Research on Key Methods of Autonomous sailboat's Position Keeping Control

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OCEANS 2022 - Chennai | 978-1-6654-1821-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/OCEANSChennai45887.2022.9775464

Abstract: This paper proposes an unmanned sailboat's position keeping control strategy, which is based on the ES optimization algorithm to control the speed of the unmanned sailboat, and uses the fuzzy PID to control the heading. As a carrier that relies on wind energy, the unmanned sailboat has a dead zone when sailing against the wind, and the speed of the unmanned sailboat in the dead zone is zero. When the unmanned sailboat is controlled at a fixed point, the heading required for the unmanned sailboat to reach the target point is calculated in real time. If the angle between the target heading and the wind direction enters the dead zone, it will move 10 degrees outside the dead zone boundary. When the sailboat moves out of the dead zone, the sailboat moves along the heading required for the unmanned sailboat to reach the target point. Simulation experiments show that this method can reach the target point, and shuttle around the target point after reaching the target point, and has better positioning performance.

Keywords—unmanned sailboat, ES speed control, fuzzy PID, position keeping control, sail against the wind

I. INTRODUCTION

Wind energy is a clean and renewable energy source. Using wind energy as a driving force in surface equipment can greatly improve the endurance, so that it can be used for long-term unmanned ocean-related tasks and play an important role in ocean exploration, development and monitoring. Unmanned sailboats, as a surface equipment that relies on wind energy, can carry out large-scale long-endurance detection missions. In tasks such as collecting seabed data and tracking underwater equipment to provide positioning and data exchange, the positioning capability of unmanned sailboats is a prerequisite. Compared with other self-powered surface crafts, unmanned sailboats use external wind as the power input and are highly dependent on the environment. Due to the complex and changeable marine environment, it becomes very difficult for unmanned sailboats to control their heading and speed.

In the past two decades, many scholars have conducted a lot of research on the structural design, navigation control, path tracking, path planning, and collision avoidance of unmanned sailboats. In terms of the structural design of unmanned sailboats, the types of unmanned sailboats include stable plate, keel and multi-hull types, and multi-hull types include catamarans and trimarans[1]. As the entire power source of unmanned sailboats, sails mainly include traditional soft sails, balanced sails and rigid sails (wing sails for short)[1]. Due to the presence of sails, unmanned sailboats will tilt during the sailing process. When the heel angle is too large, the sailboat will overturn. In order to reduce the roll and prevent overturning, a keel is installed at the bottom of the sailboat to increase the lateral resistance and provide Better directional stability. The rudder is the course control device of a sailboat. The most common rudder is installed under the stern of the hull, and the course of the ship is controlled by water force, generally a single rudder.

The navigation control of unmanned sailboat is divided into two aspects: sail control and rudder control. Sails are the only power source for unmanned sailboats. The wind acts on the sails to generate forward force and push the sailboat forward. The wind acting on the sail will also generate lateral forces, which will cause the sailboat to tilt, which poses a greater challenge to the sailboat control. Therefore, it is necessary to establish a 4-DOF dynamic model of an unmanned sailboat. Literature [2] puts forward the 4-DOF dynamic equation of the sailboat by analyzing the forces and moments of the hull, sail, rudder, and keel of the unmanned sailboat. In terms of sail control, the common method is to use the polar coordinate curve of the unmanned sailing speed obtained by dynamic simulation to determine the best sail angle for different wind directions and headings by looking up the table to control the sailboat to obtain the maximum speed on the reference heading. Literature [3] proposed an unmanned sailing speed optimization algorithm based on ES (Extremum seeking) extreme value search algorithm. The sail angle determined by the speed polar coordinate curve was used as the feedforward input of the system, and the ES algorithm was used to find the optimal sail angle.

In the heading control of an unmanned sailboat, both the rudder and the sail have an impact on the heading control. Due to its coupling effect, most documents adopt decoupling control to control the rudder and the sail separately. The rudder control is relatively simple and common control algorithms. There are PID control, LQG control, adaptive control, etc.[1]. Because the unmanned sailboat is disturbed by ocean currents, waves and other external environments during its movement, it is difficult for conventional PID control to achieve online adjustment of parameters in complex environments, and problems such as overshoot and high-frequency adjustment are prone to occur in the control. However, fuzzy control can be based on expert real-time adjustment of PID parameters can be achieved by formulating fuzzy rules and combining PID control to achieve the desired control effect. This paper uses the fuzzy PID algorithm proposed in the literature [4] for heading control.

