Research on Course Control of Unmanned Surface Vehicle

Xinming Hu, Huaichun Fu, and Qixing Cheng(✉)

School of Mechatronics Engineering and Automation,
Shanghai University, Shanghai 200444, China
xing_shu@shu.edu.cn

Abstract. The unmanned surface vehicle (USV) system has the characteristics of large inertia, long time delay and under-actuated, the traditional linear control method is not robust enough to achieve course control. Therefore, a course controller of USV has been proposed based upon the fuzzy control theory in this paper. On this basis, the mathematical model of USV has been established and the model parameter has also been identified by least-square method in different speed. In addition, a hardware platform of USV are obtained. The control method has been verified and validated through computer simulation and marine experiment; the results validate that the course control of USV has an excellent effect.

Keywords: USV · Fuzzy control · Course control · Model identification

1 Introduction

With the application of USV in port patrol, environment monitoring, antisubmarine etc. the research is more and more in-depth of USV at home and abroad, one of the key technologies of USV is course control, because it determines the track tracking error. Sonnenburg Cr, Woolsey C A. et al. [1] investigated the trajectory control of USV, the modeling, identification and control of USV are obtained, a back-stepping [2, 3] trajectory controller and a PD cascade trajectory control law was developed, the performance of the two controllers was compared using aggressive trajectories. A kind of fuzzy self-adaptive PID [4] course controller for USV had been designed and implemented by Fan Yunsheng et al. [5], the simulation of the conventional PID and fuzzy self-adaptive PID [6] course control was carried out in the case that whether there is environmental disturbance and parameter perturbation. Ashrafiuon et al. [7] presented a novel nonlinear trajectory tracking control [8] framework for general planar models of underactuated vehicles [9] with six states and two control inputs. A nonlinear sliding mode control [10, 11] law was employed to stabilize the error dynamics. It was shown that the control law is uniformly asymptotically stable if unknown disturbances and modeling uncertainties were bounded. A sliding mode control law of formation control for multiple underactuated surface vessels was proposed by Wei Meng, Chen Guo et al. [12], The stability analysis of the sliding mode control law was taken based on Lyapunov

Y. Chen et al. (Eds.): BICT 2020, LNICST 329, pp. 141–151, 2020.
https://doi.org/10.1007/978-3-030-57115-3_12

[13, 14] theory. Numerical simulations were provided to validate the effectiveness of the proposed formation controller for underactuated surface vessels. Ren Junsheng et al. [15] proposed a nonlinear backstepping controller [16] to solve the nonlinear problem of ship motion when research the ship steering controller, and compensated the course angle tracking deviation based on Lyapunov candidate function. The controller did not need prior knowledge of ship mathematical model. The simulation object was “Yulong” ship, and the results showed that the controller was effective.

2 Fuzzy PID Controller

2.1 Mathematical Model

Select the second-order response model of “Nomoto” [17–20] to describe the plane motion mathematical model of USV:

$$T_1T_2\ddot{r} + (T_1 + T_2)\dot{r} + r = K\delta + KT_3\dot{\delta} \tag{1}$$

where δ is rudder, r is course angular velocity, K is gain, T_1, T_2, T_3 is time delay constant.

In this paper, the parameter identification of model is carried out by the least-square method [21]. In addition, the goodness of fit [22] is used to identify result, the measure of goodness of fit is a determinable coefficient R, as shown in formula 2. The value range of R is [0, 1].

$$R = 1 - \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \tag{2}$$

where y_i is the sampling value, $\hat{y}_i$ is the output value of identification model, $\bar{y}$ is the average value of all sampling values.

2.2 Design of Course Controller

The course controller of USV is based on the theory of fuzzy control [23]. The structure design of course controller is shown in Fig. 1. The input of the controller is the course deviation and the course deviation change. Output is actual course.

