Course Control of Unmanned Sailboat Based on BAS-PID Algorithm

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***Abstract*— Unmanned sailboat course control is the core of unmanned sailboat automatic navigation. In order to improve the stability of navigation course control, a compound PID controller combining beetle search algorithm (BAS-PID) and PID strategy is proposed to control the steering gear to achieve the course control of unmanned sailboat. Firstly, the Nomoto motion and steering gear mathematical model were established by *Matlab/Simulink* modeling tools. Secondly, the PID parameter adjustment problem is transformed into a three-dimensional parameter optimization problem, and the beetle search algorithm is used to optimize the PID parameters. Finally, the comparison of the performance indicators of different algorithms is simulated, and the result shows that the BAS-PID controller has a better control effect which provides a reference for the course control design of unmanned sailboat.**

Keywords—sailboat, BAS-PID, course control, Nomoto.

I. Introduction

The unmanned sailboat is a new type of green marine data monitoring equipment which is mainly powered by the wind. In the field of unmanned sailboat motion control, current research idea tends to separate the sail control and the rudder control into two independent controllers: the sail control and rudder control [1]. When an unmanned sailboat autonomously sails at sea, the course control is very important. Therefore, the course control has attracted the attention of many scholars.

At present, the algorithms of course control mainly include classic PID, Backstepping, Lyapunov, sliding mode control, neural network control, fuzzy control and some other intelligent control methods combined with each other. Deng and Ahmed et al. used fuzzy control and PD controller to control the course and applied it to the actual navigation path planning[2, 3]. Emami et al. used a PID algorithm to design a course holding controller for a small two-meter autonomous sailboat to achieve the course control. However, because the sailboat is a time-varying system with strong interference and model uncertainty, the PID controller is Big restrictions and challenges[4]. Based on the experience of the steering expert, Wang Qian et al. summarized and formulated 245 fuzzy control rules, and directly used the rudder angle as an output to implement track navigation control for a one-meter-five sailboat[5]. Saoud et al. used a three-degree-of-freedom sailboat model as the research object, ignoring the yaw effect of rolling on the sailboat, and used Backstepping and switching functions to design a course controller to achieve the sailboat course control[6, 7]. The above research used different control methods to achieve the control of sailboat course.

PID control is commonly used in the field of unmanned sailboat course control since its advantages over simple structure, easy implementation and strong robustness. The difficulty of PID control lies in its parameter tuning. Different parameter tuning methods will make a huge difference in the performance of the PID controller. The traditional PID control parameter optimization method generally uses a trial and error method which requires a large number of experiments. So, it is difficult to meet the real-time requirements and obtain the optimal PID parameters. Aiming at the shortcomings of traditional PID control, scholars have proposed a large number of PID parameter optimization methods combined with intelligent algorithms. The more commonly used are particle swarm algorithm, genetic algorithm and neural network algorithm, but these algorithms have obvious shortcomings. The implementation of genetic algorithm programming is very complicated, with a large amount of calculations, poor stability, and difficult to deal with nonlinear problems; the particle swarm algorithm is not good at dealing with discrete problems, and it is as easy to fall into a local optimum as neural network algorithms. The Beetle Antennae Search (BAS) algorithm is a highly efficient bionic optimization algorithm recently proposed. It does not need to know the specific form of the function and does not require gradient information to achieve efficient optimization[8]. Compared with particle swarm optimization, the BAS algorithm only needs a beetle to achieve efficient optimization which greatly reduces the amount of calculation, shortens the optimization time, and makes the efficiency of optimization more efficient. Aiming at the shortcomings of traditional PID control methods, this paper proposes a method for tuning PID parameters based on the BAS algorithm which is called BAS-PID control to achieve the course control of unmanned sailboat. Also, in order to verify the performance of the BAS-PID controller, the controllability of the BAS-PID controller was compared

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with other algorithms(Z-N, PSO-PID). The experimental results show that the BAS-PID controller is superior.

II. MATHEMATICAL MODEL OF UNMANNED SAILBOAT

A. Sailboat model parameters

This paper takes the self-designed unmanned sailboat model as the simulation research object. The main dimensions of the hull (attachment) and sail are shown in TABLE.1. The NACA0018 airfoil was used for the rudder profile.