Unmanned sailboats rely on wind to provide navigational power, and there is a dead zone for navigation. In the dead zone, unmanned sailboats cannot obtain sufficient forward thrust, resulting in stalling[5]. In order to avoid entering the dead zone of navigation, this paper proposes a navigation strategy to avoid entering the dead zone.

The overall structure is as follows: Section I introduces the current situation of autonomous sailboat position keeping control and introduces the purpose of the study. Section II constructs the 4-DOF dynamic equation of the sailboat. Section III introduces ES algorithm for speed control. Section IV proposes a fuzzy PID algorithm to control the heading. Section V presents the methods of string changing against the wind and position keeping control algorithm. Section VI shows the simulation results, and Section VII is the conclusion.

II. 4-DOF MODEL OF SAILBOAT

Unmanned sailboat is a water surface carrier, when building a mathematical model, the pitch and heave motions can be ignored in the 6-DOF model, which is simplified to a 4-DOF model. Define the inertial coordinate system as O-XYZ, the X axis is the true north direction, the Y axis is the true east direction, and the Z axis is the vertical downward direction. Define the body-fixed frame o-$x_b y_b z_b$, the x_b axis is the forward velocity direction of the hull, y_b is the starboard direction, and z_b is the vertical downward direction. Let U=$[u\ v\ p\ r]^T$ represent the forward velocity, lateral velocity, heel angular velocity and yaw angular velocity in the body coordinate system, respectively; P=$[x\ y\ \varphi\ \psi]^T$ respectively represent the X coordinate, Y coordinate, and horizontal angle of inclination and heading. According to the literature [2], the description of coordinate system is shown in fig.1,and the wind velocity and forces on the sail is shown in fig. 2.

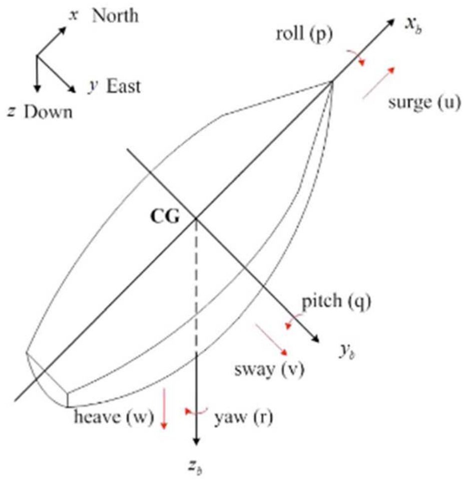

Fig.1 the description of coordinate system[2]

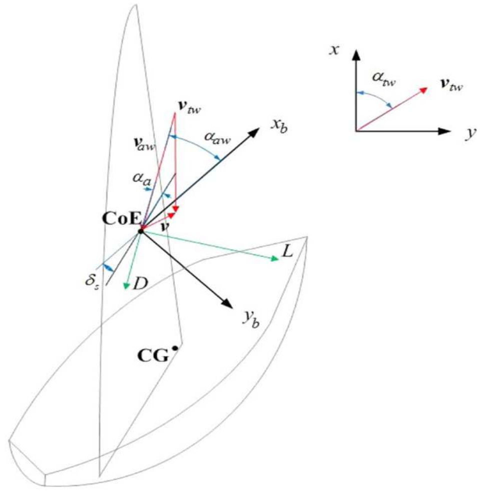

Fig.2 the wind velocity and forces on the sail[2]

The four-degree-of-freedom kinematic equation is:

$$\begin{cases} \dot{x} = u\cos(\psi) - v\cos(\varphi)\sin(\psi) \\ \dot{y} = u\sin(\psi) - v\cos(\varphi)\cos(\psi) \\ \dot{\varphi} = p \\ \dot{\psi} = r\cos(\varphi) \end{cases}$$