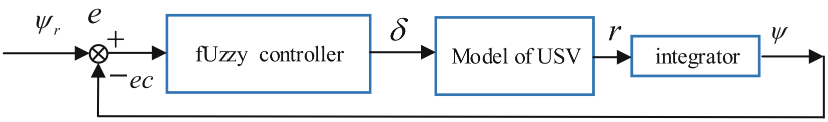


Fig. 1. The structure of course controller

where ψ_r is expected course, e is course deviation, ec is course deviation change, δ is rudder, r is course angular velocity, ψ is actual course.

2.3 Fuzzy Control Principle

The input of fuzzy control [24, 25] is course deviation and course deviation change. According to the rule table, the control value is obtained by Mamdani [26, 27] reasoning and fuzzy settlement. As shown in Fig. 2 below.

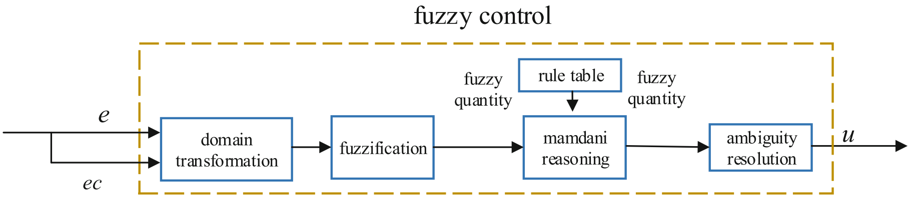


Fig. 2. The structure of fuzzy control

where e is course deviation, ec is course deviation change, u is control value.

Fuzziness. In order to change the input variable into a fuzzy set that can be identified by the controller, it is necessary to deal the input with fuzzy measure [24]. In this paper, the fuzzy set is divided into seven subsets: {PB, PM, PS, Z, NS, NM, NB}. The triangle membership function [28] is used to deal the input of course deviation, the change of course deviation and the output of fuzzy control with fuzzy measure. As shown in Fig. 3 below. Where E, EC, U is domain transformation of e, ec, u.

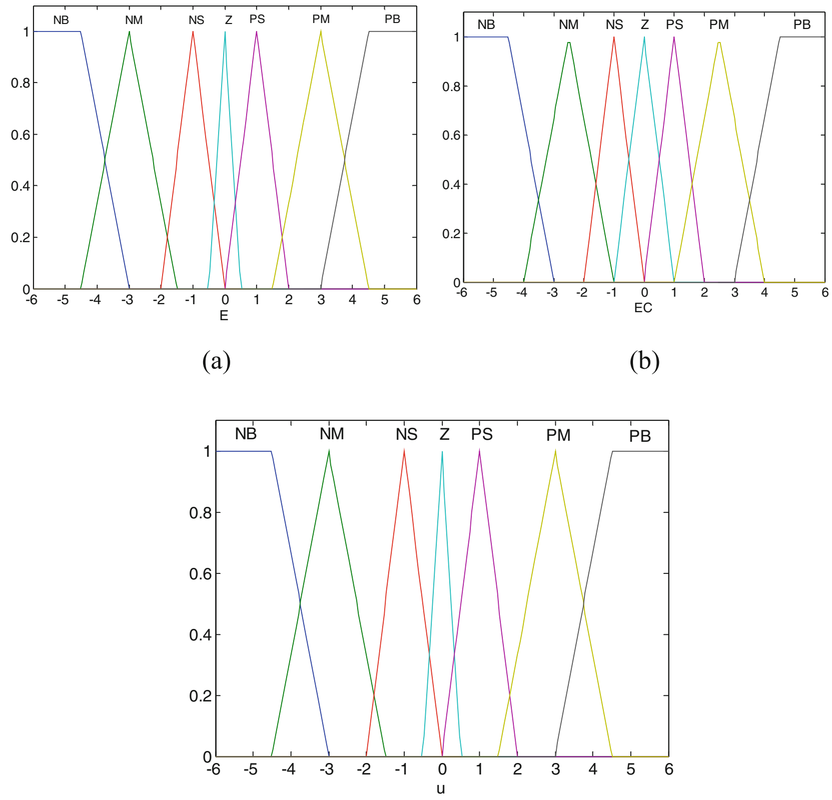
Fuzzy Rule Table. The fuzzy rule table is obtained through the experience of manual operation. The control rule table with the output of each parameter is shown in Table 1 below.

