shijiazhuang
Shijiazhuang, China
E-mail: tiniimd@sina.com

Yang Seng

Department of UAV Engineering
Army Engineering University, Shijiazhuang
Shijiazhuang, China
E-mail: 568657132@qq.com

Lu Ping

Department of UAV Engineering
Army Engineering University, Shijiazhuang
Shijiazhuang, China
E-mail: m15931090961@163.com

Ji Jinjian

PLA Unit 66336
Gaobeidian, China
E-mail: laoji_lion@163.com

Abstract—ADRC controller has the advantages of simple structure, high precision and strong robustness, which can estimate and compensate the uncertainties and disturbances online. However, in practical application, it is found that the controller contains too many parameters, and the range and tuning direction of these parameters can not be determined, which makes it difficult to tune the controller parameters. Therefore, on the basis of in-depth analysis of ADRC and parameter tuning, this paper adopts DLADRC controller with fewer adjusting parameters, and proposes an improved PSO to adjust parameters. Finally, the optimized controller is analyzed under Simulink environment, and is applied to the trajectory tracking simulation of quadrotor aircraft to verify the performance of the controller.

Keywords—Component; ADRC; Quadrotor Aircraft; PSO; Parameter Tuning

I. INTRODUCTION

Active disturbance rejection control (ADRC) is improved in the process of absorbing the essence of the PID error feedback and improving the inherent defects. This method has strong anti-interference, which has good adaptability to nonlinear control systems[1]. In recent years, ADRC has been widely used in flight control of quadrotor aircraft[2-4]. To stabilize the quadrotor attitude, Zhang applies ADRC in attitude control with good dynamic quality and robustness[2]. Yang designs an ADRC attitude decoupling controller to decouple the output[3]. Aiming at overcoming the model uncertainty and external disturbance, Dou designs an ADRC attitude controller based on Lyapunov analysis, which shows better stability and dynamic performance[4]. With further exploration, scholars attempt to improve the applicability of ADRC by linearizing non-linear functions or structural changes, so as to make it easier to realize in engineering.

Reasonably adjust the controller parameters will directly improve the performance of the control system in reality. However, classical ADRC contain many kinds of non-linear functions and many coupling parameters need to be tuned, which hinders the application of ADRC in engineering. To solve this problem, Zhou analyzes ADRC controller in engineering application and summarizes some ADRC parameter tuning rules, but these rules are limited to some specific systems[5]. Zheng attempts to linearize controller and tune parameters by sweeping frequency[6]. Zhu proposes chaotic search to improve particle swarm optimization, which can avoid the algorithm fall into local optimum conditions[7]. Li uses genetic algorithm to optimize ADRC parameters with the performance index improved by generation [8].

In order to optimize the parameter tuning of ADRC, this paper will propose a parameter tuning method of quadrotor DLADRC controller based on improved particle swarm optimization (PSO) algorithm.

II. DYNAMIC MODELING OF QUADROTOR AIRCRAFT

A. Background of Quadrotor Aircraft

Firstly, to establish dynamic model of quadrotor aircraft, the assumptions are as follows:

- 1) In the inertial coordinate system, the acceleration of gravity is constant and ignoring the influence of the curvature of the earth and the earth's rotation.
- 2) In the process of flight, regarding the quadrotor as a rigid body, and the vibration and deformation are neglected.
- 3) The center of gravity of a quadrotor coincides with the center of the body structure.
- 4) The mass and torque of inertia are constant.
- 5) Ignoring ground effect and air drag, quadrotor is only pulled by gravity and propeller.