The dynamic equation is：

$$\begin{cases} \dot{u}=\dfrac{1}{m-X_{\dot{u}}}(F_{xs}+F_{xr}+F_{xh}+F_{xk}+(m-Y_{\dot{v}})vr) \\ \dot{v}=\dfrac{1}{m-Y_{\dot{v}}}(F_{ys}+F_{yr}+F_{yh}+F_{yk}+(m-X_{\dot{u}}vr)ur) \\ \dot{p}=\dfrac{1}{I_{xx}-K_{\dot{p}}}(M_{xs}+M_{xr}+M_{xh}+M_{xk}-c|p|p-a\varphi^2-b\varphi) \\ \dot{r}=\dfrac{1}{I_{zz}-N_{\dot{r}}}(M_{zs}+M_{zr}+M_{zh}+M_{zk}+(X_{\dot{u}}+Y_{\dot{v}})uv-d|r|r\cos(\varphi)) \end{cases}$$

where：

$$F_{xs}=L_s\sin(\alpha_{aw})-D_s\cos(\alpha_{aw})$$

$$F_{ys}=L_s\cos(\alpha_{aw})+D_s\sin(\alpha_{aw})$$

$$M_{xs}=F_{ys}|z_s|$$

$$M_{zs}=-F_{xs}y_s cos(\delta_s)+F_{ys}x_s sin(\delta_s)$$

$$L_s=\frac{1}{2}\rho_a A_s v_{aw}^2 sin(2(\alpha_s-\delta_s))$$

$$D_s=\frac{1}{2}\rho_a A_s v_{aw}^2(1-cos(2(\alpha_s-\delta_s)))$$

$$v_{aw}=\sqrt{v_{awu}^2+v_{awv}^2}$$

$$v_{awu}=v_{tw} cos(\alpha_{tw}-\psi)-u+ry_s$$

$$v_{awv}=v_{tw} sin(\alpha_{tw}-\psi)-v-rx_s+pz_s$$

$$\alpha_{aw}=atan2(v_{awv},v_{awu})$$

The meaning and value of each parameter are shown in the literature [2].

III. SPEED OPTIMIZATION BASED ON EXTREMUM SEEKING

Extremum seeking (ES)[6] control is a model-free, real-time adaptive control algorithm that is useful for adapting to unknown system dynamics and unknown mappings from control parameters to an objective function.

In unmanned sailing control, the system contains a square system with two inputs (sail angle and rudder angle) and two outputs (forward speed and heading angle)[3]. The forward speed of the unmanned sailboat is controlled by adjusting the sail angle, and the rudder angle is adjusted to control the heading angle of the unmanned sailboat. In the speed control, the control algorithm based on ES extreme value optimization is used to adjust the sail angle so that the unmanned sailboat has the maximum speed in the forward direction. The ES algorithm flow is shown in figure 3.

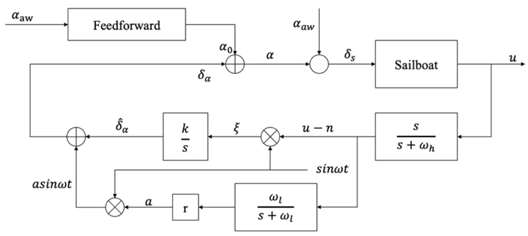

Fig.3 the ES algorithm

First, the speed of the carrier is filtered by high pass to remove the deviation in the objective function. Then the objective function signal is multiplied by a sine curve with the same frequency as the modulation signal. Subsequently, the signal passes through a low-pass filter to filter out high-frequency noise from the demodulated signal. The demodulated signal after filtering updates the parameter value through the integrator. Finally, a low-amplitude sinusoidal signal is used to perturb the parameter value being optimized to obtain the optimal parameter[6].

IV. HEADING CONTROL BASED ON FUZZY PID

The traditional PID algorithm controls the heading according to the error between the current heading ψ and the target heading ψ_d, and the output rudder angle δ_s is obtained through the traditional PID algorithm. The fuzzy PID control algorithm calculates the control parameters K_p, K_d and K_i according to the set fuzzy rules in real time according to the error e and error change rate e_r during the calculation process, combined with the traditional PID algorithm to get the output rudder angle δ_s. The flow chart of fuzzy PID control is shown in figure 4.