2.4 Mamdani Fuzzy Reasoning

Using the Mamdani reasoning method [29], any group of fuzzy output sets of course deviation and course deviation change can be obtained. The result of Mamdani fuzzy reasoning ergodic output is shown in Fig. 4 below.

Defuzzification. The output of the fuzzy controller is the exact value, and the solution of fuzzy is the process of transforming the fuzzy set obtained by fuzzy reasoning into the exact value. In this paper, bisector [30] is used to solve the fuzzy problem. As shown in Formula 3.

$$u = \frac{\sum_{i=1}^{n} \mu_i(u_i) \cdot u_i}{\sum_{i=1}^{n} \mu_i(u_i)} \tag{3}$$



(a) (b)

(c)

Fig. 3. Membership function of controller (a) Input *E* (b) Input *EC* and (c) Output *U*

Table 1. Table of fuzzy rules

U		*EC*						
		NB	NM	NS	Z	PS	PM	PB
E	NB	NB	NB	NB	NB	NM	NM	NM
	NM	NB	NB	NB	NM	NM	NS	NS
	NS	NM	NM	NM	NS	NS	NS	Z
	Z	NB	NM	NS	Z	PS	PM	PM
	PS	P	Z	PS	PS	PM	PM	PM
	PM	PS	PS	PM	PM	PB	PB	PB
	PB	PM	PM	PM	PB	PB	PB	PB

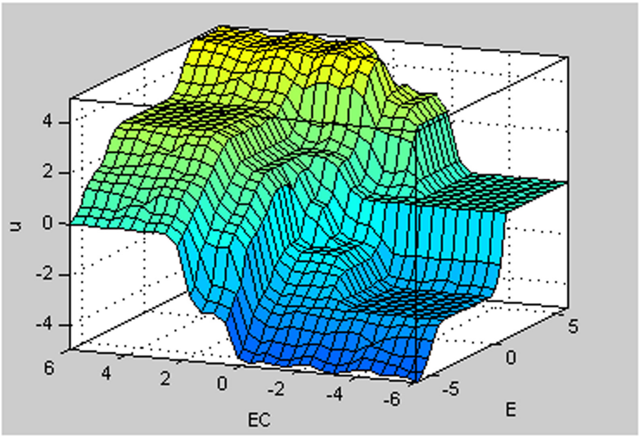


Fig. 4. The results of traversal output of Mamdani fuzzy reasoning

where n is the number of fuzzy sets after fuzzy reasoning, μ_i is membership value corresponding to the ith bisector of fuzzy set area. u is the exact result of defuzzification.

3 Hardware Platform of USV

3.1 Parameters

The research object of this paper is "Jinghai 2" of Shanghai University. "Jinghai 2" belongs to the category of water jet propulsion. It adopts the design principles of standardization, modularization and systematization, and it is applied to marine surveying and mapping. The Fig. 5 shows the appearance and internal structure of "Jinghai 2".

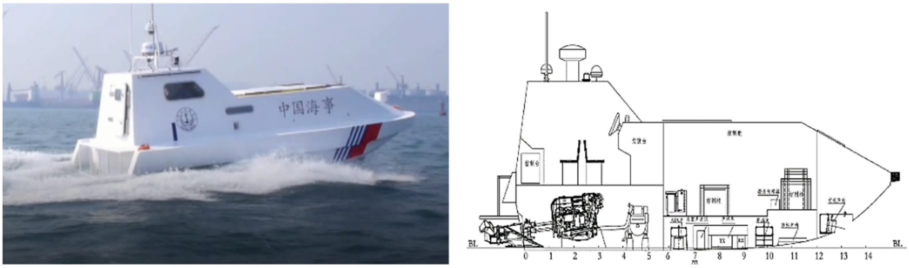


Fig. 5. The appearance and internal structure of "Jinghai 2"

The parameters of "Jinghai 2" are shown in Table 2 below.

