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Heading Control of USV by Expert-Fuzzy Technology

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Abstract

As we all know that the heading control of unmanned surface vessel (USV) is often with complex nonlinearity and uncertainty, it is difficult to establish accurate mathematical model, so the conventional control algorithm which is applied to linear system has some limitations. As fuzzy control does not rely on the specific mathematical model, and with control robustness, it is widely used in motion control system. However, the conventional fuzzy control is not high accuracy, usually with a large overshoot and steady-state error. In order to improve the dynamic and steady-state performance of fuzzy controller and further more improve its control quality, this paper combined expert system and fuzzy control then constitutes the Expert-Fuzzy controller, and applied to the heading control system of USV, simulation results shows that Expert-Fuzzy control system can achieve better heading control performance of USV compared to conventional fuzzy control system.

Keywords: *unmanned surface vessel (USV), heading control, fuzzy technology, expert technology, Expert-Fuzzy controller*

1. Introduction

USV(unmanned surface vessel) is a kind of small surface ship that could autonomous navigation in the real ocean, and complete the corresponding mission designed. As it has outstanding advantages on intelligence gathering, detection, armed protection, mine-sweeping, anti-submarine, precision strike, search and rescue, navigation and hydrographic survey, much of the world's attention from the navy leads to the rapidly development in recent decades.

A considerable amount of research has already been done on USV, particularly in the field of heading control which is a basis part. A fractional-order PID(proportion integration differentiation) controller is proposed for heading control of USV in [1], while an adaptively adjusted PID is designed in [2], and a provably stable nonlinear PID controller addressed in [3]. Li introduce an improved PSO(particle swarm optimization) algorithm to optimize parameters of PID controller which is used in course control for USV in [4]. Sun describes a control methodology of SVM(support vector machine) inverse model for USV system heading control in paper [5], which is composed of SVM inverse model and PID feedback compensation. However, Jeong-Hong Park [6] found that it was hard to obtain the optimal control performance for the heading control using PD controller, since the developed USV is a nonholonomic with two fixed thrusters and is coupled dynamics of the surge and yaw motion. Then their team proposed the dynamic model estimation of the USV and design of the optimal LQ(linear quadratic) controller based on the estimated model in their paper. You proposed a robust S surface control law for heading control of USV by introducing a robust compensator into the S surface control method in [7], while Wu designed a hybrid human simulated intelligent schema S

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surface method for it in [8]. A fuzzy controller of USV is designed to automatically control of USV heading in [9], and three methods is discussed for heading control of USV in [10], including PD control, slide mode control and fuzzy control. An ADRC(active disturbance rejection controller) is applied to the USV heading control in [11], and an dynamic feedback control algorithm base on multiple identification models switching is proposed in [12] for it.

Most researchers pay their attention to PID control for heading control of USV recent years, but heading control of USV is highly nonlinear as it usually sailing in high speed, so classic PID controller is not suitable. Though some researchers designed complex algorithms to optimize parameters of PID controller in order to improve it, it is usually only effective in simulation as its complexity.

Fuzzy control technology does not rely on a mathematical model of controlled object, and thus very suitable for heading control of USV as it is hard for us to establish precise mathematical model. Expert control technology is a simple and effective technique based on expert experience. We combined fuzzy control technology with expert control technology and then proposed a simple and effective Fuzzy-Expert control technology for heading control of USV in this paper. The paper is organized as follows. In Section 1, we introduce the background of the research and show the organization of the paper, Section2 describes the first-order nonlinear simulation model of the USV. Section 3 is devoted to design Expert-Fuzzy controller. Simulations of the USV heading control is taken in Section 4 using Expert-Fuzzy controller designed. We wrap up this paper with some concluding remarks in Section 5.

2. Nonlinear Model of USV

The following first-order nonlinear equation of yawing response describes the nonlinear heading control system of USV, as the steering is not very frequent. See Equation 1 below:

$$\begin{cases} \dot{\psi} = r \\ \dot{r} = -\dfrac{1}{T} r - \dfrac{\alpha}{T} r^3 + \dfrac{K}{T}\delta + w \end{cases} \tag{1}$$

where ψ = heading angle, r = yaw angular velocity, T = stability constant, K = turning constant, α = nonlinear coefficient of the model, δ = rudder angle, w = uncertainties of the system.