TABLE I

THE MAIN DIMENSIONS OF SMALL AUTONOMOUS SAILBOAT MODEL

parameter	Value
Sailboat length L/m	2.19
Sailboat width B/m	0.80
Draught	0.08
Square factor C_b	0.89
Center of gravity distance X_c/m	0.085
Sail area S_s/m^2	3.25
Mast length L/m	1.5
Rudder speed n/(Deg· s^{-1})	10.2
Effective rudder area S_r/m^2	0.085

B. Sailboat coordinate system

In the process of actual sea surface movement, a sailboat can be generally approximated as a rigid body with six degrees of freedom. To facilitate the description of the sailboat's motion, two right-handed coordinate systems were established in Fig.1. As shown in Fig.1, $O_0 - x_0 y_0 z_0$ is the inertial coordinate system centered on the ship's center of gravity at t = 0, $O_0 - x_0$ axis is the north direction of the stationary water surface, $O_0 - y_0$ axis is the east direction of the stationary water surface, and the $O_0 - z_0$ axis is perpendicular to the water surface. $o - xyz$ is the attached coordinate system with the ship's center of gravity as the center. The $o - x$ axis is the hull axis. The direction is from bow to bow, the $o - y$ axis is to starboard, and the $o - z$ axis is to the water surface. In order to facilitate the analysis of the relationship between the course angle ψ and the rudder angle δ , under the premise of meeting the research requirements, the rolling, pitching and heave motions can be ignored, and only the rolling, forward and sway motions are considered, and the sailboat motion mathematical motion model is simplified to three degrees of freedom[9, 10].

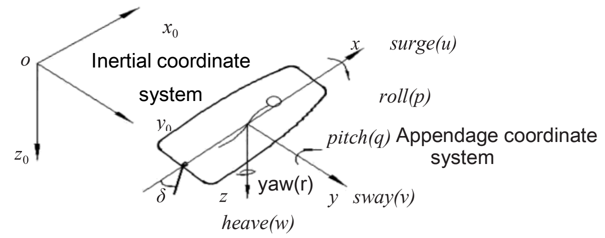

Fig. 1. The coordinate system of hull

C. Nomoto motion mathematical model

Based on Newton's theorem of momentum and moment of mass, combined with coordinate system and speed conversion relationship, a three-degree-of-freedom mathematical motion model of unmanned sailboat in still water is established:

$$\begin{cases} m\left(\dot{u}_{\mathrm{G}} - v_{\mathrm{G}} r\right) = F_x \\ m\left(\dot{v}_{\mathrm{G}} + u_{\mathrm{G}} r\right) = F_y \\ I_{z\mathrm{G}} \dot{r} = M_z \end{cases} \tag{1}$$

Where m is the total mass of the ship; $u_{\mathrm{G}}, v_{\mathrm{G}}, \dot{u}_{\mathrm{G}}, \dot{v}_{\mathrm{G}}$ are the forward and lateral speeds at the center of gravity and their derivatives with respect to time; $r, \dot{r}$ are the yaw angle rate and its derivative with respect to time ; F_x, F_y and M_z are the external forces and moments acting at the center of gravity of the x, y, z axes, respectively; I_{zG} is the moment of inertia of the ship about the axis z_0 .

From the perspective of control engineering, considering the relationship between the hull sway angle change and the rudder angle motion, the three-degree-of-freedom state-space equation of equation (1) is transformed into a transfer function expression according to the hydrodynamic model of the sailboat and the output equation. The simplified Nomoto mathematical model[11]:

$$\frac{\psi(s)}{\delta(s)} = \frac{K}{s(Ts+1)} \tag{2}$$

Where the rotary parameter K and the stability parameter T are the angular velocity after steering and the time required reaching the maximum turning angular velocity; s is the Laplace transform factor.

D. Mathematical model of steering gear

The steering gear has a certain delay effect in the actual control process, which will affect the accuracy of course control to a certain extent. Generally, the steering gear can be regarded as a first-order inertial link:

$$\frac{\delta}{\delta_{\mathrm{c}}} = \frac{1}{T_0 s + 1} \tag{3}$$

Where δ_{c} is the target rudder angle, T_0 is the time constant of the servo, generally takes 1~3s, here T_0 = 1.

III. UNMANNED SAILBOAT COURSE CONTROL METHOD

Sailboat with different characteristics will have different restricted navigation areas. Generally, this area is considered to be between 30 ° and 45 ° against the wind. At this time, Z-type wind breaking is required. In addition, the sailboat can achieve arbitrary course. The sailboat discussed in this paper is a non-headwind sail, which is a straight sailboat segment. This paper presents a PID control based on BAS algorithm for course control of unmanned sailboat without considering the influence of waves.