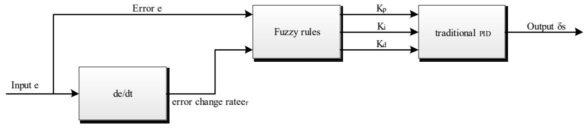

Fig. 4 The flow chart of fuzzy PID control

According to the literature [4], the domain of fuzzy input (deviation e, deviation change rate e_r) and output (proportional term coefficient K_p, integral term coefficient K_i and differential term coefficient K_d) are both (-1,1), which has 7 fuzzy subsets, respectively Negative Large (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Large (PB). The specific fuzzy rules are shown in Table1(at the next page). The membership function is shown in figures 5, 6 and 7.

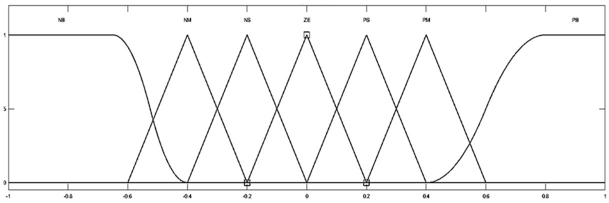

Fig. 5 the fuzzy rule of e

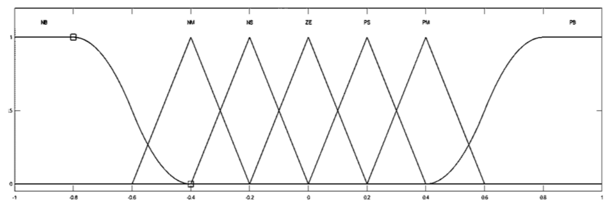

Fig. 6 the fuzzy rule of e_r

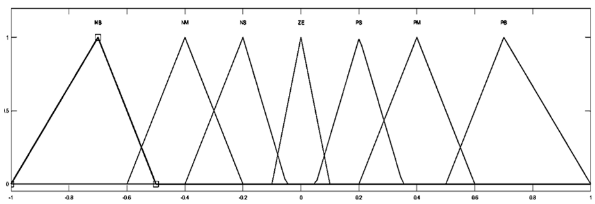

Fig. 7 the fuzzy rules of K_p, K_i and K_d

V. STRING CHANGING AND POSITION KEEPING CONTROL

This article adopts the simplest positioning control algorithm, based on the heading angle control, calculates the angle of the target position relative to the current position in real time during the movement, and sets it as the target heading of the unmanned sailboat. In the process of unmanned sailing, the target heading of unmanned sailing is continuously updated according to the relative angle calculated in real time.

Since the propulsion of the unmanned sailboat is determined by the wind direction and speed, the unmanned sailboat has a dead zone when sailing in the wind[5]. In the dead zone, the unmanned sailboat cannot obtain enough propulsion power to sail at a speed due to insufficient navigation power is close to zero. Therefore, if the angle between the heading angle and the wind direction is within the dead zone angle during the position keeping control of the unmanned sailboat, it is necessary to change the string in the wind to prevent the unmanned sailboat from entering the dead zone. This process is shown in figure 8.

Table 1 the specific fuzzy rules

	e_r						
e	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
	$K_p/K_i/K_d$	$K_p/K_i/K_d$	$K_p/K_i/K_d$	$K_p/K_i/K_d$	$K_p/K_i/K_d$	$K_p/K_i/K_d$	$K_p/K_i/K_d$
NB	PB\NB\PS	PB\NM\NB	PM\NM\NB	PM\NM\NB	PS\NS\NB	PS\ZE\NM	ZE\ZE\ZE
NM	PB\NB\PS	PM\NM\NB	PM\NM\NB	PS\NS\NM	PS\NS\NM	ZE\ZE\NS	NS\ZE\ZE
NS	PM\NB\ZE	PM\NB\NM	PS\NS\NM	PS\NS\NM	ZE\ZE\NS	NS\PS\NS	NS\PS\PS
ZE	PM\NM\ZE	PS\NB\NM	PS\NS\NS	ZE\ZE\ZE	NS\PS\NS	NS\PM\NS	NM\PM\PM
PS	PS\NM\ZE	PS\NS\NS	ZE\ZE\ZE	NS\PS\ZE	NS\PS\ZE	NM\PM\ZE	NM\PB\PB
PM	PS\ZE\PB	ZE\ZE\ZE	NS\PS\PS	NS\PS\PS	NM\PM\PS	NM\PB\PS	NB\PB\PB
PB	ZE\ZE\PB	NS\ZE\ZE	NS\PS\PM	NM\PM\PM	NM\PM\PS	NB\PB\PS	NB\PB\PB