3. Design of Controller

3.1. Expert-Fuzzy Control System

Fuzzy control technology does not rely on the model of the control object, and the robustness of control system is relatively good in most cases, while sometimes the control accuracy is not high enough, with relatively large overshoot and longer settling time. There will also be some steady-state error, prone to oscillations in the vicinity of expectations, while anti-jamming capability is weak, in some special systems, such as the heading control system of USV, with high nonlinear and uncertainties. The above phenomenon is mainly due to the design of fuzzy controller is usually simple, and the subjective factors of designer influences, at the same time, fuzzy control rules can not be modified online.

Expert system have extensive knowledge of a particular field, is able to make an effective optimization of complex problems. Therefore, in order to improve the performance of the fuzzy controller, and then improve control quality, this paper introduces expert system into the fuzzy control technology, and then obtain Expert-Fuzzy controller. Expert-Fuzzy control technology is hybrid intelligent control technology which combines expert system with fuzzy technology, it express human experience knowledge through fuzzy logic language, and combined with the knowledge rules of the expert system in order to construct control strategies. Expert-Fuzzy controller is usually composed of basic fuzzy controller and expert intelligent coordinator, shown in Figure 1:

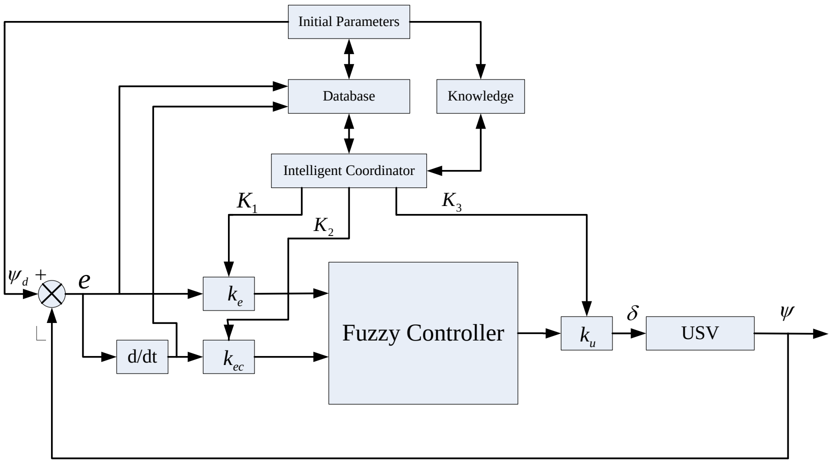

Figure 1. Expert-Fuzzy Control System

3.2. Basic Fuzzy Controller

The basic fuzzy controller is composed of fuzzification, fuzzy rules, fuzzy inference and defuzzification, as show in Figure 2:

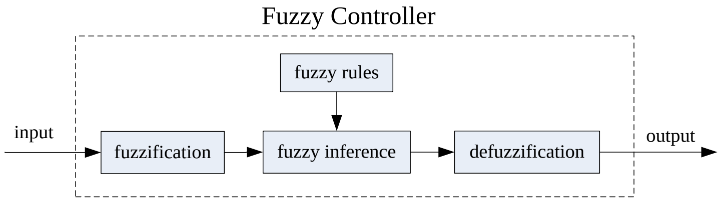

Figure 2. Basic Fuzzy Controller

3.2.1. Fuzzification: Let x^* be the value need to be fuzzed, $\tilde{A}^*$ be the fuzzy value for x^* after fuzzificaiton, and then expression of the triangular fuzzificaiton could see in Equation 2:

$$\mu_{\tilde{A}^*}(x) = \begin{cases} \left(1 - \dfrac{\left|x - x^*\right|}{\sigma}\right) & \left|x - x^*\right| \le \sigma \\ 0 & \left|x - x^*\right| > \sigma \end{cases} \tag{2}$$

where $\sigma > 0$ is a parameter, $\mu_{\tilde{A}^*}(x)$ = the membership. The schematic of fuzzification is shown in Figure 3:

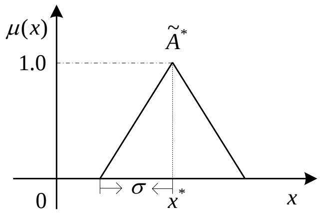

Figure 3. Schematic of Triangular Fuzzification

Dividing the fuzzy sets universe of input and output into [NB, NM, NS, ZO, PS, PM, PB], where heading error and its change rata is treated as input while rudder angle is output. All of them are fuzzed as follows show in Figure 4, where [-6, +6] is responded to [NB, PB]:

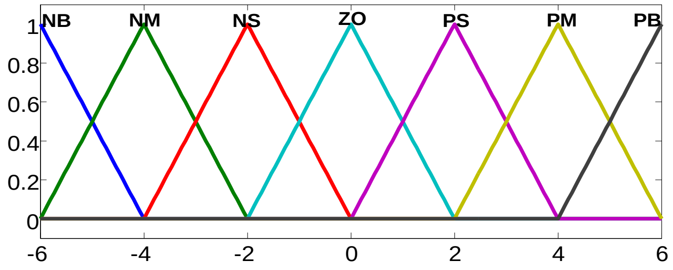

Figure 4. Fuzzification of Input and Output

3.2.2. Fuzzy Rules: Generally it is mainly by virtue of human's steering experience to achieve heading control of ships, while for USV how to change the human's experience into fuzzy control language that fuzzy control system could identify is a key point. Combing with the human's steering experience, we design the following fuzzy control rules:

If e is NB and $\dot{e}$ is NB, then u is NB

......

If e is PB and $\dot{e}$ is PB, then u is PB

And tabulation as follows in table 1 below:

Table 1. Fuzzy Rules

	$\dot{e}$						
e	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NM	NM	NS	ZO	PS
NS	NB	NM	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	ZO	PM	PB	PB	PB	PB

3.2.3. Fuzzy Inference: Let $\tilde{A}^*$, $\tilde{A}_1$, $\tilde{A}_2$, $\tilde{B}^*$, $\tilde{B}_1$, $\tilde{B}_2$ and $\tilde{C}^*$, $\tilde{C}_1$, $\tilde{C}_2$ be fuzzy sets of universe X , Y and Z . And $\tilde{R}_{M1}(X,Y,Z)$ is fuzzy relation among $\tilde{A}_1$, $\tilde{B}_1$ and $\tilde{C}_1$, $\tilde{R}_{M2}(X,Y,Z)$ is fuzzy relation among $\tilde{A}_2$, $\tilde{B}_2$ and $\tilde{C}_2$. Known fuzzy set $\tilde{A}^*$ and $\tilde{B}^*$ of X and Y , inference for $\tilde{C}^*$ of Z is show in Table 2 as follows:

Table 2. Fuzzy Inference

$Rule\,1:$	$if\ x\ is\ \tilde{A}_1\ and\ y\ is\ \tilde{B}_1$	$then\ z\ is\ \tilde{C}_1$
$Rule\,2:$	$if\ x\ is\ \tilde{A}_2\ and\ y\ is\ \tilde{B}_2$	$then\ z\ is\ \tilde{C}_2$
$Case:$	$if\ x\ is\ \tilde{A}^*\ and\ y\ is\ \tilde{B}^*$	
$Conclusion:$		$z\ is\ \tilde{C}^*$