Table 2. The parameters of “Jinghai 2”

Category	Parameter
Length	7.65 m
Width	3.0 m
Draught depth	≤0.5 m
Full load weight	4000 kg
Max speed	20 kn

3.2 Composition of Hardware System

The equipment carried by the “Jinghai 2” include INS, GPS, microwave communication, maritime radar, laser radar, forward-looking sonar, etc. the equipment for remote monitoring is mainly remote monitoring stations. As shown in Fig. 6 below.

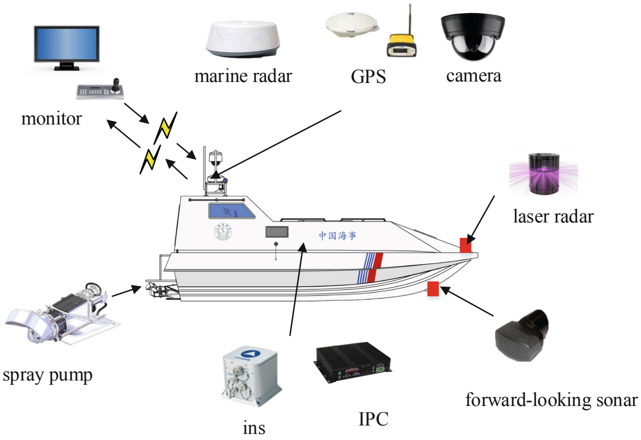


Fig. 6. Composition of hardware system

3.3 Remote Monitoring Software

The main function of remote monitoring software is route planning and USV dynamic information display. It can be divided into chart management module, route planning module, video monitoring module, obstacle information display module and USV integrated information module. As shown in the Fig. 7.

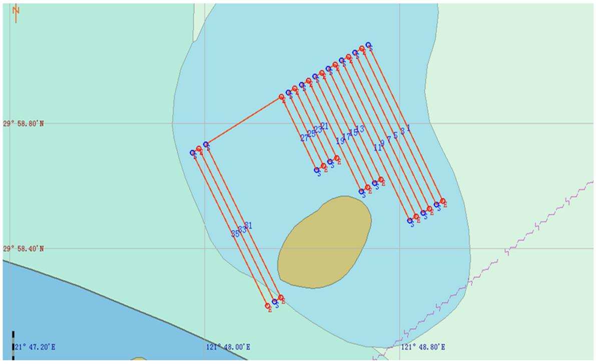


Fig. 7. Remote monitoring software

4 Simulation and Experiment

4.1 Identification Result

Identification result of model parameters of "Jinghai 2" in three different speeds. As is shown in Table 3 below.

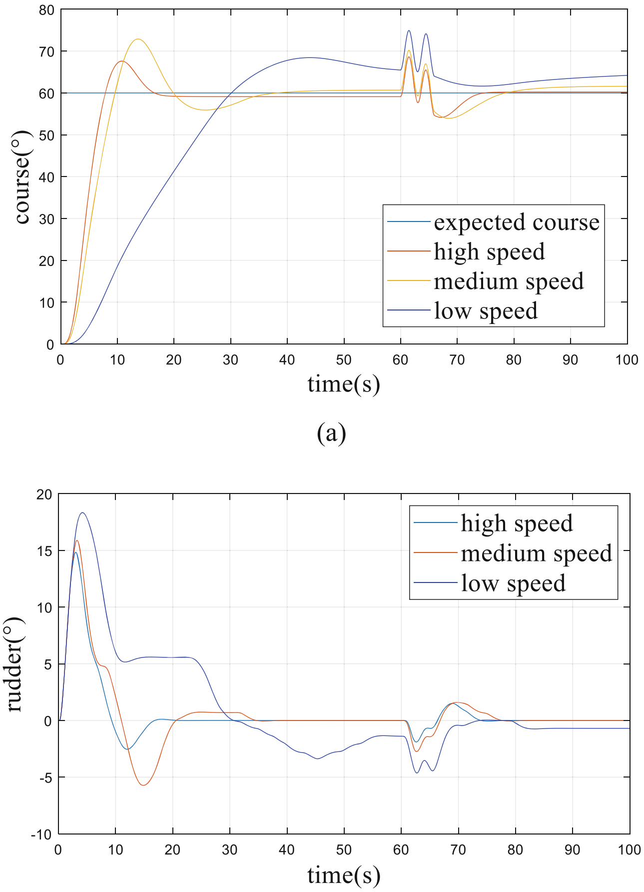
Table 3. Identification result of "Jinghai 2"

