Fractional-Order PID Controller of USV Course-Keeping using Hybrid GA-PSO Algorithm

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***Abstract*—To the problem that traditional PID control method for course-keeping is sensitive to the change of underactuated surface vessels (USV) parameters, an improved fractional-order $PI^{\lambda}D^{\mu}$ controller based on hybrid GA-PSO Algorithm was designed. The two additional adjustable parameters such as integral-order λ and differential –order μ make the controller more flexible, robust and have stronger disturbance rejection ability. The parameters of fractional-order $PI^{\lambda}D^{\mu}$ controller are determined by using hybrid GA-PSO algorithm, which reduce the probability of searching to the local optimal solution and ensure the accuracy of the global optimal solution. The simulation results show that the fractional-order $PI^{\lambda}D^{\mu}$ controller based on hybrid GA-PSO has better dynamic tracking performance and smaller overshoot and stronger immunity than the traditional PSO-PID controller.**

Keywords-USV; Particle swarm optimization algorithm (PSO); Genetic algorithm (GA); Fractional-order $PI^{\lambda}D^{\mu}$ controller; Course-keeping control

I. INTRODUCTION

In recent years, the maneuvering of underactuated surface vessels has become the focus of scholars' attention. The underactuated system is a system that the number of control system input less than the freedom degrees of system. That means the spatial dimension of control input is less than spatial dimension of configuration [1]. In USV control, when needing to rely on the rudder of transshipment torque and propeller longitudinal propulsion and controlling vessels in horizontal position and heading angle three degree of freedom motion, the USV control system belongs to the underactuated system [2].

The traditional course control device of USV is digital PID autopilot, but this PID autopilot is sensitive to high frequency interference which results in frequent steering. At present, the intelligent control algorithm of USV course has the swarm optimization algorithm, the synovial control, the Backstepping technology and the neural network technology etc. Reference [3] applied neural network decoupling control for USV, and achieved the independent control of three degrees of freedom. References [4-5] respectively designed a nonlinear Backstepping course controller and a nonlinear Backstepping adaptive robust controller, which were based on the Backstepping method, and had the effect of the global stability.

In this paper, a fractional-order $PI^{\lambda}D^{\mu}$ controller is designed for USV course autopilot, which has the characteristics of flexible structure, strong robustness and strong anti-disturbance ability. At the same time, in order to solve the problems of multi-parameters and complex design of fractional-order $PI^{\lambda}D^{\mu}$ controller, genetic algorithm (GA) is combined with the particle swarm optimization algorithm (PSO) and the global optimization ability and convergence precision of PSO is improved, the speed of the algorithm is accelerated. Compared with the fractional-order $PI^{\lambda}D^{\mu}$ controller based on hybrid GA-PSO algorithm and PID controller based on PSO algorithm, the system is simulated, and the dynamic performance and robustness of the two control methods are discussed.

II. MATHEMATICAL MODEL OF USV COURSE

In the design of USV course controller, usually the ship is a dynamic system, the system input is rudder angle δ , and the output is yaw angle ψ .In the case of steering is not very frequent, the Norrbin nonlinear mathematical model of USV course control is denoted as

$$\ddot{\psi} = -a_1\dot{\psi} - a_2\dot{\psi}^3 + b\delta \tag{1}$$

In which, ψ and δ are respectively yaw angle and rudder angle. $\alpha_1 = \alpha b$, $\alpha_2 = \beta b$, $b = K/T$ are model parameters, K and T are ship indexes, α and β are nonlinear coefficient. K , T , α and β are relevant to the speed and structure of ship.

III. FRACTIONAL-ORDE $PI^{\lambda}D^{\mu}$ CONTROLLERS

Fractional calculus is the theory of any order differential and integral calculus, and it is a generalization of the integral calculus.