A. Principle of PID controller

PID control is short for proportional, integral and derivative control. The working principle of the PID controller: take the error between the actual value and the expected value as the input of the controller to form a closed-loop feedback, and then perform the proportional, integral and differential operations on them to obtain the required new output value. After several feedback cycles, the output error is continuously reduced and gradually approaches the ideal output value. The control law u(t) obtained by a PID controller is given by:

$$u(t) = K_p\left[e(t) + \frac{1}{T_i}e(t)dt + T_d\frac{de(t)}{dt}\right] = K_p e(t) + K_i\int e(t)d\tau + K_d\frac{d}{dt}e(t) \tag{4}$$

where u(t) is the controller output, $e(t)$ is the feedback error, K_p is the proportional gain, T_i is the integration time constant, and T_d is the differential time constant, K_i is the integral coefficient and K_d is the differential coefficient. The parameter selection of PID control will directly affect its control effect, so the selection of three parameters of K_p, K_i and K_d is very important. In this paper, the proposed BAS-PID algorithm can efficiently optimize the three parameters of the PID control to find the best setting value.

B. The principle of the BAS algorithm

The BAS algorithm is a new bionic algorithm. The biological principle is that when a beetle searches for food, it is unknown where the food is located at first, but searches for food according to the strength of the food smell. The beetle has two long antennae. If the intensity of the odor received by the left antennae is greater than that of the right antennae, then the beetle will fly to the left and vice versa. According to this simple principle, beetle can find food efficiently.

The modeling process of the BAS algorithm is as follows:

1) The position and orientation of the beetle are randomly generated and normalized:

$$\vec{b} = \frac{rands(Dim,1)}{\| rands(Dim,1)\|} \tag{5}$$

Where Dim is the spatial dimension.

2) Create the space coordinates of the beetle's left and right sides and its antennae:

$$\begin{cases} x_{ri} = x^i + d_0 * \vec{b}/2 \\ x_{li} = x^i - d_0 * \vec{b}/2 \end{cases} (\mathrm{t} = 0,1,2\ldots\mathrm{n}) \tag{6}$$

where x^i represents the position of the beetle's antennae at the *i-th* iteration, x_{ri} represents the position of the beetle's right antennae at the *i-th* iteration, x_{li} represents the position of the beetle's left antennae at the *i-th* iteration, and d_0 represents the beetle's two positions.

3) Determine the direction in which the beetle is moving:

According to the selected fitness function, the respective fitness values of the left and right antennae are calculated, and the beetle moves toward the antennae with a small fitness value.

4) Iteratively update the location of the beetle:

$$x^{i+1} = x^i - eta * \vec{b} * \mathrm{sign}\left(f\left(x_{ri}\right) - f\left(x_{li}\right)\right) \tag{7}$$

$$step = eta * step \tag{8}$$

Among them, step is the initial step size of beetle, eta is the step size factor, $f(x)$ is the fitness function, and the positive and negative parameters are returned.

The algorithm flow of BAS is shown in Fig.2.

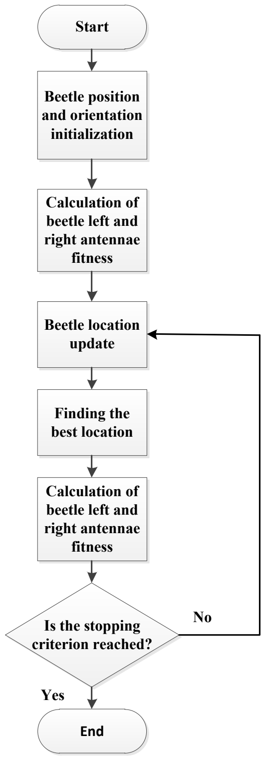

Fig. 2. Flow chart of the BAS algorithm

C. Algorithm design of BAS-PID

The principle of the BAS- PID algorithm is to use the BAS algorithm to optimize and set the three parameters of the PID controller. The dimension of the BAS algorithm is set to three, and the decomposition amount of the beetle's position information in these three dimensions is assigned to these three parameters, that is, K_p, K_i and K_d are combined as a "beetle". In the given search space, the beetle adjusts and updates the next position according to the adaptive values of the left and right antennae positions, and iteratively updates the position of the beetle to gradually approach the optimal target. When the traditional PID algorithm controls the course, the deviation e of the given target course angle ψ_c from the current actual course angle ψ is used as the input of the controller and the rudder angle value δ is used as the output.

The block diagram of the BAS-PID based unmanned sailboat course control system is shown in Fig. 3.