No.	Speed (Kn)	Transfer function	Coefficient of determination (%)
1	15–18	$G(s) = \frac{4.09s+3.95}{s^2+10.12s+4.01}$	77.7
2	7–10	$G(s) = \frac{1.26s+0.85}{s^2+4.01s+0.75}$	78.08
3	1–4	$G(s) = \frac{0.0501s+0.000486}{s^2+0.1845s+0.000201}$	58.43

4.2 Simulation

In the simulation experiment, the input signal source is step signal, the initial course is set as 0°, the expected course is 60°, the sampling frequency is 0.1 s, the random interference signal is added at 60 s, the duration is 3S, and the range is [0°, 5°]. Fig. 8 (a) and (b) below are the course change curve and the corresponding actual rudder angle change curve under random interference.

As can be seen from Fig. 8, the expected course can still be recovered after a certain degree of interference. Response index of three speed model parameters are shown in Table 4 below.



(a)

(b)

Fig. 8. Simulation of course control (a) Course change (b) Actual rudder change

Table 4. Response index of three speed model parameters

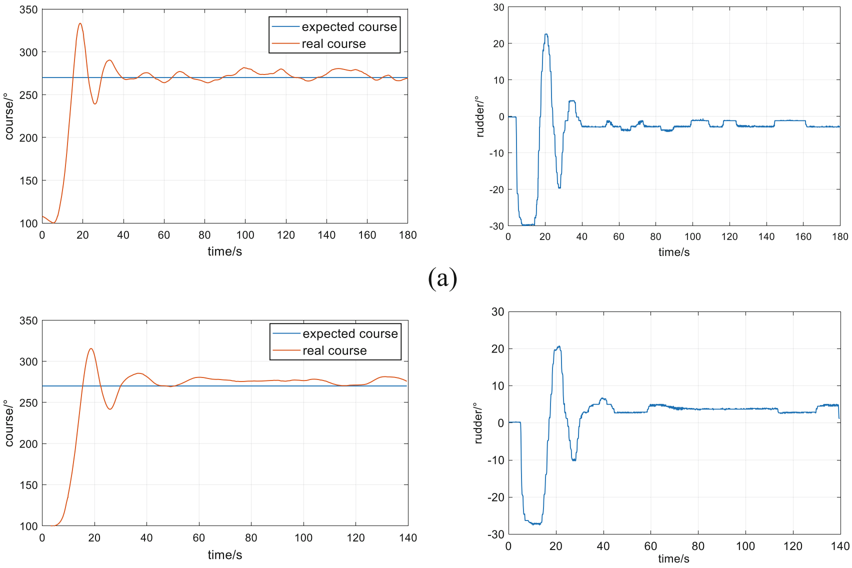
Speed	Max overshoot (%)	Rise time(s)	± 5% steady state adjustment time(s)	Static deviation (°)
High	12.5	10.5	16	−1
Medium	21.5	13.5	35	+0.5
Low	14.2	44	Infinity	+5

4.3 Experiment

The marine experiment was carried out in north shipyard, Qingdao. the marine state is 1−2, the wave height is about 30 cm, and the wind is 1−5 m per second northward. The experimental area on the chart and scene are shown in Fig. 9 below.