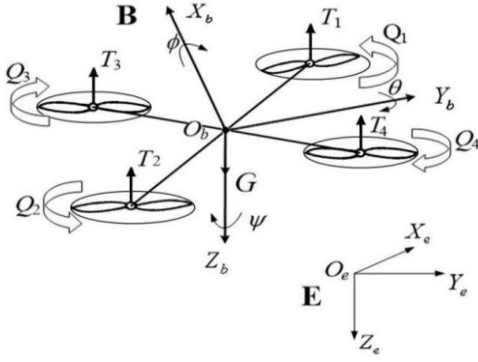


Figure 1. Body forces and coordinate system

B is the body coordinate system, and E is the earth fixed coordinate system. $\Theta = [\theta \ \phi \ \psi]^T$ is defined as a column vector consisting of roll angle, pitch angle and yaw angle of the body. The matrix $R(\Theta) \in R^{3 \times 3}$ is the rotation which is used to relate a vector in the body coordinate system to earth fixed coordinate system defined as

$$R(\Theta) = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} = \begin{bmatrix} c_\theta c_\psi & s_\theta s_\phi c_\psi - c_\phi s_\psi & c_\theta s_\phi c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\theta s_\phi s_\psi + c_\phi c_\psi & c_\theta c_\phi s_\psi - s_\phi c_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta \end{bmatrix} \quad (1)$$

Where the abbreviations $c_{(\bullet)}$ and $s_{(\bullet)}$ have been used for $\cos(\bullet)$ and $\sin(\bullet)$ respectively. According to Newton-Euler theorem, establish the dynamic equation of quadrotor under the B-system as

$$\begin{bmatrix} mI_{3 \times 3} & \mathbf{0}_{3 \times 3} \\ \mathbf{0}_{3 \times 3} & J_{3 \times 3} \end{bmatrix} \begin{bmatrix} v_b \\ \omega_b \end{bmatrix} + \begin{bmatrix} \omega_b \times m v_b \\ \omega_b \times J_{3 \times 3} \omega_b \end{bmatrix} = \begin{bmatrix} F_b \\ \tau_b \end{bmatrix} \quad (2)$$

Among which $F_b = [F_x \ F_y \ F_z]^T$ is the resultant force on the body, $\tau_b = [\tau_x \ \tau_y \ \tau_z]^T$ is the resultant torque of body, $v_b = [u \ v \ w]^T$ defined as linear velocity, $\omega_b = [p \ q \ r]^T$ defined as angular velocity, m represents total mass, $I_{3 \times 3} = \text{diag}(1 \ 1 \ 1)$ represents identity matrix, $J_{3 \times 3} = \text{diag}(J_{xx} \ J_{yy} \ J_{zz})$ represents inertia matrix.

Formula (2) can be simplified to

$$M_b V + C_b(V) V = \Gamma \quad (3)$$

Where M_b is generalized inertial matrix.

$$M_b = \begin{bmatrix} mI_{3 \times 3} & Z_{3 \times 3} \\ Z_{3 \times 3} & J_{3 \times 3} \end{bmatrix} \quad (4)$$

V is generalized velocity vector.

$$V = [v_b \ \omega_b]^T \quad (5)$$

$C_b(V)$ is generalized acceleration matrix in B , and $S(\bullet)$ is cross-product matrix.

$$C_b(V) = \begin{bmatrix} Z_{3 \times 3} & -mS(v_b) \\ Z_{3 \times 3} & -S(J_{3 \times 3} \omega_b) \end{bmatrix} \quad (6)$$

Γ is forces and torques matrix of body.

$$\Gamma = [F_b \ \tau_b]^T \quad (7)$$

Define ξ as a state vector in earth fixed coordinate.

$$\xi = [\dot{x} \ \dot{y} \ \dot{z} \ \dot{\phi} \ \dot{\theta} \ \dot{\psi}]^T \quad (8)$$

Transform formula (2) into E coordinate system to get formula (9) as

$$M_e \dot{\xi} + C_e \xi = [F_e \ \tau_e]^T \quad (9)$$

Where M_e is the generalized inertial matrix, C_e is the generalized velocity vector, F_e is resultant forces, τ_e is resultant torques.

$$M_e = M_b \quad (10)$$

$$C_e = \begin{bmatrix} Z_{3 \times 3} & Z_{3 \times 3} \\ Z_{3 \times 3} & -S(J_{3 \times 3} \omega_e) \end{bmatrix} \quad (11)$$

