Rotary Inertial Navigation Active Disturbance Rejection Controller Based on Adaptive Genetic Algorithm

Jinyang He1 and Chao Zhuo1
1 Beijing Aerospace Automatic Control Institute, Beijing, China
hejinya@mail.nwpu.edu.cn

Abstract. The high-precision control of the rotary servo is an important way to improve the navigation accuracy of the inertial navigation system. This paper proposes a parameter tuning method of active disturbance rejection controller based on adaptive genetic algorithm. Specifically, in order to ensure that the genetic algorithm has strong capability of global search and convergence performance, it adjusts the mutation probability and crossover probability of the genetic algorithm according to the individual fitness. Compared with traditional PID controller, the simulation results show that the optimized active disturbance rejection controller (ADRC) has fast response speed, no oscillation and no static error. And finally it realizes faster and high-precision control on rotary inertial navigation.

1. Introduction
The inertial navigation system has become the preferred navigation device of the vehicle due to its high autonomy and concealment. In order to improve the accuracy of navigation, the inertial navigation system usually employs the rotary servo to achieve online calibration, alignment and error period modulation. The high-precision and stable control of the rotary servo is a prerequisite for achieving the above functions. In recent years, scholars have proposed various optimized control algorithms for high-precision control, such as sliding mode control[1,2], ADRC[3-5] and PID control[6,7], and have achieved good simulation and experimental results. The sliding mode control system has high-frequency jitter in the control variable in the sliding mode state. Such high-frequency control input can easily arouse the unmodeled characteristics of the system, which is the biggest obstacle to the application of sliding mode control. ADRC promotes and enriches the essence of PID control. It does not rely on the mathematical model of the controlled plant, and has good suppression of the structure and change of parameters, internal and external interference. Moreover, ADRC has been widely used in engineering due to its fast convergence speed, high accuracy and strong anti-interference ability. However, it is difficult to adjust the parameters of the ADRC due to the large number of parameters. Thus, this paper proposes a parameter tuning method of ADRC based on adaptive genetic algorithm.

2. Design of ADRC for Rotary Inertial Navigation System
ADRC is mainly divided into three parts: tracking differentiator (TD), extended state observer (ESO) and nonlinear state error feedback control (NLSEF). Its outstanding feature is that all uncertain factors acting on the controlled plant are attributed to "unknown disturbance". If the input and output of the plant are known, the disturbance can be estimated and compensated in real time. This technology inherits the essence of PID "eliminating errors based on error feedback", and fundamentally improves control quality and control accuracy. Specifically, the ADRC is more advantageous in situations where
high-speed and high-precision control is required in extreme environments. Structure of ADRC is shown in figure 1.

![Figure 1. Structure of ADRC](image)

For second-order systems, the formula is written as

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= f(x_1, x_2) + w(t) + bu(t) \\
y &= x_1
\end{align*}
\]

(1)

Where \(x_1, x_2\) is state variables, Take \(x_1\) as the angle, \(x_2\) as the angular rate, \(f(x_1, x_2)\) is the unknown function of the system, \(w(t)\) is system unknown disturbance, \(b\) is the system coefficient, \(u(t)\) is system control amount. The design steps of ADRC are as follows.

2.1. Design tracking differentiator (TD)

In order to reduce the initial error and solve the contradiction between rapidity and overshoot, TD is used as the transition process. The output of TD is \(R_1, R_2\). \(R_1\) is the input signal of TD, \(R_2\) is the differential signal of TD. Using the nonlinear function \(f_{\text{han}}()\) and the formula of TD is given as

\[
\begin{align*}
\dot{R}_1 &= R_2 \\
\dot{R}_2 &= f_{\text{han}}(e, R_2, r, h_0)
\end{align*}
\]

(2)

Where, \(e = R_1 - R_2\), \(r\) is the speed factor, and the selection of \(r\) determines the performance of the tracking signal. With the increase of \(r\), the output of TD is closer to the original input, and its tracking effect is better. The selection of \(r\) depends on the ability of the controlled plant and the control system. \(h_0\) is the filter factor, and \(h_0\) is appropriately larger than the simulation step size to better suppress the noise in the differential signal \(R_2\). The formula of \(f_{\text{han}}(x_1, x_2, r, h)\) is given as

\[
\begin{align*}
d &= rh \\
d_0 &= hd \\
y &= x_1 + hx_2 \\
a_0 &= \sqrt{d^2 + 8r}\|y\| \\
a &= \begin{cases} 
\frac{(a_0 - d)}{2} \text{sign}(y), & |y| > d_0 \\
\frac{x_2 + \frac{a_0}{h}\|y\|}{d}, & |y| \leq d_0 
\end{cases} \\
f_{\text{han}} &= \begin{cases} 
rsign(a), & |a| > d \\
r, & |a| \leq d 
\end{cases}
\end{align*}
\]
2.2. Design extended state observer (ESO)