Taking multi-fuzzy rules' inference as the union of a single fuzzy rule's inference, the above inference can be expressed as follows in Equation 3:

$$\begin{aligned}
\mu_{\tilde{C}^*}(z) &= \bigvee_{\substack{x\in X\\ y\in Y}} [\mu_{\tilde{A}^*}(x)\wedge\mu_{\tilde{B}^*}(y)]\wedge[\mu_{\tilde{R}_{M1}}(x,y,z)\vee\mu_{\tilde{R}_{M2}}(x,y,z)]\\
&= \{\bigvee_{\substack{x\in X\\ y\in Y}} [\mu_{\tilde{A}^*}(x)\wedge\mu_{\tilde{B}^*}(y)]\wedge\mu_{\tilde{R}_{M1}}(x,y,z)\}\\
&\quad \vee\{\bigvee_{\substack{x\in X\\ y\in Y}} [\mu_{\tilde{A}^*}(x)\wedge\mu_{\tilde{B}^*}(y)]\wedge\mu_{\tilde{R}_{M2}}(x,y,z)\}\\
&= \mu_{\tilde{C}_1^*}(z)\vee\mu_{\tilde{C}_2^*}(z)
\end{aligned} \tag{3}$$

where $\mu_{\tilde{R}_{M1}}(x,y,z)=\mu_{\tilde{A}_1}(x)\wedge\mu_{\tilde{B}_1}(x)\vee\mu_{\tilde{C}_1}(z)$, $\mu_{\tilde{R}_{M2}}(x,y,z)=\mu_{\tilde{A}_2}(x)\wedge\mu_{\tilde{B}_2}(x)\vee\mu_{\tilde{C}_2}(z)$, and $\mu_{\tilde{C}_1^*}(z)$ is the fuzzy set under inference of Rule 1, $\mu_{\tilde{C}_2^*}(z)$ is the fuzzy set under inference of Rule2. Specific fuzzy inference process show as follows in Figure 5 below:

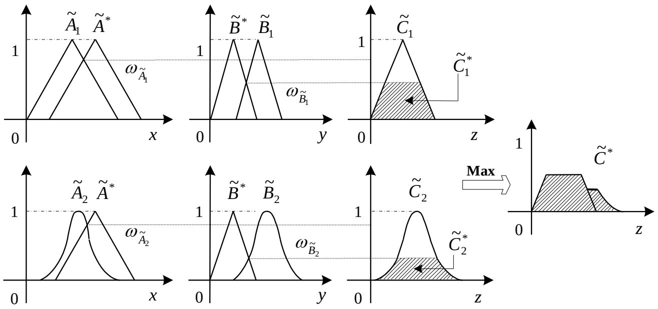

Figure 5. Fuzzy Inference Process

3.2.4. Defuzzification: As output of fuzzy controller must be precise values, fuzzy result from fuzzy inference should be defuzzification. The defuzzification method of area average for USV heading control could describe as follow in Equation 4:

$$y^* = \frac{\sum_{i=1}^{N}(y_i^*\mu^i(y))}{\sum_{i=1}^{N}\mu^i(y)} \tag{4}$$

where N = number of fuzzy set, y_i^* indicates the value associated with the bisector of area that surrounded by fuzzy set i and axes, $\mu^i(y)$ shows the membership.

Taking a fuzzy result that includes two fuzzy set for example, the defuzzification method of area average could show as follows in Figure 6:

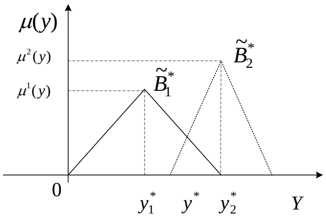

Figure 6. Schematic of Defuzzification

And the precise value of y^* above is:

$$y^* = \frac{y_1^*\mu^1(y) + y_2^*\mu^2(y)}{\mu^1(y) + \mu^2(y)} \tag{5}$$

3.3. Expert Intelligence Coordinator

Experts Intelligence Coordinator is based on experts' empirical knowledge of the control system, which is an online adjustment calculation method for basically control level calculated by inference mechanism, and at the same time forming a control strategy and parameter modification mode for controller. As the rule base of Experts Intelligence Coordinator is usually less, the search space of inference mechanism is limited, which leads to inference mechanism becomes simple, and then usually uses forward inference mechanism model to match the control rules one by one.

Firstly we analyze that how quantization scale factor affecting the performance of fuzzy control system, and then get online correction rules of quantization scale factor.