Based on the model shown in Fig.1 and the above assumptions, define $U = [U_1 \ U_2 \ U_3 \ U_4]^T$ as a matrix of force and torque (U_1 is the resultant pull of four propellers, U_2, U_3 and U_4 represents the pitch, roll and yaw moment, respectively.). According to the blade element theory, the pull T_i and torque Q_i of the i th propeller are written as

$$\begin{cases} T_i = k_T \Omega_i^2 \\ Q_i = k_Q \Omega_i^2 \end{cases} \quad (12)$$

B. Analysis of Forces

Quadrotor aircraft is subjected to gravity G and the pull of four propellers T_i ($i=1,2,3,4$) during flight. $G_e = [0 \ 0 \ mg]^T$ is under E-system. Based on (12), The resultant pull of four propellers in B-system is

$$T_b = [0 \ 0 \ U_1]^T = \begin{bmatrix} 0 & 0 & k_T \sum_{i=1}^4 \Omega_i^2 \end{bmatrix}^T \quad (13)$$

Combining (1) and (13), the resultant forces under the E-system are as follows:

$$F_e = G_e + R T_b = \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} + U_1 \begin{bmatrix} C_{13} \\ C_{23} \\ C_{33} \end{bmatrix} \quad (14)$$

C. Analysis of Torques

The quadrotor is affected by the rotational moment τ_b^r and the gyro moment τ_b^g . According to (12), the gyro moment can be expressed as

$$\tau_b^r = \begin{bmatrix} U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} k_r d (\Omega_1^2 + \Omega_3^2 - \Omega_2^2 - \Omega_4^2) \\ k_r d (\Omega_1^2 + \Omega_4^2 - \Omega_2^2 - \Omega_3^2) \\ k_r d (\Omega_1^2 + \Omega_2^2 - \Omega_3^2 - \Omega_4^2) \end{bmatrix} \quad (15)$$

Where d is the distance from the center of the motor to the center of mass. When the rotational moment acts on the body, the direction of the angular momentum changes, so the gyro moment generated can be expressed as

$$\tau_b^g = \omega_b \times J_r \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \Omega = J_r \begin{bmatrix} -q \\ p \\ 0 \end{bmatrix} (\Omega_1 + \Omega_3 - \Omega_2 - \Omega_4) \quad (16)$$

Where J_r is the moment of inertia of the rotor and Ω is the relative rotational speed of the fuselage. Combined with (15) and (16), the combined torque is

$$\tau_b = \tau_b^r + \tau_b^g = \begin{bmatrix} U_2 \\ U_3 \\ U_4 \end{bmatrix} + J_r \begin{bmatrix} -q \\ p \\ 0 \end{bmatrix} \Omega, \quad (17)$$

Combined (17) with (1), the combined torque under the E-system is

$$\tau_e = \tau_e^r + \tau_e^g = \begin{bmatrix} U_2 \\ U_3 \\ U_4 \end{bmatrix} + J_r \begin{bmatrix} -\dot{\theta} \\ \dot{\phi} \\ 0 \end{bmatrix} \Omega. \quad (18)$$

Under E-system, the coordinates of the quadrotor can be represented as $\rho = [x \ y \ z]^T$. Substitute the F_e and τ_e into the (9), the dynamic model of the quadrotor under the E-system can be obtained as

$$\ddot{\rho} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} C_{13} \frac{U_1}{m} \\ C_{23} \frac{U_1}{m} \\ -g + C_{33} \frac{U_1}{m} \end{bmatrix} \ddot{\Theta} = \begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} \dot{\theta} \dot{\psi} \frac{J_{yy} - J_{zz}}{J_{xx}} - \frac{J_r}{J_{xx}} \dot{\theta} \Omega + \frac{U_2}{J_{xx}} \\ \dot{\phi} \dot{\psi} \frac{J_{zz} - J_{xx}}{J_{yy}} + \frac{J_r}{J_{yy}} \dot{\phi} \Omega + \frac{U_3}{J_{yy}} \\ \dot{\phi} \dot{\theta} \frac{J_{xx} - J_{yy}}{J_{zz}} + \frac{U_4}{J_{zz}} \end{bmatrix}. \quad (19)$$

