Motion Control of an One-meter Class Autonomous Sailboat

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Abstract—In order to compensate for the limitation of the endurance of electrically powered autonomous ships, a sailboat prototype was built to use natural wind power efficiently. Two actuators of the sailboat were controlled separately. The fuzzy control algorithm is used for rudder, and table look-up control method is used for the wing sail based on velocity polar prediction diagram. The specifications of the hardware system and detailed information on motion control strategy are illustrated. Subsequently, ship trial conditions and experimental results were presented. The prototype performance showed that the control strategy was feasible for such a boat. This laid the foundation for the follow-up study of the autonomous sailboat.

Keywords—autonomous sailboat, fuzzy control, velocity polar prediction diagram.

I. INTRODUCTION

Marine resources have been paid more and more attention by coastal countries. Autonomous watercraft are widely used in marine resource exploration and environmental monitoring [1]. However, conventional autonomous marine robotics (i.e., underwater vehicles, surface vehicles, and fixed-point buoys) [2] used for marine resources exploration and environmental monitoring have certain limitations. Due to the limited battery capacity, the endurance capability of major marine robotics cannot be well qualified for long-term and large-scale tasks. In such a case, autonomous sailing technology has been put forward to solve these limitations [3].

Numerous international institutes have studied motion control strategies for different kinds of autonomous sailing boats, and achieved valuable results. Some of these autonomous sailboats are summarized [4-8] in Table I. Among these projects, the Iboat and Roboat are closely related to our sailboat which inspired us to design a wing-sailed autonomous boat.

TABLE I Sailboats and controllers.

Sailboat	Rudder Control	Sail Control
Iboat	Fuzzy	Fuzzy
Roboat	Fuzzy	Fuzzy
Fast	PI	Optimal Angle of Attack
VAIMOS	Line Following	Human Behavior Observation
Avalon	PID	Optimal Angle of Attack
Hyrail	PID	Optimal Angle of Attack

The Iboat project [4] was designed to participate in the Microtransat challenge, whose rudder and sail both used fuzzy controllers [9]. Roboat [7] is the another project which was supported by the Austrian Society for Innovative Computer Sciences researchers. It also participated in the Microtransat challenge and was regard as the first successful long-distance autonomous sailboat. Besides, it is applied in detection of a certain area of interest and marine investigations. Both of these two autonomous sailboats use soft sails, which are not as durable as wing sails, especially for long-term navigation or tasks in atrocious weather.

Therefore, the wing sail was involved in our sailboat with the control strategy based on velocity polar prediction diagram. Fuzzy control algorithm was used for the rudder. In order to simplify the control strategy, two independent controllers were designed to control the rudder and the wing sail.

The rest of the paper is organized as follows. In Section II, the hardware system of the sailboat is introduced. Next, detailed information of the motion control strategy is presented in Section III. Subsequently, the trail test results are shown in section IV to demonstrate the performance of the sailboat. Finally, the paper ends with the concluding remarks and discussions.

II. HARDWARE SYSTEM

The unmanned sailing vessel is expected to achieve autonomous navigation, information exchange with the shore base station and short-range remote control functions. Therefore, the hardware system is designed as shown in Fig. 1.

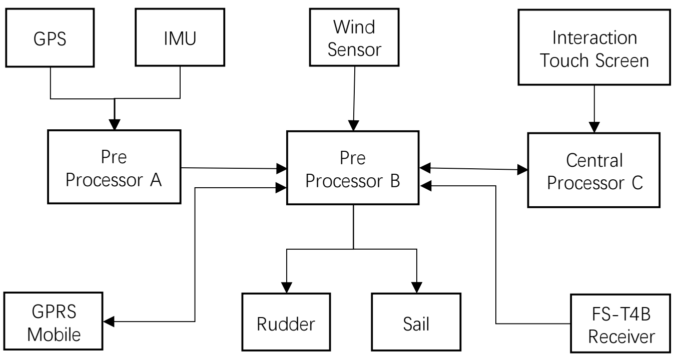

Fig. 1 Hardware diagram of autonomous sailboat.