In 1999, the fractional-order $PI^{\lambda}D^{\mu}$ controller was proposed by I Podlubny. Compared with the traditional PID controller, the fractional-order $PI^{\lambda}D^{\mu}$ controller has more than two parameters, such as the integral-order λ and the

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differential-order μ , which make the control system more robust and flexible [6-7], its differential equation expression is

$$u(t) = K_p e(t) + K_i D_t^{-\lambda} e(t) + K_d D_t^{\mu} e(t) \cdot \quad (2)$$

In which, $D_t^{\alpha} \equiv {}_a^C D_t^{\alpha}$ is Caputo definition. $\lambda > 0$ and $\mu > 0$ are any real number, and can be the order of fractional-order controller. The Laplace transform of Caputo definition is

$$L\left\{ {}_a^C D_t^{\alpha} f(t) \right\} = s^{\alpha} F(s) - \sum_{k=0}^{n-1} s^{\alpha-k-1} f^{(k)}(0) \quad . \quad (3)$$

By (2) and (3), the transfer function of fractional-order $PI^{\lambda} D^{\mu}$ controller is obtained

$$G_c(\mathrm{s}) = \mathrm{K_p} + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \quad . \quad (4)$$

In this paper, we use the modified Oustaloup approximation method. s^{α} is approximated as integer-order calculus, and fitting frequency range is $(\omega_{\mathrm{b}}, \omega_{\mathrm{k}})$, order is N . The approximation integer-order transfer function is shown as

$$s^{\alpha} = \left(\frac{d\omega_b}{b} \right)^{\alpha} \left(\frac{ds^2 + bs\omega_k}{d(1-\alpha)\mathrm{s}^2 + bs\omega_k + d\alpha} \right) \left[\frac{1 + \frac{s}{d\omega_b / b}}{1 + \frac{s}{d\omega_k / b}} \right]^{\alpha} . \quad (5)$$

Where $0 < \alpha < 1, \mathrm{b} > 0, \mathrm{d} > 0, \mathrm{s} = \mathrm{j}\omega$, the fractional part $K(\mathrm{s})$ of (5) expresses as zeros, poles form of a rational transfer function

$$K(\mathrm{s}) = \lim_{N \to \infty} K_N(\mathrm{s}) = \lim_{N \to \infty} \prod_{k=-N}^{N} \frac{1 + s / \omega_k'}{1 + s / \omega_k} . \quad (6)$$

The k zero, pole is

$$\omega_k' = \omega_b \left(\frac{\omega_k}{\omega_b} \right)^{\frac{N+k+\frac{1}{2}(1-\alpha)}{2N+1}} \quad (7)$$

$$\omega_k = \omega_b \left(\frac{\omega_k}{\omega_b} \right)^{\frac{N+k+\frac{1}{2}(1+\alpha)}{2N+1}} . \quad (8)$$

Construct the continuous rational transfer function model of fractional calculus operator is

$$G(\mathrm{s}) = \mathrm{K} \left(\frac{\mathrm{ds}^2 + b\omega_k s}{d(1-\alpha)\mathrm{s}^2 + b\omega_k s + d\alpha} \right) \prod_{k=-N}^{N} \frac{1 + s / \omega_k'}{1 + s / \omega_k} . \quad (9)$$

In which $K = (\omega_b \omega_k)^{\alpha}$.

IV. HYBRID GA-PSO ALGORITHM

Particle swarm optimization is an evolutionary computation technique, which was proposed by Dr. Eberhart and Dr. Kennedy in 1995 [8]. It is essentially a random search algorithm, which has the characteristics of parallel processing and good robustness, but it is also prone to fall into local extremum, premature convergence or stagnation phenomenon. Genetic algorithm is a random search method which gets the final optimal results through the selection, crossover and mutation to optimize the community's renewal. The advantage is that it is not easy to fall into local optimum by adjusting the appropriate parameters. However, because of the dependence of the parameters, the selection of fitness function and the subtle changes of the parameters will have a direct impact on the final results.