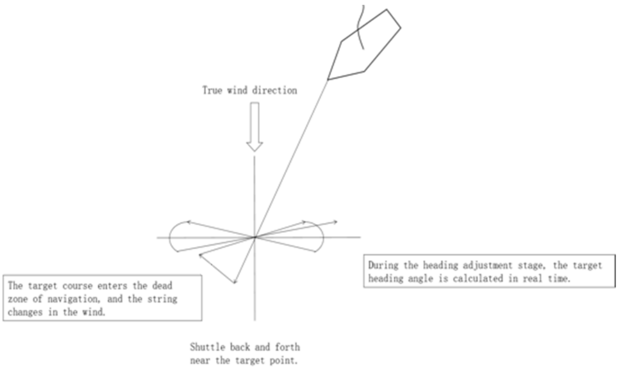

Fig. 8 the process of the position keeping

This paper proposes a string changing strategy, when the desired heading angle and wind direction between the current position of the unmanned sailboat and the target position enters the dead zone, in order to prevent the unmanned sailboat from entering the dead zone, set the heading angle to 10° outside the dead zone. After the relative angle between the current position and the target position and the angle between the wind direction leave the navigation dead zone, the unmanned sailboat continues to sail towards the target position.

Suppose the position of the target point is (x_d, y_d), the current position of the unmanned sailboat is (x_t, y_t), the target heading angle is ψ_d, the wind direction angle is ψ_{tw} and the dead zone angle is d_z. Target heading angle $\psi_d = atan2(y_d - y_t, x_d - x_t)$. If the angle between the target heading of the unmanned sailboat and the wind direction is within the dead zone, that is, if $\psi_{tw} - \psi_d \geq \pi$ and $|\psi_{tw} - \psi_d - \pi| \leq d_z/2$, then the target heading angle is set to 10° outside the dead zone. When the angle between the target heading and the wind direction is on the left half of the dead zone, that is, if $\psi_{tw} - \psi_d \geq \pi$ and $-d_z/2 \leq \psi_{tw} - \psi_d - \pi < 0$, set the target heading to 10° to the left of the dead zone, that is, set $\psi_d = \psi_{tw} - \pi - d_z/2 - (10/180)*\pi$; when the angle between the target heading and the wind direction is in the right half of the dead zone, that is, $0 \leq \psi_{tw} - \psi_d - \pi \leq d_z/2$, set the target heading as 10° to the right of the dead zone, that is, set $\psi_d = \psi_{tw} - \pi + d_z/2 + (10/180)*\pi$.

VI. Simulation Results

Refer to the literature [4] set ES algorithm parameters, the specific parameters are shown in figure 9, and the ES algorithm Simulink block diagram is shown in figure 9. Use the unmanned sailing dynamic model derived in the literature [2]. Take $K_p = 2$, $K_i = 0.001$, and $K_d = 0.001$ in fuzzy PID control. The block diagram of Fuzzy PID Simulink is shown in figure 10. Suppose the real wind speed is 10m/s and the real wind direction is 0°, and set the target point to (-500,500).

Then, using the Simulink to get the control result. The control simulation result is shown in figures 11,12,13 and 14.