A. Onboard controller

Three processors are used in the whole system, among which preprocessors A and B are STM32F103 series processors made by ST Company. Seven-channel Direct Memory Access, seven timers, can be processed more quickly for a program that requires a lot of math to solve the pose. At the same time, the parallel operation of DMA and UART make the whole system have higher and more reliable communication rates.

In addition, the central processor C has adopted an embedded platform based on Samsung S3C6410A processor. A powerful multimedia processing unit is integrated into the platform, which can provide powerful computing ability and good human-computer interaction interface for the control system of unmanned sailboats.

The preprocessor A collects the raw data from the GPS and IMU sensors, and then filters and calculates the attitude and position information. Subsequently, the result is packaged and sent to the preprocessor B. The processor B collects wind speed and direction sensor information, and then sends the wind, position and attitude information to the processor C.

B. Sensors

Two wind sensors are used to determine the local wind vector. The wind speed is determined by the rotor anemometer, and the apparent wind direction is determined by the vane. Wind speed and direction sensor are displayed in Fig. 2.

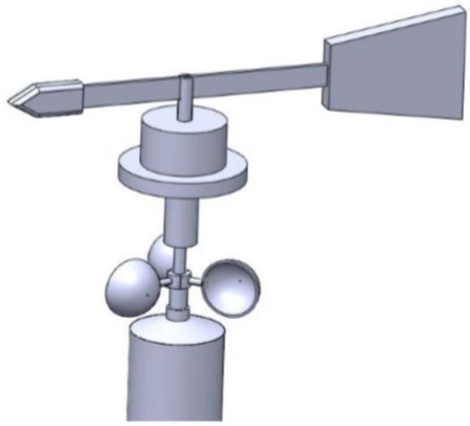

Fig. 2 Solidworks diagram of wind vane.

In order to obtain the position and speed information of the sailboat, GPS is used to locate and track the sailboat. The AI-GPS-V03 module is selected as the GPS satellite signal receiver. The location deviation is less than 5 meters, and the data update frequency is 1Hz. When the number of visible satellites (more than 6) is sufficient to calculate the geographic location, the GPS outputs standard ASCII packets to processor A.

IMU attitude sensor calculates the angle and angular acceleration of three degrees of freedom in the hull-fixed coordinate system, and obtains the parameters of yaw, roll and pitch. The module integrated with a three-axis accelerometer and gyroscope (MPU6050), a three-axis magnetometer

(HMC5883), and a high-precision barometric altimeter (BMP180) uses complementary filtering technology and STM32F103 microcontroller for attitude calculation. Detailed information are shown in table II.

TABLE II Detail information of IMU.

	MPU6050		HMC5883	BMP180
Start-up Time	100 ms	100 ms	50 ms	10 ms
Maximum Range	±2000 °/s	±16 G	±8 gauss	300-1100 hPa
Minimum Range	±250 °/s	±2 G	±1 gauss	300-1100 hPa
ADC Digits	16 Bit	16 Bit	12 Bit	16 Bit
Resolution Ratio（max rang）	16.4 LBS/(°/s)	2.048 LBS/g	4.35 milli-gauss	0.01 hPa
Resolution Ratio（min range）	131 LBS/(°/s)	16.384 LBS/g	0.73 milli-gauss	0.01 hPa
Update Rate	4-8000 Hz	4-1000 Hz	0.75-75 Hz	4.5-25.5 ms

C. Actuators

The MG996R steering gear is used in the rudder of the autonomous mrigged ship. The micro servo control system outputs adjustable duty cycle PWM control and maintains steering angle amplitude through Arduino Mini USB16 steering control board.

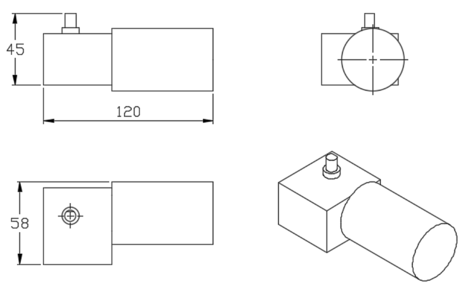

Fig. 3 GW4468-80 type worm geared motor outline dimensional drawing.