ESO is used to estimate the proportional signal and differential signal input by the controlled plant and the total disturbance amount of the system in real time. Let \( a(t) = f(x_1, x_2) + w(t) \), \( x_1 = a(t) \). The extended state formula is written as

\[
\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= bu(t) + a(t) \\
\dot{x}_3 &= \dot{a}(t) \\
y &= x_1
\end{aligned}
\] (3)

The process of compensating the nonlinear control plant with the expanded state variable and turning the original nonlinear system into a linear system is called the dynamic compensation linearization process. In this way, no matter whether the mathematical model of the controlled plant is determined, it can be transformed into a linear controlled plant through the above formula. Thus, ESO formula is written as

\[
\begin{aligned}
\dot{z}_1 &= z_1 - \mu_0 e \\
\dot{z}_2 &= z_1 - \mu_{02} e + b_0 u \\
\dot{z}_3 &= -\mu_3 e
\end{aligned}
\] (4)

Where \( e = z_1 - y \), \( z_1 \) is the estimated angle, \( z_3 \) is the estimated angle, \( z_3 \) is an estimate parameter of the total disturbance of the system, \( b_0 \) is the system parameter, \( \mu_{01}, \mu_{02}, \mu_3 \) are constants.

2.3. Design nonlinear state error feedback control (NLSEF)

Nonlinear feedback is used for the error of the proportional signal and differential signal of TD and ESO to improve the closed-loop quality of the controller and perform disturbance compensation for the output of the controller. The NLSEF formula is written as

\[
\begin{aligned}
e_1 &= R_1 - z_1 \\
e_2 &= R_2 - z_2 \\
u_0 &= -f (e_1, e_2, r_1, h_1) \\
u &= u_0 - \frac{z_3}{h_0}
\end{aligned}
\] (5)

Where \( r_1 \) is control gain, \( h_1 \) is Fast factor \( c \) is Damping factor.

The above are the three main steps of designing ADRC. ADRC does not rely on mathematical models. If select the appropriate parameters, high-precision control of the stable loop of the rotary inertial navigation system can be achieved.

3. ADRC parameters optimization based on adaptive genetic algorithm

Genetic algorithm is an adaptive global optimization search algorithm formed by simulating the genetic and evolution process of living beings in the natural environment. It draws on the viewpoint of biological inheritance, and realizes the improvement of individual adaptability through natural selection, crossover and mutation. Genetic algorithm has the advantages of global optimization, no dependence on initial values, independence of the algorithm from the solution domain, and strong robustness. It has been widely used in parameter optimization problems in many fields. This paper employs genetic algorithm to optimize the parameters of ADRC. The flowchart is as follows. There are 14 adjustable parameters in ADRC, among which \( \mu_{01}, \mu_{02}, \mu_3 \) in ESO and \( r_1, h_1, c \) in TD are the most critical 6 parameters. The former determines the estimated compensation capacity of disturbances, and the latter directly determines the magnitude of the control quantity. Thus, these 6 parameters are regarded as the individuals of the genetic algorithm, and the design steps of adaptive genetic algorithm are as follows.
3.1. Initial population
Real number coding is used directly. The parameter to be optimized is \([\mu_0, \mu_2, \rho_0, r, h, c]\). The 6 parameters are stringed together to form a solution string, which becomes an individual. Randomly generate a group of individuals to initialize the population.

3.2. Determine fitness function
In order to obtain satisfactory dynamic characteristics, the absolute value of error time integral performance index is used as the fitness function of the system control parameter selection. In order to prevent the control energy from being too large, the square term of control is added to the fitness function. Moreover, in order to meet the rapid convergence of the system, the rise time is added to the fitness function. The formula is written as

\[
J = \int_0^\infty \left( w_1 |e(t)| + w_2 u^2(t) + w_3 t_r \right) dt
\]

Where \(e(t)\) is system error, \(u(t)\) is output of controller, \(t_r\) is rise time is weights. Let \(w_1 = 0.5, w_2 = 0.5, w_3 = 1\).