III. DESIGN OF DISCRETE LINEAR ACTIVE DISTURBANCE REJECTION CONTROLLER

The LADRC consists of three major components: Tracking Differentiator, Linear Extended State Observer, and Linear State Error Feedback. Professor Gao proposes a linear ESO with parameter bandwidth and a linear SEF, which facilitates theoretical research and engineering application [10].

A. Tracking Differentiator(TD)

The function of the TD is to arrange the transition process for the input signal, so that the input signal is smooth and continuous. The second-order discrete control system can be expressed as

$$\begin{cases} v_1(k+1) = v_1(k) + T v_2(k) \\ v_2(k+1) = v_2(k) + T u(k) \end{cases} \quad |u(k)| \leq r \quad (20)$$

Where T is the sampling period and r is the input range. In this paper, an optimal speed control synthesis function is proposed as

$$u = f_{st}(v_1, v_2, r, h), \quad (21)$$

$$\begin{cases} l = rh \\ l_0 = lh \\ y = v_1 + h v_2 \\ s_0 = \sqrt{l^2 + 8\delta|y|} \end{cases} \quad f_{st}(v_1, v_2, r, h) = \begin{cases} -r \text{sign}(s), & |s| > l \\ -rs/l, & |s| \leq l \end{cases} \quad (22)$$

$$s = \begin{cases} v_2 + (s_0 - l) \text{sign}(y), & |y| > l_0 \\ v_2 + y/h, & |y| \leq l_0 \end{cases}$$

Where r is the velocity coefficient, h is the filter coefficient and s is the linear saturation function which can avoid the system falling into high frequency tremor after the discretization of the TD.

Taking (21) into (20) gives the expression of TD as

$$\begin{cases} v_1(k+1) = v_1(k) + T v_2(k) \\ v_2(k+1) = v_2(k) + T f_{st}(v_1(k) - v(k), v_2(k), r, h) \end{cases} \quad (23)$$

B. Linear Extended State Observer(LESO)

LESO is the core of the LADRC, which can extend the total disturbance of the system to a new state and observed it in real time. Meanwhile, it can dynamically compensate the estimation of the total disturbance to the system. Assuming a second-order uncertain system as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + bu \\ x_3 = f(x_1, x_2, t) + \omega(t) \\ y = x_1 \end{cases} \quad (24)$$

Where b is the gain coefficient, $\omega(t)$ is the disturbance caused by external factors, and $f(x_1, x_2, t)$ is the uncertainty of the internal model of the system, $x_3 = f(x_1, x_2, t) + \omega(t)$ is the total disturbance of the system.

Design an extended state observer for the system in which z_1, z_2, z_3 is observed with x_1, x_2, x_3 , and define $e = z_1 - y$. The formula of discrete linear extended state observer is as below:

$$\begin{cases} e(k) = z_1(k) - y(k) \\ z_1(k+1) = z_1(k) + h(z_2(k) - \beta_1 e(k)) \\ z_2(k+1) = z_2(k) + h(z_3(k) - \beta_2 e(k) + b_0 u(k)) \\ z_3(k+1) = z_3(k) - h\beta_3 e(k) \end{cases} \quad (25)$$

$z_1(k)$ is the estimate of $y(k)$, $z_2(k)$ is the differential of $z_1(k)$, $z_3(k)$ is the estimate of the total disturbance, $L = [b_0 \ \beta_1 \ \beta_2 \ \beta_3]^T$ is the gain matrix of the observer.