In order to reduce power consumption, the autonomous sailing vessel adopts a semi-balanced sail structure and use a turbo-worm reducer (shown in Fig. 3) as the prime motor.

D. Wireless module

GPRS mobile phone module is bound to the autonomous sailing vessel to establish data communication with PC monitoring software to realize real-time monitoring and debugging purposes. In addition, the unmanned sailboat also carries the FS-T4B model telecontrol system. It is used to realize manual emergency control under manual intervention.

E. Model and real ship

The sailboat designed by ourselves is shown in Fig. 4. Main Parameters are shown in Table III. The boat would be used to test and verify the control strategy.

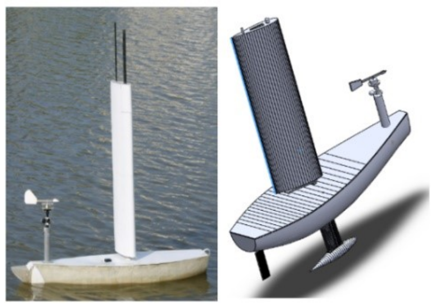

Fig. 4 Actual boat (left) and model ship (right).

TABLE III Main parameters of autonomous sailboat.

Parameters	**Value**
Length	1.35 m
Width	0.37 m
Displacement	16.50 kg
Draft	0.10 m
Area of sail	0.33 m^2

III. MOTION CONTROL STRATEGY

In this section, detail information of control strategy applied to our autonomous sailboat is introduced. The data collected by sensors is preprocessed and shared to subsequent modules. After collecting information of wind direction, wind speed, ship speed, and heeling angle, the processor C makes decisions to control rudder and sail according to the direction of the target. Two independent controllers are used to control the action of rudder and sail respectively, so as to control the attitude and navigation process of the sailboat. Feedback information of the GPS position and attitude through sensors forms a closed-loop control.

A.Fuzzy control of rudder

The fuzzy control system of the autopilot adopts Mamdani type.[10] In order to reduce the amount of computation of embedded processing, all the triangle membership curves of the conclusion part of the fuzzy control system adopt central average defuzzer to clarify the output results [11].

The fuzzy controller in the subsystem collects the current heading and direction of the target. The course deviation is directly input into the fuzzy controller as input variables. The input domain is [-180, +180], and the domain is divided into five fuzzy sets of SL, L, M, R, and SR. Figure 5 shows the membership function of its fuzzy set.

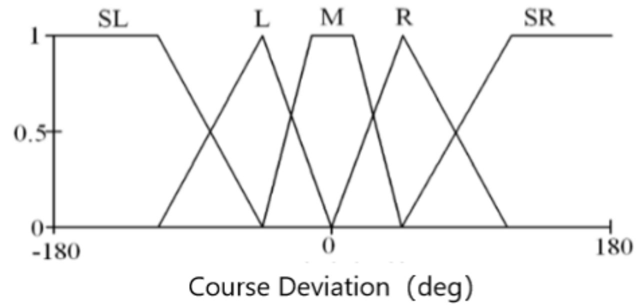

Fig. 5 Fuzzy sets for input course deviation.

At the same time, in order to avoid over-steering (course overshoot), the boat's turning velocity (the differential of course deviation) is used as another input variable. The input domain is [-50, +50], and the domain is divided into three fuzzy sets of L, N, and R. The membership function of its fuzzy set is shown in Fig. 6.

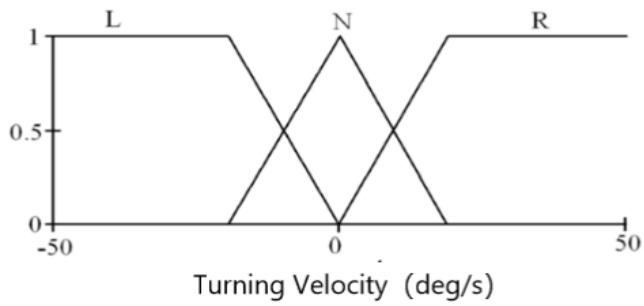

Fig. 6 Fuzzy sets for input turning velocity.