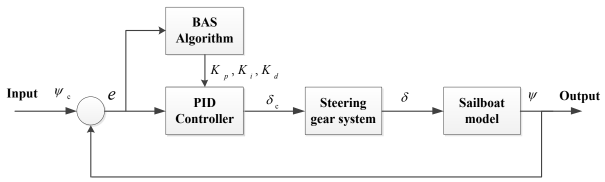

Fig. 3. System block diagram of BAS-PID

The flow of the BAS-PID algorithm is as follows:

1) Initialize the beetle's position and beetle antennae orientation information, calculate the fitness values of its left and right antennae respectively, and determine the beetle's movement direction.

2) Update the beetle's position and orientation information, and calculate the fitness value of the left and right antennae at the current position to determine the moving direction of the beetle in the next step.

3) The decomposition amount of the position information obtained in each iteration of the BAS algorithm in three dimensions is assigned to K_p , K_i *and* K_d respectively. The BAS-PID system is simulated in the *Simulink* environment, and the error generated by the system is substituted into the fitness function to calculate Its fitness value.

4) Pass the fitness value obtained in *Simulink* to the BAS algorithm, and compare the size between the fitness value and the set minimum threshold. If the fitness value is less than the threshold set in the set algorithm or the algorithm reaches the maximum Number of iterations, go to the next step, otherwise go to the second step.

5) Get the optimal parameters of the PID controller and end the simulation.

IV. SIMULATION METHOD AND DISCUSSION

A. Simulation method

In this paper, a real-scale sailboat model is used for simulation research. Assume that the ship's initial course angle and rudder angle are both 0, and the target course angle ψ_c = 20° ,25° , and be in a non-headwind sailboat area. Due to different speeds, the rotary parameters K and stability parameters T of the sailboat will also be different. When the speed V = 2.0 m / s, the rotary parameter K is -21.99, the stability parameter T = -22.96. *Matlab* is used to simulate the implementation of the BAS-PID algorithm, *Simulink* is used to build the structure of the PID control system, the BAS algorithm is stored in the M file, and the PID simulation model is continuously called during the BAS operation process. Realize the optimization of PID parameters, and then complete the course control of unmanned sailboat.

Select error performance index ITAE as fitness function:

$$ITAE = \int_0^\infty t\left|e(t)\right|dt \tag{9}$$

In the algorithm simulation, the parameters of the BAS algorithm are selected as follows: the distance between the two antennae of the beetle is 3, the initial step size is 10, the step factor is 0.95, the number of iterations is 100, and the accuracy of the fitness function is 0.01. The initial step size should be selected as large as possible to cover the current search area without falling into a local optimum. At the same time, a variable step size control strategy is adopted to ensure the refinement of the search.

B. Simulation disscussion

Figure 4 shows the trend of the three parameters of the BAS-PID with the number of iterations. It can be seen that at about 10 iterations, the BAS algorithm has found the optimal PID parameters. In order to prove the superiority of the BAS-PID-based controller, the simulation results are compared with the traditional critical proportional method (Z-N) and PSO-PID. For PSO-PID, parameters were set as: learning factors $c_1 = c_2 = 2$, inertial weight ω = 0.6, the number of iterations is 100. The parameters are shown in Table 2.

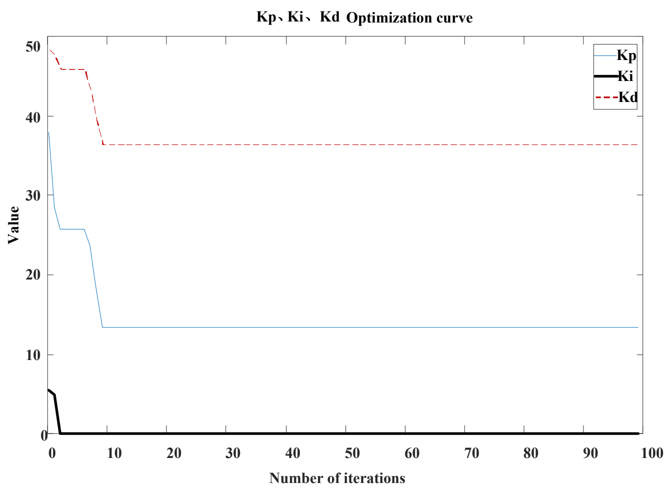

Fig. 4. Iterative curve of BAS-PID

TABLE II.