In this paper, genetic algorithm is introduced into the optimization of PSO algorithm, and the global optimization ability of PSO algorithm is enhanced, and the speed of the algorithm is improved. Optimization idea is: search early, PSO first search, when search to the optimal solution, assuming that the optimal solution, at this time through the GA idea, the suspected optimal solution directly copied into the next generation, in order to ensure that the late search will not be lost PSO search to the best solution; Reusing GA mutation idea will have folded particle population variation, so as to ensure the diversity of population, all particles are spread over the entire search space in, and then to search; If the mutation found than previously suspected optimal solution better solutions, abandoned the suspected optimal solution, the standard PSO optimization process until again furled find suspected optimal solution; If the continuous replication, variation N times has not found a better solution, it is considered that the current suspected optimal solution is the global optimal solution. The Hybrid GA-PSO Hybrid algorithm flow is shown in Fig. 1.

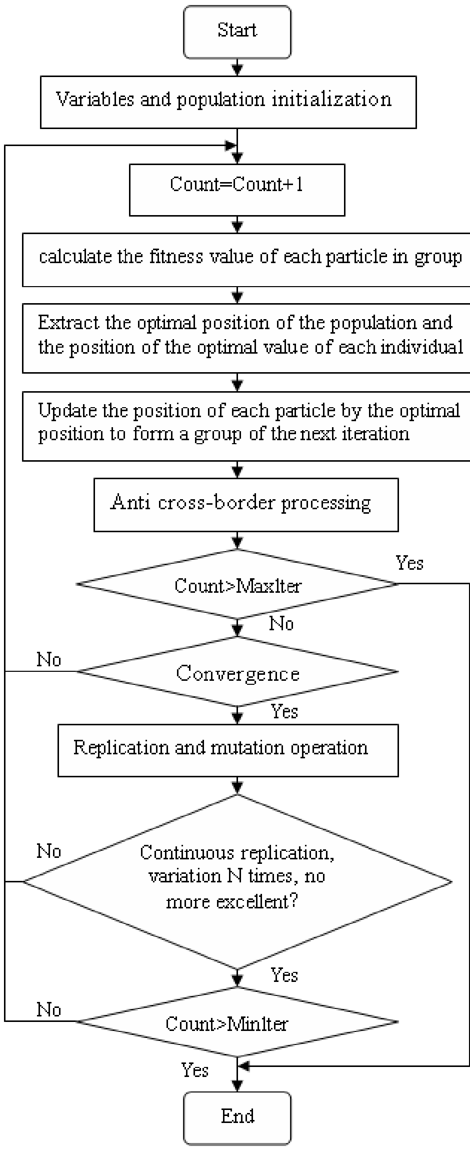


Figure 1. Hybrid GA-PSO algorithm flow

V. Objective Function Selection

In this paper, the Hybrid GA-PSO algorithm is used to solve the parameters $(K_p, K_i, K_d, \lambda, \mu)$ of fractional-order $PI^{\lambda}D^{\mu}$ controller. The solution space dimension is 5, and the method is using the improved Oustaloup filtering method. The optimization objective function formula is as follows

$$J = \omega_1 \int_0^{+\infty} e^2(\mathrm{t})\mathrm{dt} + \omega_2 \sigma \quad . \tag{10}$$

In which $e(\mathrm{t})$ is systematic error, σ is system overshoot, ω_1 and ω_2 are weights.

VI. Simulations

The simulation experiment uses the data of 5446TEU container ship of COSCO Group. Supposing the rated speed of this ship is $v = 24.51 knots$, the parameters are shown in Table 1.

