Design of Wind Pendulum Control System Based on Improved Genetic PID Algorithm

QU Zhi 1,2, a, XU Kai 1,3, b,*, HE Xin 1, c and LIN Lu-chao 1, 2

1 Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China; 2 University of Chinese Academy of Sciences, Beijing 100049, China; 3 Changguang Satellite Technology Co. Ltd, Changchun 130033, China; 4 quzhi3399@163.com, b xukai118@126.com, c hexin6627@sohu.com

Abstract. Aiming at the attitude disturbance of the airborne ground tracking system and the problem of pointing stability under high-frequency vibration, and effectively utilizing the wind power outside the cabin, a new type of airborne ground tracking simulation platform—wind pendulum control system is designed, designed to TMS320F28335 for the control system of the main control chip, the controller adopts an improved genetic PID algorithm to realize the function of rapid braking and movement according to any desired trajectory. The simulation results show that, compared with the traditional PID algorithm, the improved genetic PID algorithm can better solve the problem of chattering, overshoot and non-fast convergence in a limited time in the system. At the same time, it has strong robustness to external disturbances, and can get the full physical simulation needs of airborne ground tracking systems.

1. Introduction
Since the 1960s, the research on airborne ground tracking systems has been greatly advanced. Both system development and equipment research and development have reached a very high level. In missile guidance, artillery control, spacecraft and astronomical tracking, Range measurement and other aspects have been increasingly used. Airborne ground tracking systems usually use gyroscopes to directly stabilize the gimbal to stabilize the system's boresight. The system is generally small in size and light in weight. The load is usually photoelectric reconnaissance equipment such as synthetic aperture radar and real-time transmission camera. This paper focuses on the design and simulation of a new type of airborne ground tracking simulation wind-sway control system [1].

2. Structure Of The System
When the wind pendulum is stationary, the spot of the laser pen is the center of the circle, and the anti-jamming motion along any desired trajectory in the radius of 0-60 cm, the wobble amplitude offset error is <4 mm, and the wobble angle offset error is <1°. With a fast braking capability, when the outside world gives a disturbance, the laser pointer recovers to the center of the circle within 3 s of the ground.

2.1. Structural Design
The length of the wind swing pen is 60cm~65cm, and the bracket adopts the "work" type base structure to ensure the structural stability. The plastic thin tube with light weight, strong durability and low cost is selected as the swing rod material, and the lightweight iron material is used for rigid connection with the fan, which can reduce the burden of the base and ensure the stability of the joint. With a four-rotor configuration, each rotor is directly activated by a hollow cup DC motor and the speed of each motor is scheduled. The mechanical structure of the wind pendulum is shown in Figure 1.

2.2. Actuator

The maneuverability of the wind pendulum refers to the ability of the motor to change the speed and direction of movement within a certain time range. The thrust-to-weight ratio of the motor can reflect the maneuverability of the motor. Compare the thrust-to-weight ratio of the three DC motors. Select the brushless motor or the hollow cup motor from the perspective of improving the maneuverability as much as possible. The bandwidth can be met at 0.8 Hz to meet the system requirements. The fan has strong anti-interference ability, but the system bandwidth is small. If the maneuverability is improved, the bandwidth cannot meet the requirements. The hollow cup motor has the advantage of low speed fluctuation, and a hollow cup motor is selected. The selection and scheme of DC motor are shown in Table 1, and the physical diagram is shown in Figure 2.

![Figure 1. Wind pendulum](image1.png) ![Figure 2. Hollow cup motor](image2.png)

| Motor            | Push-to-weight ratio | Frequency response | Anti-interference ability |
|------------------|----------------------|--------------------|---------------------------|
| Axial flow motor | <0.5                 | <2Hz               | strong                    |
| Brushless motor  | 7~12                 | 3~7Hz              | moderate                  |
| Hollow cup       | 3~8                  | 2~8Hz              | weak                      |

3. Algorithm Design

The bandwidth of the wind pendulum control system will reflect the speed of the wind pendulum tracking. The greater the bandwidth, the faster the wind pendulum tracking speed. According to the formula of the single pendulum motion cycle:

$$T = 2\pi \sqrt{\frac{L}{g}}$$

In the formula: $T$ is the single pendulum motion cycle, $L$ is the pendulum length and $g$ is the local gravity acceleration. Since the length of the pendulum is 60-65 cm, the period $T$ is between 1.5547-1.6793 s and the frequency is between 0.5955-0.6432 Hz. A control system with a bandwidth parameter greater than 0.6432 Hz can complete the task. The bandwidth parameter is set to 0.8 Hz, the sampling frequency is set to 200 Sa/s, and the control period is 5 ms.

3.1. Wind Pendulum Model Design
It is assumed that the wind swing pendulum is a uniform rigid body, and the friction coefficient of the inertia coefficient does not change. The kinematic coordinate system of the wind pendulum is established as shown in Figure 3.