Table IV is the complete fuzzy rule table.

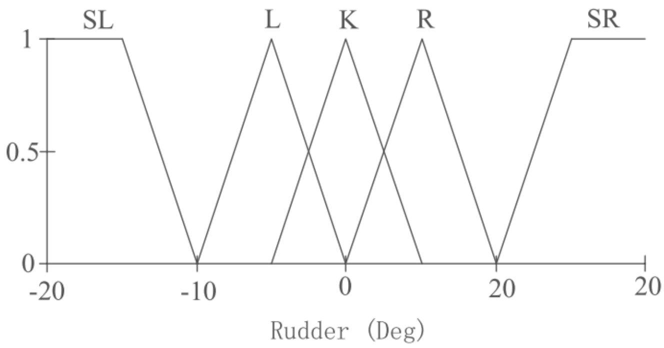

Fig. 7 Fuzzy sets for rudder output.

TABLE. IV Fuzzy rules for rudder FIS.

Rudder		**Turning Velocity**		
		L	**N**	**R**
Course Deviation	**SL**	L	SL	SL
	L	K	L	SL
	M	R	K	L
	R	SR	R	K
	SR	SR	SR	R

B. Table look-up control based on velocity polar prediction diagram

According to the direction of the target and the direction and speed of the current local wind, the optimal sailing angle of attack for the autonomous sailboat can be obtained from Table V which was calculated based on the dynamical characteristics of wing sail.

In addition, considering the sudden change of direction and speed of local wind, and the influence of the wave, the heeling angle may exceed the calculated value. Therefore, in order to avoid accidents like water intake in the cabin caused by large heeling angle, the wing sail controller adds heeling angle feedback. The specific control flow is shown in Fig. 8.

TABLE V Maximum v_s and corresponding parameters at v_T=4m/s.

ε (deg)	α (deg)	$v_s(m/s)$	$v_A(m/s)$	β (deg)
30	2.01	0.40	4.34	29.80
45	4.76	0.65	4.48	39.54

60	9.17	0.89	4.51	50.42
75	12.03	0.99	4.36	62.46
90	13.75	1.04	4.12	75.64
105	16.04	1.07	3.87	89.39
120	19.48	1.07	3.59	104.86
135	25.21	1.04	3.34	122.62
150	35.53	1.03	3.15	140.96
165	48.13	1.07	2.98	159.87
180	80.79	1.21	2.79	179.92

Note: $\varepsilon, \alpha, \beta$ are angles of true wind, attack and apparent wind. v_s and v_A are speeds of sailboat and apparent wind.

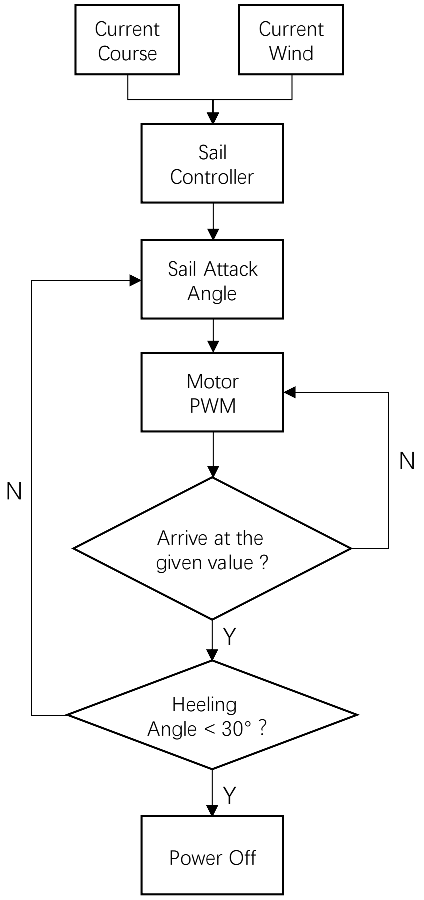

Fig. 8 Wing sail control flow.