C. Linear State Error Feedback(LSEF)

Professor Han proposed NLSEF, which uses state error for feedback control, that is, the error between the state observation of the extended state observer and the output signal of the tracking differentiator [11]. The state error of the second-order system is

$$\begin{cases} e_1(k) = v_1(k) - z_1(k) \\ e_2(k) = v_2(k) - z_2(k) \end{cases} \quad (26)$$

Next, linearize the state error feedback and adopt control law of PD form.

$$\begin{cases} u_0(k) = k_p(v_1(k) - z_1(k)) + k_d z_2(k) \\ u(k) = \frac{u_0(k) - z_3(k)}{b_0} \end{cases} \quad (27)$$

The controller gain matrix is $K = [k_p \ k_d]^T$.

IV. PARAMETER TUNING METHOD BASED ON IPSO

Particle swarm optimization (PSO) is a bionic intelligent optimization algorithm. PSO has advantages in fewer parameters, simple process, easy implementation, fast convergence, and ideal optimization effect. Reference [12] introduces the standard PSO algorithm. In search space, the updating formula of particles is as follows:

$$\begin{cases} v_{t+1} = \omega v_t + c_1 r_1 (P_t - x_t) + c_2 r_2 (G_t - x_t) \\ x_{t+1} = x_t + v_{t+1} \end{cases} \quad (28)$$

x is the position of the particle, v is the velocity of the particle, c_1 and c_2 are the acceleration constants, r_1 and r_2 are the random numbers in $[0,1]$, P_t is the individual extreme value, G_t is the group extreme value and ω is an inertia factor improved by the exponential curve decay form which has impact on the convergence of the algorithm [13].

$$\omega = \omega_e + (\omega_s - \omega_e) e^{-\frac{k}{T}} \quad (29)$$

ω_s and ω_e are the initial and final value of ω , T is the number of iterations, k is the current number of iterations. Formula (30) demonstrates that, at the beginning stage, PSO can search the solution space in a large range, and then

search the local part in a small range when ω decrease gradually. Therefore, this improvement can significantly improve the search efficiency of PSO [14].

Integral Time and Absolute Error (ITAE) is regarded as the adaptive of each particle. The basic form of ITAE is:

$$f = \int_0^{\infty} t|e(t)|dt \quad (30)$$

The parameters of the ADRC are optimized by using the improved particle swarm optimization algorithm.

The process of the IPSO algorithm is as follows:

- 1) Initialize the particle swarm, set parameters, randomly generate the positions and velocities of all particles and determine the value of P_t and G_t .
- 2) Update the particle swarm based on formula (28).
- 3) Take each particle into the controller simulator to calculate its ITAE value.
- 4) Compare the P_t of the past with current adaptive of each particle, choose the better one as a new P_t .
- 5) Compare the G_t of the past with whole particle swarm, choose the better one as a new G_t .
- 6) If the requirement is not satisfied or the maximum number of iterations or the minimum adaptive is not reached, then return to step (2). Otherwise, exit the optimization process.

V. SIMULATION RESULTS AND ANALYSIS

Firstly, establish an attitude controller of quadrotor aircraft based on DLADRC in Simulink, the structure of control system is shown in Fig.2.

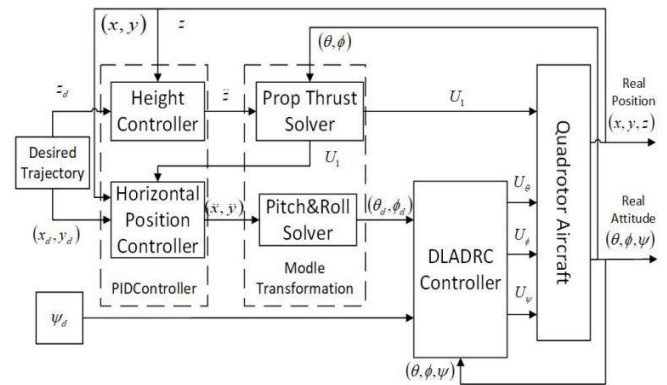


Figure 2. Structure of control system for quadrotor aircraft

The outer loop controller uses the PID to obtain the position error, and then outputs the height control value and the angle. The inner loop controller first solves the angle information to obtain the desired roll angle and pitch angle, and then uses the DLADRC to track the desired angle. The outputs of the model transformation are as follows:

$$\begin{cases} U_1 = m(\ddot{x}C_{13} + \ddot{y}(s_\theta c_\phi s_\psi + s_\theta s_\psi)) - (\ddot{z} + g)C_{33} \\ \theta_d = \arctan\left(\frac{\ddot{x}c_{\psi_d} + \ddot{y}s_{\psi_d}}{\ddot{z} + g}\right) \\ \phi_d = \arctan\left(\frac{\ddot{x}s_{\psi_d} - \ddot{y}c_{\psi_d}}{\sqrt{\ddot{x}^2 + \ddot{y}^2 + (\ddot{z} + g)^2}}\right) \end{cases} \quad (31)$$

The physical parameters related to the simulation model of the quadrotor are set as Table 1.

TABLE I. SIMULATION PARAMETERS OF QUADROTOR

Parameter	Value
m/kg	0.51
l/m	0.225
$g/(m/s^2)$	9.81
$I_x/(kg \cdot m^2)$	1.25×10^{-2}
$I_y/(kg \cdot m^2)$	1.25×10^{-2}
$I_z/(kg \cdot m^2)$	2.357×10^{-2}
$k_r/(N/(rad/s)^2)$	1.39×10^{-5}
$k_Q/(N \cdot m/(rad/s)^2)$	2.106×10^{-7}

The control period is 0.01s, and the initial parameters of three channels of DLADRC are shown in Table 2 in which $b_{0i}, \beta_1, \beta_2, \beta_3, k_p$ and k_d require to be adjusted by the IPSO.

TABLE II. INITIAL PARAMETERS OF THREE CHANNELS OF DLADRC

Controller	Parameter	Value
TD	r	80
	h	0.1
LESO	$b_{0\phi}$	80
	β_1	30
	β_2	300
	β_3	120
LSEF	k_p	100
	k_d	20

The ADRC parameters are optimized by the IPSO, and the parameters of the improved particle swarm optimization algorithm are shown in Table 3.

TABLE III. PARAMETERS OF IPSO

Parameter	Value
$[c_1, c_2]$	[2,2]
$[D, N, T]$	[6,50,50]
$[\omega_s, \omega_e]$	[0.9,0.4]
x_{max}	[100,50,500,300,200,200]
x_{min}	[10,10,100,50,10,10]
v_{max}	[1,0.25,2,1,1,1]
v_{min}	[-1,-0.25,-2,-1,-1,-1]

Taking the quadrotor roll angle channel as an example, other parameters are unchanged and 0.6 radian is used as input. The variation of each parameter and the simulation results of angle tracking are shown in Fig.3-6.