Figure 3. Wind pendulum kinematics coordinate system

The hollow cup motor is:

\[
\begin{align*}
X(t) &= L \sin \theta_1 \sin \dot{\theta}_2 \\
Y(t) &= L \sin \theta_1 \cos \theta_2 \\
Z(t) &= -L \cos \theta_1
\end{align*}
\]

The triaxial speed is:

\[
\begin{align*}
V_x(t) &= \frac{dX(t)}{dt} = L(\dot{\theta}_1 \cos \theta_2 \sin \theta_1 + \dot{\theta}_2 \sin \theta_1 \cos \theta_2) \\
V_y(t) &= \frac{dY(t)}{dt} = L(\dot{\theta}_1 \cos \theta_2 \cos \theta_1 - \dot{\theta}_2 \sin \theta_1 \sin \theta_2) \\
V_z(t) &= \frac{dZ(t)}{dt} = L \dot{\theta}_1 \sin \theta_1
\end{align*}
\]

Force analysis:

\[F = G \tan \theta_1\]

The wind swing speed is:

\[v = \omega R = \sqrt{GL} \sin \theta_1 \tan \theta_1 = \sqrt{V_x^2 + V_y^2 + V_z^2}\]

The moment of inertia of the wind pendulum is:

\[J = \int_0^L r^2 \sin \theta_1 dr = \frac{1}{3} mL^2 \sin \theta_1\]

3.2. Hollow Cup Motor Mathematical Model

Establish a differential equation for a hollow cup motor:

\[
T_m \frac{d\omega_m(t)}{dt} + \omega_m(t) = K_1 U_m(t) - K_2 M_m(t)
\]

Write the angular displacement and the transfer function of the control voltage:

\[
\frac{\theta(s)}{U(s)} = \frac{1}{C_v}, \quad T_m = \frac{R_m J_m}{R_m F_m + C_m C_v}
\]

Where: \(\theta\) is the angular displacement of the hollow cup motor; \(U\) is the control voltage; \(T_m\) is the time constant; \(1/C_v\) is the speed constant of the hollow cup motor.
The parameters of the hollow cup motor are as follows: hollow cup motor resistance $R = 3.53$, torque constant $C = 0.002 Nm/A$, speed constant $1/C = 0.21 V/1Krpm$, viscous friction coefficient $F = 2 \times 10^{-4} kg.m^2.s^{-1}$, motor torque $J = 1.0 \times 10^{-6} kg.m^2$.

The final motor control transfer function is:

$$\frac{\theta(s)}{U(s)} = \frac{1/C}{s(T_a s + 1)} = \frac{0.21}{s(0.003 s + 1)} \quad (9)$$

4. Improved Genetic PID Controller Design

The wind pendulum motion design PID controller includes proportional, integral and differential links. The mathematical description is in the form of:

$$U(t) = K_p E(t) + \frac{1}{T_i} \int_0^t E(t) dt + T_d \frac{dE(t)}{dt} \quad (10)$$

The PID controller transfer function is:

$$\frac{U(s)}{E(s)} = \frac{K_p T_i T_d s^2 + T_d s + 1}{s T_i} \quad (11)$$

The design improves the genetic algorithm self-tuning PID parameters. The core of the improved genetic algorithm is to adaptively improve the crossover and mutation operators and solve the global convergence problem of PID parameters under ill-conditioned conditions. The theoretical expression is as follows [2]:

Step1 Initialize the population:

Before optimizing the PID parameters, the genetic algorithm first encodes $K_p$, $k_i$, $k_d$ is the three variables of the PID controller, and encodes the genes into: $C = [k_p^1, k_i^1, k_d^1] [k_p^0, k_i^0, k_d^0] \in R^1$, $K_p$, $k_i$, $k_d$ is the proportional, integral, and differential coefficients of the PID controller, which are individual in the population. Serial number. A randomly generated string $N$ is taken as a group of individuals, and (12) is a mathematical representation of the initial population.

$$k_{PID} = \begin{bmatrix} C^1 \\ C^2 \\ \vdots \\ C^N \end{bmatrix} = \begin{bmatrix} k_p^1 & k_i^1 & k_d^1 \\ k_p^2 & k_i^2 & k_d^2 \\ \vdots & \vdots & \vdots \\ k_p^N & k_i^N & k_d^N \end{bmatrix} \quad (12)$$

Step2 Determine the fitness:

The fitness function represents the strength of the individual's ability to adapt to the environment in the population, the fitness function is determined as $F = \frac{1}{R}$, and then the variance is calculated.

The mathematical form of the objective function is:

$$R = \int_0^\infty (w_1 |e(t)| + w_2 u^2(t)) dt + w_3 t_u \quad (13)$$

$$R = \int_0^\infty (w_1 |u(t)| + w_2 |y(t) - y(t-1)| + w_3 |e(t)|) dt + w_3 t_u \quad (14)$$

Equation (15) is no overshoot, and equation (16) is an objective function under PID control with overshoot.

Step3 Is morbid:

Judging whether the data is too early to fall into local optimum, the morbid sample "premature" phenomenon adds new operators to ensure the diversity of the population and deal with the repeated individuals, and adopts the survival of the fittest strategy to adapt the fitness of the next generation to
the contemporary individual in the population. Compare, randomly replace the corresponding number of individuals in the worst next-generation group.