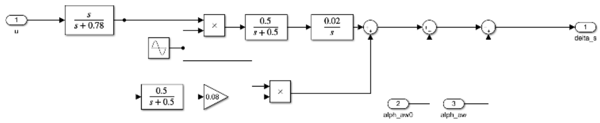

Fig.9 the block diagram of ES Simulink

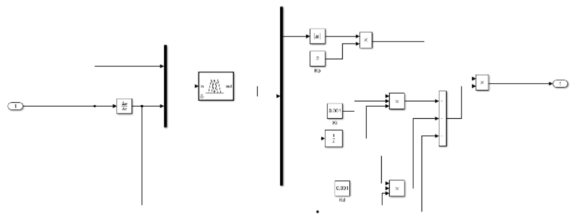

Fig. 10 the block diagram of Fuzzy PID Simulink

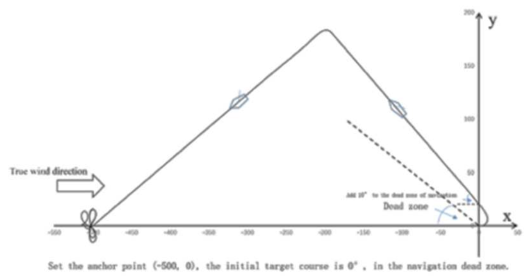

Fig.11 the trajectory of the unmanned sailboat for the first simulation

Fig.12 the trajectory of the unmanned sailboat for the second simulation

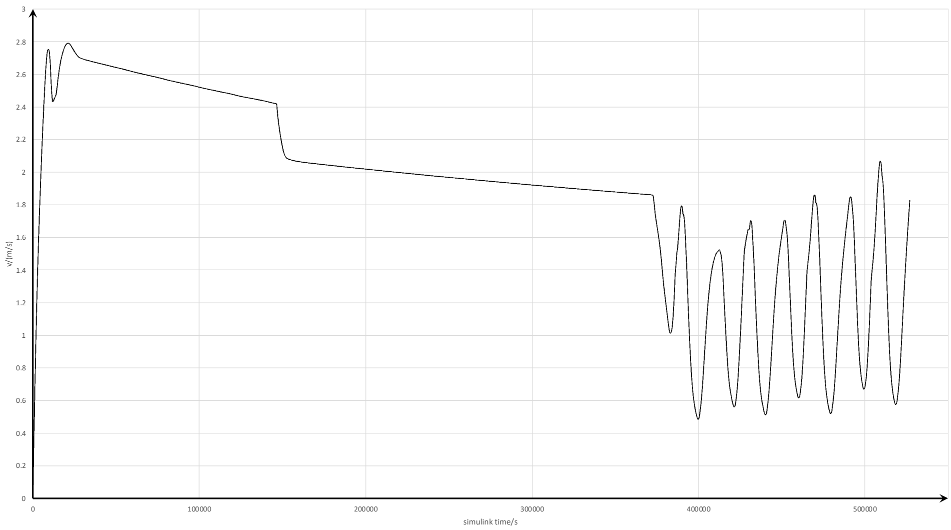

Fig.13 the forward speed of the unmanned sailboat for the second simulation

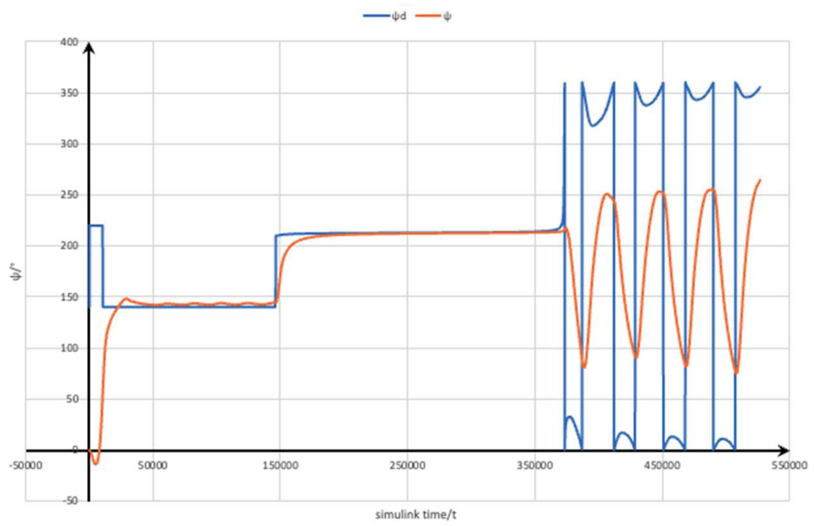

Fig. 14 the desired heading ψ_d and the heading ψ for the second simulation

VII. CONCLUSION

We propose an unmanned sailboat's position keeping control strategy, which is based on the ES optimization algorithm to control the speed of the unmanned sailboat, and uses the fuzzy PID to control the heading. When the unmanned sailboat is controlled at a fixed point, the heading required for the unmanned sailboat to reach the target point is calculated in real time. If the angle between the target heading and the wind direction enters the dead zone, it will move 10 degrees outside the dead zone boundary. When the sailboat moves out of the dead zone, the sailboat moves along the heading required for the unmanned sailboat to reach the target point. Simulation experiments show that this method can reach the target point.

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