IV. TRAIL AND ANALYSIS

The trail experiment was conducted at Xinhai Lake. According to the weather forecast of China Meteorological Station, there was southeast wind on that day. The wind speed was about 2-3 m/s.

Expected objectives of the experiment: this sailboat would start from point A then turn around O and go back to A again. The track record is shown in Fig. 9. The wind direction was described as the direction of arrow.

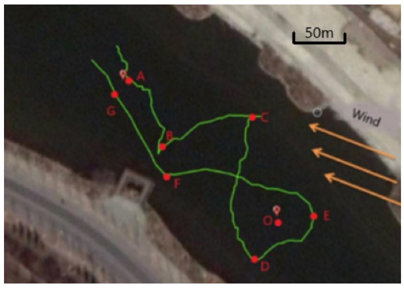

Fig. 9 Sailboat motion test. (Google Earth logging)

For sailing control, the sailing ability of sailboats against the wind is highly emphasized in general. The major part of the sailing ability of sailboats against the wind depends on the capability of tacking. Figure 10 shows the sailing angle and apparent wind direction and speed of the sailboat before and after point C in 100 seconds.

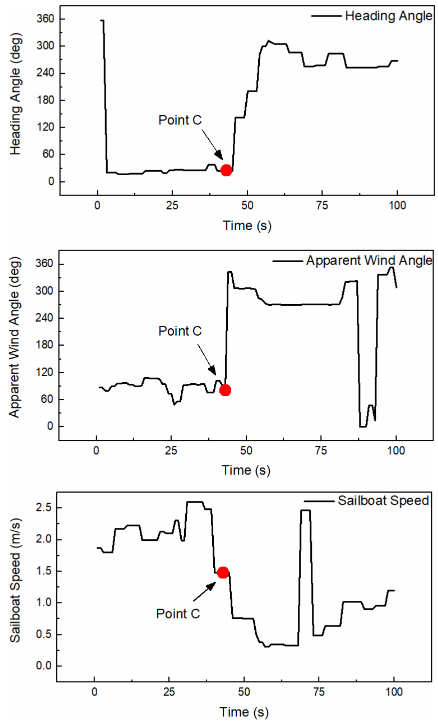

Fig. 5 Time-dependent curves of heading angle, apparent wind angle and ship speed around point C (red point).

According to the heading angle curve in Fig. 10, when the sailing boat passed through the point C, the sailboat turned by 60° clockwise. This was consistent with the track. The apparent wind direction also changed. When the sail angle was too late to adjust, the sail could not provide enough propulsion force. Finally, the sailboat speed dropped. But when the angle of attack finished adjustment, the sailboat speed increased. The tacking process was finished. The time cost for tacking is about 25 seconds, the voyage was about 10 meters. This tacking process also occurred at point B, D and E. The whole process of the tacking was continuous and stable within our expectation.

V. CONCLUSIONS

The one-meter class sailboat with the hardware system is the first prototype developed at the lab which can record data of the angle and the speed of sailboat and wind, heeling angle and so on for further improvement. The sailboat completed the navigation covering about 500 meters against the wind. In particular, the ability of tacking and seakeeping performed well. The trial results show that the control strategy which uses the fuzzy control for rudder and table look-up control for sail is feasible.

However, there are still many issues left for improvement. For instance, how to reduce speed loss when sailboat tacks and optimize the route. But based on the lab-scale sailboat prototype, we will explore these challenges in the follow-up investigation.

VI. ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China [grant numbers 51809100 and 51579111], the Fundamental Research Funds for the Central Universities [grant numbers 2018KFYYXJJ015 and 2017KFYXJJ005], and HUST Scientific Research Foundation for the introduction of talent [grant number 3004140108].

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