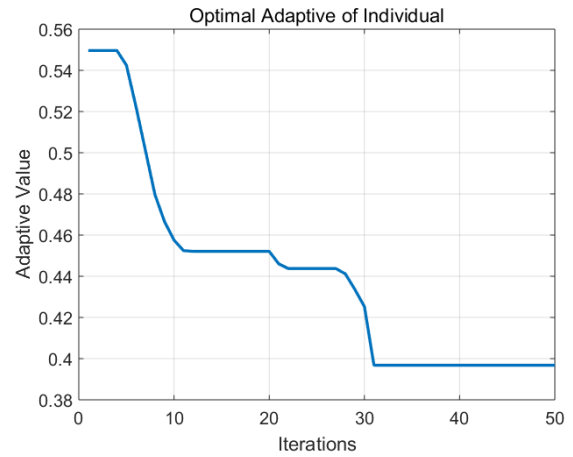


Figure 3. Adaptive value of global optimal particle

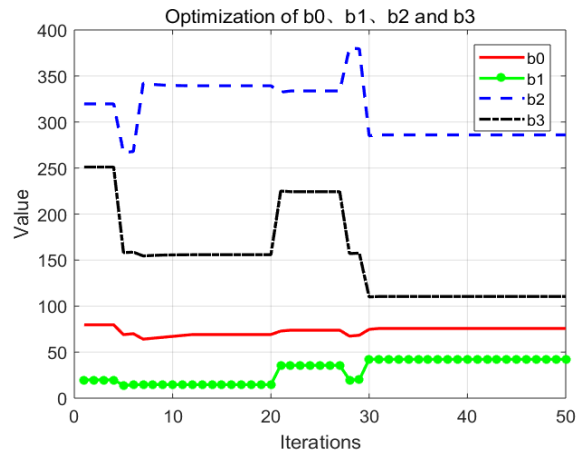


Figure 4. Optimization of b0, b1, b2 and b3

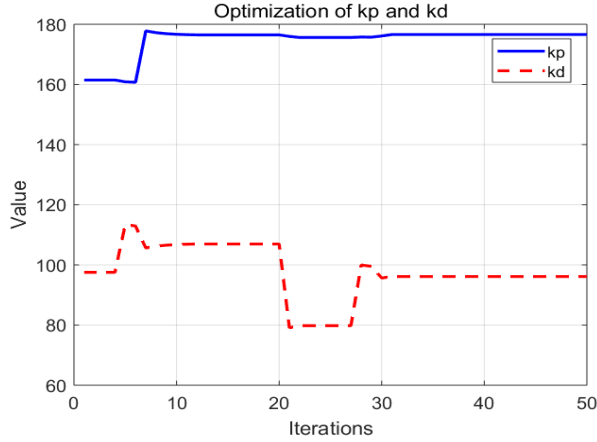


Figure 5. Optimization of k_p and k_d

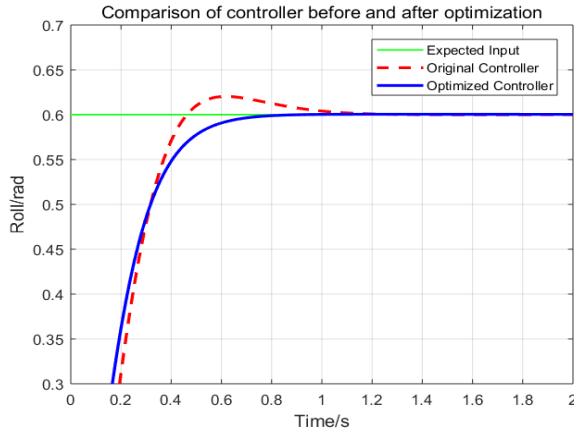


Figure 6. Control performance of roll channel before and after optimization

The changes of parameters and performance indexes before and after optimization are shown in Table 4.

TABLE IV. CONTRAST OF PARAMETERS AND PERFORMANCE INDEXES OF ROLL ANGLE BEFORE AND AFTER OPTIMIZATION

Item	Before	After
$b_{0\phi}$	80	75.75
β_1	30	42.20
β_2	300	286.01
β_3	120	110.45
k_p	100	176.60
k_d	20	96.14
Overshoot/%	3.39	0.08
Transition time($\pm 2\%$)/s	0.82	0.58
ITAE value	0.9886	0.3968

The simulation results show that the improved DLADRC controller has smaller overshoot and shorter transition time without manual parameter adjustment. According to all the above simulation results, it can see that using the improved

particle swarm optimization algorithm to optimize the parameters of DLADRC controller is an effective method.

VI. CONCLUSION

In this paper, a parameter optimization method based on PSO is proposed. To improve the efficiency of PSO, the inertia factor in exponential decay equation and ITAE are adopted. The optimization is tested in Simulink and the results show that IPSO algorithm can effectively optimize the parameters of DLADRC, which betters dynamic and steady state performance of the controller.

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