Fig. 9. Marine experiment of “Jinghai 2” in Qingdao

As shown in Fig. 10 below, it can be seen from the experimental results that after the start of control, the actual course of USV can rotate rapidly to the expected course, and finally vibrate near the expected course. The oscillation is caused by uncertain wind, wave and current. these external forces will make the USV course deviate when they act on USV. Practice shows that USV can still keep straight-line operation effectively When the course vibration is within ±10°.



(a)

(b)

Fig. 10. Marine experiment result of course control (a) 15–18 Kn, Course change (Left), actual rudder change (Right) (b) 7–10 Kn, Course change (Left), actual rudder change (Right)

Marine Experiment Results Of course Control are shown in Table 5 below.

Table 5. Marine experiment results of course control

Speed	Max overshoot (%)	Rise time(s)	± 10% steady state adjustment time(s)	Static deviation (°)
High	25.9	10.5	14	±10
Medium	18.5	13.5	17	±10

5 Conclusion

The USV has the characteristics of large inertia, long time delay, under drive, etc. the traditional linear controller cannot meet the needs of course control. In this paper, a fuzzy PID course controller based on fuzzy control theory is designed. The mathematical model is established. The parameters of the model are different with the driving force of different speed. The parameters are identified under three speeds. At last, the simulation experiment of the model with three parameters shows that the control effect is good in medium and high speed. Furthermore, the hardware platform is built, and the experiment is done in the sea. The experiment shows that the design of the course controller work effectively.

Acknowledgement. This work was supported in part by the National Science Foundation of China under Grant 61525305, Grant U1813217, and Grant 61773254.

References

1. Sonnenburg, C.R., Woolsey, C.A.: Modeling, identification, and control of an unmanned surface vehicle. J. Field Robot. **30**(3), 371–398 (2013)
2. Belabbas, B., Allaoui, T., Tadjine, M., Denai, M.: Comparative study of back-stepping controller and super twisting sliding mode controller for indirect power control of wind generator. Int. J. Syst. Assur. Eng. Manag. **10**(6), 1555–1566 (2019)
3. Liu, N., Shao, X., Li, J., Zhang, W.: Attitude restricted back-stepping anti-disturbance control for vision-based quadrotors with visibility constraint. ISA Trans (2019)
4. Xu, S.-W., Lu, J., Zhao, X.: The driving control strategy of pure electric vehicle based on fuzzy self-adaptive PID [P]. In: Proceedings of the 2016 4th International Conference on Machinery, Materials and Computing Technology (2016)
5. Fan, Y., Sun, X., Wang, G., et al.: On fuzzy self-adaptive PID control for USV course. In: Control Conference, pp. 8472–8478. IEEE (2015)
6. Yunsheng, F.: Fuzzy self-adaptive proportional integration differential control for attitude stabilization of quadrotor UAV. J. Donghua Univ. (Engl. Edn.) **33**(05), 768–773 (2016)
7. Ashrafiuon, H., Nersesov, S., Clayton, G.: Trajectory tracking control of planar underactuated vehicles. IEEE Trans. Autom. Control **62**(4), 1959–1965 (2016)