TABLE I. PARAMETERS OF 5446TEU CONTAINER SHIP

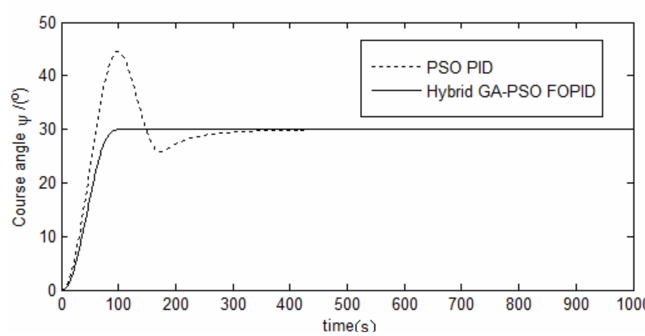
Parameter	Value	Parameter	Value
Ship length LOA	*280 M*	*Two column length L*	*267M*
Ship width B	*39.8 M*	*gravity center distance* X_c	*2.64M*
Rudder area A_δ	*61.0 M2*	*Square coefficient* C_b	*0.67*
No load mass m	*3.5453 Million tons*	*Fully load mass m*	*6.5531 Million tons*
Design draft T	*12.532M*	*Fully load draft*	*14.023M*

According to Table 1, the parameters can be calculated K=0.2419, T=206.7958, $\alpha = 11.6049$ and $\beta = 10.1966$ in the rated speed.

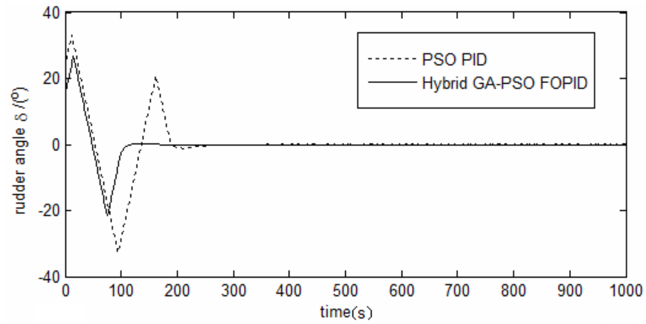
According to the design procedure of the controller, maximum rudder angle is limited between -35°～+35°, the expected course angle takes 30 °in 0 ~ 1000 seconds. At the same time, when the ship is sailing, the wind and wave interference has become one of the main causes of the ship's yaw. In order to verify the robustness of fractional-order control system, the interference of the wave is added in this design. A simple simulation method is used in the simulation, which is used to drive a typical two-order oscillation process with white noise [9-10]. The transfer function of the wave model is obtained under the action of the six-level wind

$$h(\mathrm{s}) = \frac{0.4198\mathrm{s}}{\mathrm{s}^2 + 0.3638s + 0.3675} \quad . \tag{11}$$

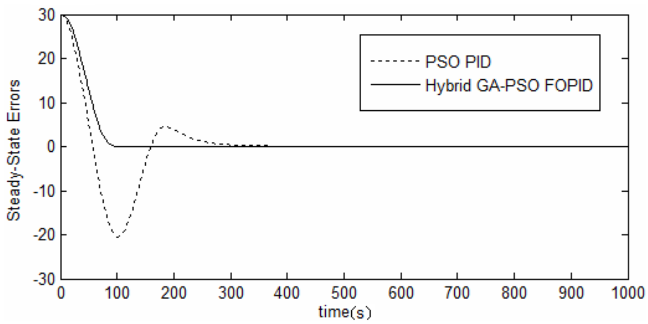
By simulation, the step response curves corresponding to the two control methods are shown in Fig. 2 (a) (b) (c).



(a) USV course tracking curve when wind and waves interfere



(b) USV output rudder angle curve when wind and waves interfere



(c) USV output course tracking error curve when wind and waves interfere

Figure 2. USV course control curve when wind and waves interfere

From Fig. 2, we can see that the fractional-order $PI^{\lambda}D^{\mu}$ controller based on the hybrid GA-PSO can achieve stability and control effect is better than the conventional PSO - PID controller.

VII. CONCLUSION

In this paper, for the characteristics of USV course control, an improved fractional-order $PI^{\lambda}D^{\mu}$ controller based on hybrid GA-PSO Algorithm was designed, and it improved the dynamic and static performance of the system. Simulation results show that the performance of the controller is better than the conventional PSO-PID controller. When the controller output is affected by the disturbance of wind and waves and the control object itself, it can also overcome these effects. It has strong robustness and anti-disturbance ability.

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