Affection of k_e : It is obvious that the adjustment of k_e could change the control efficiency of $e(t)$. Increasing of k_e could shrink the basic universe $[-X_e, +X_e]$ and then strengthen the control efficiency of $e(t)$, as universe of fuzzy sets $[-N_e, +N_e]$ is fixed, which would lead to lager overshoot, longer settling time, and somehow oscillations, though rising time is shorter. However in a similar way, reducing of k_e would lead to longer rising time, lager steady state error, and longer settling time, though overshoot is smaller.

Affection of k_{ec} : It is obvious that the adjustment of k_{ec} could change the control efficiency of $\dot{e}(t)$. Increasing of k_{ec} could strengthen the control efficiency of $\dot{e}(t)$, which would suppress overshot effectively and improve the control precision of fuzzy controller. If k_{ec} is too large, it is equivalent to achieve the efficiency of $\dot{e}(t)$ earlier and would have the control system too sensitive to changes of $\dot{e}(t)$, and then increasing the settling time. While k_{ec} is too small, it could not suppress overshoot effectively.

Affection of k_u : Adjustment of k_u could change the control efficiency of controller as it would directly change output of the controller. Increasing of k_u

could improve the rising time while it could lead to serious overshoot and somehow oscillation. Reducing of k_u could improve the stability while it could lead to longer settling time.

Through above analysis we can see that the affection to control system of k_e, k_{ec}, k_u is different, and for the same system performance it varies at different stages. Therefore, in order to control the system fast, steady and accurately, it is necessary to correct them online by expert intelligence coordinator, which is composed of Knowledge and control rules. The Knowledge is composed of error and error universe, control area of quantifying factors and some adjustment parameters. As the analysis description given above, here given a set of adjustment rules in order to correct the quantifying factors:

Rule 1 $If \ \ e > d_1 \cap \dot{e} > d_2, \ then \ k_1 = 0, k_2 = 0, k_3 = \Delta k_u$
Rule 2 $If \ \ e > d_1 \cap e > 0 \cap \dot{e} < d_2, \ then \ k_1 = 0, k_2 = \Delta k_{ec}, k_3 = \Delta k_u$
Rule 3 $If \ \ e > d_1 \cap e < 0 \cap \dot{e} > -d_2, \ then \ k_1 = \Delta k_e, k_2 = \Delta k_{ec}, k_3 = 0$
Rule 4 $If \ \ e > d_1 \cap \dot{e} < -d_2, \ then \ k_1 = 0, k_2 = -\Delta k_{ec}, k_3 = 0$
Rule 5 $If \ e > 0 \cap e < d_1 \cap \dot{e} > d_2, \ then \ k_1 = \Delta k_e, k_2 = 0, k_3 = \Delta k_u$
Rule 6 $If \ e > 0 \cap e < d_1 \cap \dot{e} > 0 \cap \dot{e} < d_2, \ then \ k_1 = \Delta k_e, k_2 = \Delta k_{ec}, k_3 = 0$
Rule 7 $If \ e > 0 \cap e < d_1 \cap \dot{e} < 0 \cap \dot{e} > -d_2, \ then \ k_1 = \Delta k_e, k_2 = \Delta k_{ec}, k_3 = \Delta k_u$
Rule 8 $If \ e > 0 \cap e < d_1 \cap \dot{e} < -d_2, \ then \ k_1 = 0, k_2 = \Delta k_{ec}, k_3 = \Delta k_u$
Rule 9 $If \ e < 0 \cap e > -d_1 \cap \dot{e} > d_2, \ then \ k_1 = 0, k_2 = \Delta k_{ec}, k_3 = \Delta k_u$
Rule 10 $If \ e < 0 \cap e > -d_1 \cap \dot{e} > 0 \cap \dot{e} < d_2, \ then \ k_1 = \Delta k_e, k_2 = \Delta k_{ec}, k_3 = \Delta k_u$
Rule 11 $If \ e < 0 \cap e > -d_1 \cap \dot{e} < 0 \cap \dot{e} > -d_2, \ then \ k_1 = \Delta k_e, k_2 = \Delta k_{ec}, k_3 = 0$
Rule 12 $If \ e < 0 \cap e > -d_1 \cap \dot{e} < -d_2, \ then \ k_1 = \Delta k_e, k_2 = 0, k_3 = \Delta k_u$
Rule 13 $If \ \ e < -d_1 \cap \dot{e} > d_2, \ then \ k_1 = 0, k_2 = -\Delta k_{ec}, k_3 = 0$
Rule 14 $If \ \ e < -d_1 \cap e > 0 \cap \dot{e} < d_2, \ then \ k_1 = \Delta k_e, k_2 = \Delta k_{ec}, k_3 = 0$
Rule 15 $If \ \ e < -d_1 \cap e < 0 \cap \dot{e} > -d_2, \ then \ k_1 = 0, k_2 = \Delta k_{ec}, k_3 = \Delta k_u$