8. Dumlu, A.: Design of a fractional-order adaptive integral sliding mode controller for the trajectory tracking control of robot manipulators. Proc. Inst. Mech. Eng. Part I J. Syst. Control Eng. **232**(9), 1212–1229 (2018)
9. Liao, Y.L., Zhang, M.J., Wan, L., Li, Y.: Trajectory tracking control for underactuated unmanned surface vehicles with dynamic uncertainties. J. Cent. S. Univ. **23**(2), 370–378 (2016)
10. Tong, D., Xu, C., Chen, Q., Zhou, W.: Sliding mode control of a class of nonlinear systems. J. Franklin Inst. **357**(3), 1560–1581 (2020)
11. Chu, X., Li, M.: H ∞ non-fragile observer-based dynamic event-triggered sliding mode control for nonlinear networked systems with sensor saturation and dead-zone input. ISA Trans. **94**, 93–107 (2019)
12. Wei, M., Chen, G., Yang, L.: Nonlinear sliding mode formation control for underactuated surface vessels. In: Intelligent Control and Automation, pp. 1655–1660. IEEE (2012)
13. Zhang, X., Jiang, W., Li, Z., Song, S.: A hierarchical Lyapunov-based cascade adaptive control scheme for lower-limb exoskeleton. Eur. J. Control **50**, 198–208 (2019)
14. Sliding mode control of uncertain systems with distributed time-delay: parameter-dependent Lyapunov functional approach. J. Control Theor. Appl. (02) 159–167 (2006)
15. Ren, J., Zhang, X.: Backstepping adaptive tracking fuzzy control for ship course based on compensated tracking errors. In: Control Conference, pp. 3464–3469. IEEE (2012)
16. Coban, R.: Adaptive backstepping sliding mode control with tuning functions for nonlinear uncertain systems. Int. J. Syst. Sci. **50**(8), 1517–1529 (2019)
17. Larrazabal, J.M., Peñas, M.S.: Intelligent rudder control of an unmanned surface vessel. Expert Syst. Appl. **55**, 106–117 (2016)
18. Li, D.P.: Ship motion and modeling. National Defense Industry Press (2008)
19. Ghorbani, M.T.: Line of sight waypoint guidance for a container ship based on frequency domain identification of nomoto model of vessel. J. Cent. S. Univ. **23**(8), 1944–1953 (2016)
20. Mu, D., et al.: Course control of USV based on fuzzy adaptive guide control. In: Proceedings of the 28th China Control and Decision-Making Conference, pp. 1554–1558 (2016)
21. Wei, L., Hongmin, W., Zheng, T.: Parameter identification of steering system based on recursive least square method. J. Chongqing Jiaotong Univ. (Nat. Sci. Edn.) **38**(08), 124–128 (2019). Author, F.: Article title. Journal 2(5), 99–110 (2016)
22. Songshan, Z.: Analysis and evaluation of influencing factors on goodness of fit R^2. J. Northeast. Univ. Financ. Econ. **3**, 56–58 (2003)
23. Lv, J., Zhang, B., Liu, F.: Ship trajectory control system based on fuzzy control. J. Coast. Res. **98**(SI), 110–112 (2019)
24. Chen, C.H., Chen, G.-Y., Chen, J.J.: Design and implementation for USV based on fuzzy control (2013)
25. Chen, J., Pan, W., Guo, Y., Huang, C., Wu, H.: An obstacle avoidance algorithm designed for USV based on single beam sonar and fuzzy control (2013)
26. Belarbi, K., Titel, F., Bourebia, W., et al.: Design of mamdani fuzzy logic controllers with rule base minimisation using genetic algorithm. Eng. Appl. Artif. Intell. **18**(7), 875–880 (2005)
27. Elnaggar, M.I., Ashour, A.S., Guo, Y., El-Khobby, H.A., Abd Elnaby, M.M.: An optimized mamdani FPD controller design of cardiac pacemaker. Health Inform. Sci. Syst. **7**(1), 2 (2019)
28. Weihua, H.: Analysis and design of fuzzy-PID controller with generalized linear membership function, pp. 2366–2370 (2014)
29. Mohanty, S.N., Pratihar, D.K., Suar, D.: Influence of mood states on information processing during decision making using fuzzy reasoning tool and neuro-fuzzy system based on Mamdani approach. Int. J. Fuzzy Comput. Model. **1**(3), 252–268 (2015)
30. Passino, K.M., Yurkovich, S.: Fuzzy Control. Tsinghua University Press (2001)