Step 4 is in line with the optimal solution:

- If the genetic process converges, then the optimal solution is met. The string with high fitness value is used as the result of the final search for the PID controller parameters; otherwise, it is transferred to the process of copying, crossing, and mutation.

Step 5 Copy, cross, and mutate:

- When the optimal solution is not met, the selected individuals are exchanged according to the arithmetic crossover to generate two new individuals.

\[
GE(i,:) = \alpha \cdot k_{PID}(i,:)+(1-\alpha) \cdot k_{PID}(i+1,:)
\]

\[
GE(i+1,:) = \alpha \cdot k_{PID}(i,:)+(1-\alpha) \cdot k_{PID}(i+1,:)
\]

(15)

The cross-variation parameter \(P_c, P_m\) is defined as:

\[
P_c = \begin{cases} 
(P_c - P_{c-2})(f_{med} - f_a) 
\quad \text{if } f_{med} \leq f_a \\
1 - \frac{(P_c - P_{c-2})(f_{med} - f_a)}{f_{max} - f_a} \quad \text{if } f_{med} > f_a 
\end{cases}
\]

(16)

\[
P_m = \begin{cases} 
(P_m - P_{m-2})(f_{med} - f_a) 
\quad \text{if } f \leq f_a \\
1 - \frac{(P_m - P_{m-2})(f_{med} - f_a)}{f_{max} - f_a} \quad \text{if } f > f_a 
\end{cases}
\]

(17)

\(f_a\) is the average fitness value of each generation of population; \(f_{max}\) is the maximum value of the fitness value in the population; \(f_{med}\) is the larger fitness value of the two intersecting bodies; \(f\) is the fitness value of the current variant individual.

The PID parameter calculation formula is:

\[
k_p = \left(\frac{k_{P_{MAX}} + k_{P_{MIN}}}{2}\right) + (k_{P_{MAX}} - k_{P_{MIN}}) \cdot (\beta - 0.5)
\]

\[
k_i = \left(\frac{k_{I_{MAX}} + k_{I_{MIN}}}{2}\right) + (k_{I_{MAX}} - k_{I_{MIN}}) \cdot (\beta - 0.5)
\]

\[
k_d = \left(\frac{k_{D_{MAX}} + k_{D_{MIN}}}{2}\right) + (k_{D_{MAX}} - k_{D_{MIN}}) \cdot (\beta - 0.5)
\]

(18)

The neutralization \(k_{P_{MAX}}\) and \(k_{P_{MIN}}\) of the controller is the upper and lower limits of the controller parameters \(k_p\), and \(k_{I_{MAX}}\) and \(k_{I_{MIN}}\) is the upper and lower limits of the controller parameters \(k_i\), and \(k_{D_{MAX}}\) and \(k_{D_{MIN}}\) is the upper and lower limits of the controller parameters \(k_d\), \(\beta \in [0, 1]\) are random numbers.

Step 6 Output the optimal PID value:

- Will converge to the optimal string output, while decoding becomes the parameters required by the actual PID controller, output the best individual as the three parameters of the PID parameters; end.

5. Simulation Results

For the PID controller parameters \(k_p = 60\), \(k_i = 1\), \(k_d = 800\), the input sinusoidal signal is tracked, the simulation result is shown in Figure 4, and the error curve (1) is shown in Figure 5. Analyze the simulation results. In theory, the swing amplitude offset error between the PID target value and the actual wind swing value is <6mm, the swing angle offset error is <1.5°, the roundness radius offset error is <6mm, and the actual wind swing value is 2s. The upper PID target value can be tracked.
The number of samples used in the improved genetic algorithm is 100, the crossover probability is: $P_c = 0.9$, and the probability of variation is $P_m = 0.9$. The value range of the parameter is [0,100], the value range is [0,1], the value range is [0,100], take $w_1 = 0.999$, $w_2 = 0.001$, $w_3 = 2.0$, $w_4 = 100$, input sinusoidal curve by MATLAB software Tracking is performed and the simulation results are shown in Figure 6. The error curve (2) is shown in Figure 7, theoretically, the wobble amplitude offset error is <3 mm, the roundness radius offset error is <3 mm, and the wobble angle offset error is <1°. The convergence curve of the genetic algorithm is shown in Figure 8. The optimal fitness when convergence is 24.4478, and the actual value of the wind pendulum can track the upper PID target value within 2s.
Compared with the traditional PID algorithm and the improved genetic PID algorithm for the wind pendulum simulation results, the wind pendulum offset error is increased the offset error from <6mm to <3mm.

6. Summary
In this paper, aiming at the attitude disturbance of airborne ground tracking system and the pointing stability problem under high frequency vibration, a new airborne ground tracking full physical simulation platform-wind pendulum control system is designed. The designed wind pendulum system can achieve fast braking. Compared with the traditional PID algorithm, the improved genetic PID algorithm can better solve the chattering, overshoot and rapid convergence in the system in a limited time, and it is strong in the external interference. It is capable of meeting the full physical simulation requirements of the airborne ground tracking system.

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