PARAMETER COEFFICIENT TABLE OF THREE OPTIMIZATION METHODS

Optimization method	K_p	K_i	K_d
Z-N	0.55	0.001	1.12
PSO	10.5	0.06	24
BAS	13.5309	0.1	35.8789

With given courses of 20° and 25° , the simulation results of the system after operation are shown in Fig. 5 and Fig.6.

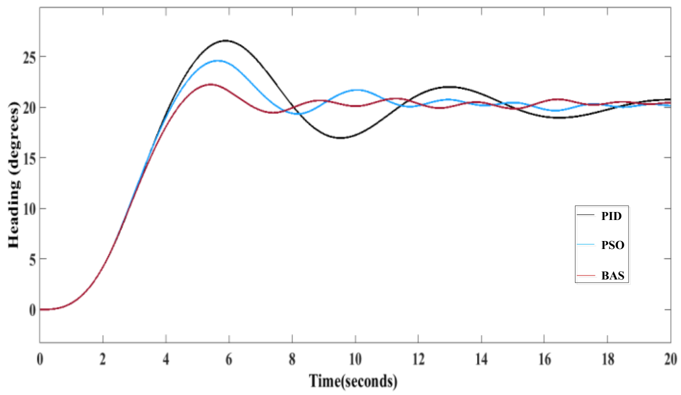

Fig. 5. Simulation comparison of three control methods (course angle is 20°)

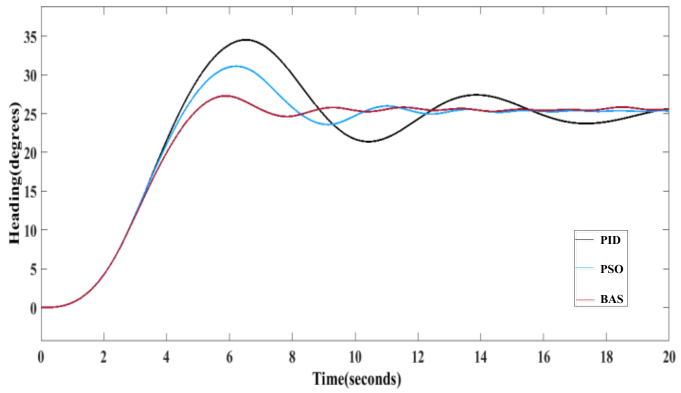

Fig. 6. Simulation comparison of three control methods (course angle is 25°)

According to the simulation Fig.5 and Fig.6, the performance of the sailboat course PID control system optimized by Z-N, PSO, and BAS can be summarized as Table 3 and Table 4 below.

TABLE III.

COURSE CONTROL SYSTEM PERFORMANCE INDEX (COURSE ANGLE 20 DEGREES)

Optimization method	Peak time t_p/s	Setting time t_s/s	Overshoot $\sigma\%$	Rise time t_r/s
Z-N	5.885	14.229	32.8	2.409
PSO	5.663	10.78	22.95	2.543
BAS	**5.403**	**6.272**	**11.15**	3.102

TABLE IV.
COURSE CONTROL SYSTEM PERFORMANCE INDEX (COURSE ANGLE 25 DEGREES)

Optimization method	Peak time t_p/s	Setting time t_s/s	Overshoot $\sigma\%$	Rise time t_r/s
Z-N	6.519	15.096	38.12	2.447
PSO	6.204	9.412	24.48	2.523
BAS	**5.892**	**3.943**	**9.2**	2.736

As shown in Table 3 and Table 4 , compared to Z-N and PSO-PID, BAS-PID shows the best performance. The response curve of the BAS-PID controller converges to the required set point with minimal overshoot and minimal settling time. The system can maintain high dynamic characteristics and stability accuracy using BAS-PID controller.

V. CONCLUSION

In this paper, a self-designed unmanned sailboat model is taken as the research object, and a mathematical model of motion is established according to the actual characteristic parameters of the sailboat. This paper adopts the BAS-PID method to design the controller, and performs simulation control research on the sailboat course. It is compared with the traditional PID control method (Z-N) and PSO-PID. The performance of these controllers has been compared in terms of system response characteristics: overshoot, peak time, rise time and setting time. Compared with traditional PID controller, BAS-PID controller has more efficient optimization ability and better control effect. Because BAS algorithm has the advantages of simple programming, easy implementation and fast optimization, BAS-PID control has broad application prospects. In this paper, only the role of the steering gear in the course control is considered. In the future control strategy of sailboat, it is attempted to combine sail control and rudder control strategy with each other.

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