3.3. Selection, crossover and mutation
In the genetic algorithm, the survival of the fittest is achieved through selection. This paper uses the roulette selection method, that is, the probability of an individual being selected is proportional to its fitness value. The crossover operation greatly improves the search ability of the genetic algorithm. Two individuals are randomly selected to generate two new individuals by random crossover with probability \(P_c\). Mutation is to randomly change the value of a bit of the genetic symbol string with a small probability \(P_m\). Mutation can not only enable the genetic algorithm to have the local random search capability, but also maintain the diversity of the population and avoid the initial convergence problem. In traditional genetic algorithms, fixed crossover probability \((P_c = 0.4 \sim 0.99)\) and mutation probability \((P_m = 0.0001 \sim 0.1)\) are usually used, and there are problems such as slow convergence speed and premature phenomenon in complex optimization problems[8,9]. This paper employs adaptive crossover probability and mutation probability, that is, \(P_c\) and \(P_m\) are automatically adjusted according to the individual fitness value to realize the selection of optimal parameters, and to ensure the algorithm’s strong global search ability and convergence performance.

\[
P_c = \begin{cases} 
  \frac{k_1 (f_{\text{max}} - f')} {f_{\text{max}} - f_{\text{avg}}} , & f' \geq f_{\text{avg}} \\
  k_1 , & f' < f_{\text{avg}} 
\end{cases}
\]

\[
P_m = \begin{cases} 
  \frac{k_2 (f_{\text{avg}} - f)} {f_{\text{max}} - f_{\text{avg}}} , & f \geq f_{\text{avg}} \\
  k_4 , & f < f_{\text{avg}} 
\end{cases}
\]

Where \(f'\) is the larger fitness value between crossover individuals, \(f\) is the fitness value of mutation individuals. \(f_{\text{max}}\) is the maximum fitness value, \(f_{\text{avg}}\) is the average fitness value. Let \(k_1 = k_2 = 1\), \(k_3 = k_4 = 0.5\). Flow of genetic algorithm is shown in figure 2.
4. Simulation and analysis

Use MATLAB/SIMULINK and compare ADRC with traditional PID controller. The block diagram of the stable control loop is shown in figure 3.

Figure 3. The block diagram of the stable control loop

Where Gyro and torque motor are equivalent to the first-order inertia link \( \frac{K}{Ts+1} \). Gyro time constant \( T = \frac{1}{500} \) and \( K = 1 \). Torque motor time constant \( T = \frac{1}{500} \) and \( K = \frac{1}{2} \). The moment of inertia of the rotary shaft is \( J = 0.074463191 \). Let PID: \( 80 + 100 \frac{1}{s} + 0.5s \); Corrective network: \( \frac{1/2s+1}{1/1500s+1} \). The amplitude margin of the stable loop is 13.8dB, and the phase angle margin is 62.5°. The bode diagram of the stable control loop is shown in figure 4.
Figure 4. The bode diagram of the stable control loop

Build ADRC simulation model and compare the performance of the ADRC and PID controllers. The value range of ADRC parameters to be optimized is shown in table 1, the fitness curve of the optimal individual during the adaptive genetic algorithm optimization process is shown in figure 5, and the results after parameter tuning are shown in table 2.

Table 1. ADRC parameters selection range

| Parameter | Ranges  | Parameter | Ranges  |
|-----------|---------|-----------|---------|
| $r$       | [650,10^5] | $r_t$     | [100,10^7] |
| $h_0$     | [0.001,0.1] | $h_i$     | [0.003,0.03] |
| $\omega_e$ | [10,500]  | $c$       | [0.1,4]   |

$\mu_{01} = 3\omega_e, \mu_{02} = 3\omega_e^2, \mu_{03} = \omega_e^3$
Figure 5. The fitness curve of the optimal individual

Table 2. ADRC optimized parameters

| Parameter | Value       | Parameter | Value               |
|-----------|-------------|-----------|---------------------|
| $r$       | 86766.8308  | $r_i$     | 1372693.186289      |
| $h_0$     | 0.004918    | $h_i$     | 0.023704344804      |
| $\mu_{01}$| 103.1944    | $c$       | 1.514677744159      |
| $\mu_{02}$| 3549.7      | $\mu_{03}$| 40701               |

The system step response is shown in figure 6. The performance comparison of the two controllers is shown in table 3.
Figure 6. The system step response

Table 3. The performance comparison of the two controllers

| System indicators     | PID+ Corrective network | ADRC |
|-----------------------|-------------------------|------|
| Overshoot             | 0.69%                   | 0.41%|
| Response time         | 0.0299                  | 0.0235|
| Steady-state error    | 0.0005                  | 10^{-16}|

In figure 6 and table 3, it can be seen that the optimized ADRC is better than the traditional PID+ Corrective network controller in terms of overshoot, response time and steady-state error, and has good response characteristics.

5. Conclusion
This paper proposes a parameter tuning method of active disturbance rejection controller based on adaptive genetic algorithm. This method effectively improves the slow convergence rate and premature phenomenon of genetic algorithm through adaptive adjustment of mutation probability and crossover probability. From simulation analysis, the dynamic performance and steady-state performance of optimized ADRC are better than PID+ Corrective network controller. The optimized ADRC achieves faster and high-precision control, which is suitable for high-precision and stable loop control of rotary servo and has reference value for engineering applications.

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