Rule 16 $If \ \ e < -d_1 \cap \dot{e} < -d_2, \ then \ k_1 = 0, k_2 = 0, k_3 = \Delta k_u$

where e = course error, $\dot{e}$ = change rate of error, k_1, k_2 and k_3 are dynamic correction factors, d_1, d_2, Δk_e, Δk_{ec} and Δk_u are designed parameters. And online correction algorithm for each parameter could express as follows in Equation 6:

$$\begin{cases} k_{e(t)} = k_{e(t-1)} + k_1 \\ k_{ec(t)} = k_{ec(t-1)} + k_2 \\ k_{u(t)} = k_{u(t-1)} + k_3 \end{cases} \tag{6}$$

where $k_{e(t)}, k_{ec(t)}, k_{u(t)}$ and $k_{e(t-1)}, k_{ec(t-1)}, k_{u(t-1)}$ are quantifying factors at time t and $t-1$.

4. Simulation

Taking a USV model as control object, adopt the Expert-Fuzzy Controller designed above for simulation. Model parameters and designed parameters are show as follows in Table 3:

Table 3. Parameters of USV Model

parameter	value	parameter	value
K	0.478	T	216
α	30	$k_{e(0)}$	1.91
$k_{ec(0)}$	229.2	$k_{u(0)}$	0.08726
Δk_e	0.04	Δk_{ec}	0.5
Δk_u	0.005	d_1	15deg
d_2	0.3deg/s	w	$\pm\frac{1}{T}\text{deg}/s^2$

Simulation case1: Initial heading angle is 0 degree, and the target heading angle is 90 degree, the simulation results are as follows:

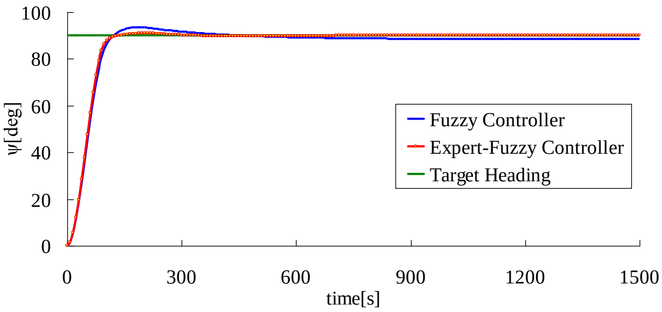

Figure 7. Response Curve of Heading Control

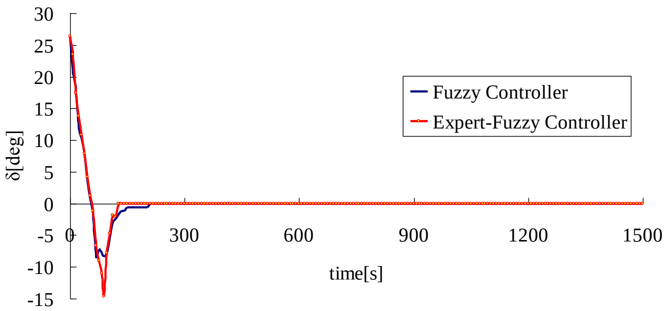

Figure 8. Response Curve of Rudder Angle

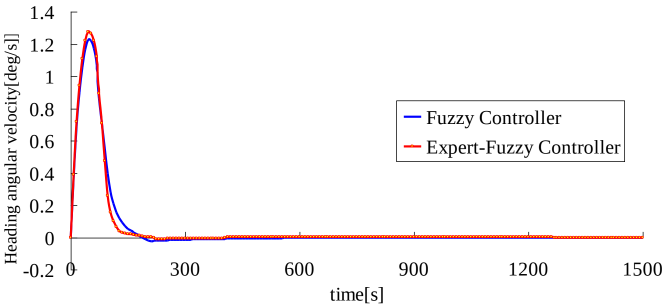

Figure 9. Response Curve of Heading Angular Velocity

Simulation case2: Initial heading angle is 60 degree, and the target heading angle is 120 degree, the simulation results are as follows:

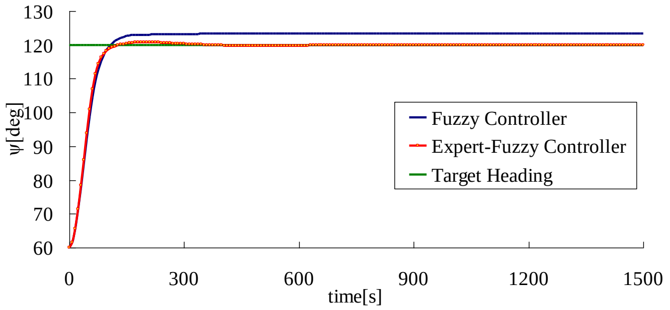

Figure 10. Response Curve of Heading Control

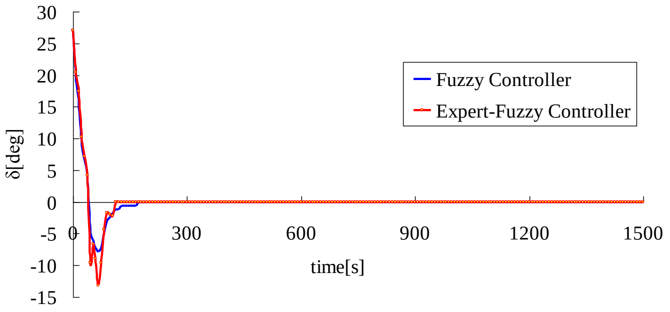

Figure 11. Response Curve of Rudder Angle

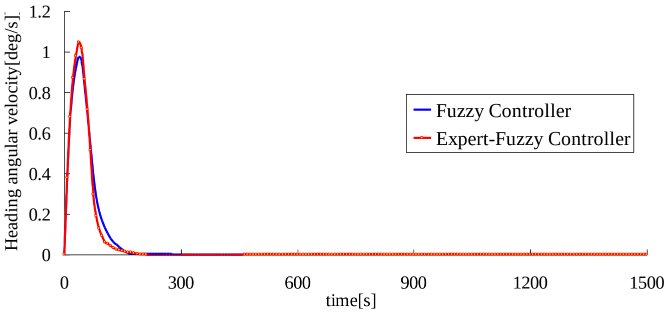

Figure 12. Response Curve of Heading Angular Velocity

Simulation results above show that Expert-Fuzzy Controller could better reduce overshoot and the steady-state error of the system closer to zero compared to conventional Fuzzy controller. Results from Figure 8, Figure 9, Figure 11 and Figure. 12 show that Expert-Fuzzy controller could steering faster and more stable than conventional fuzzy controller, and the angular velocity response faster and the settling time is shorter.

5. Conclusion

In order to overcome the shortcomings of conventional fuzzy controller, which is often with large overshoot and steady-error, this paper adopting expert control technology to modify the quantifying factors of fuzzy controller online, and then improved the control efficient of the system clearly. We take a simulation experiment on heading control of a

USV, and the simulation results show the effectiveness of the Experts Fuzzy Controlled designed.

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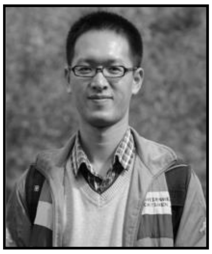

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