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A Novel Adaptive Neural Control Scheme for Uncertain Ship Course-keeping System

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Abstract: In order to improve the design method of robust controller for ship course-keeping, a nonlinear controller design is presented by combining neural network (NN) approximator with adaptive Backstepping technology. The simulation research is carried out based on the training ship "Yu long" of Dalian Maritime University as an example. The results show that the control algorithm has good adaptability, the closed-loop system has good robust performance. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Ship, Course-keeping, Neural network (NN), Adaptive control.

1. Introduction

Ship course-keeping is a complex and important issue of ship motion control which has a great impact on the economic and safety of ship operation. Ship movement displays complex dynamic characteristics such as nonlinearity, uncertainty and large lag, making ship course-keeping a complex nonlinear control problem [1]. As neural network (NN) is originated in the simulation of cranial nerve, it can approach nonlinear continuous function with arbitrary accuracy, and NN has good adaptability and high robustness. Strong nonlinear approximation ability and self-learning ability of NN bring vitality to adaptive control problem of nonlinear system, the feature of NN is significant for the research on ship course-keeping.

Directed towards nonlinear ship course-keeping control system, literature [2] presents a nonlinear controller which is based on the structure of Liapunov (Lyapunov) energy function. This kind of controller reduces the number of setting parameters in the controller and the number of nonlinear item nonlinear control law, with a better control performance and robust performance of ship course-keeping control system. Literature [3] presents a design method of nonlinear adaptive controller, Nussbaum function is introduced and Backstepping is used to design the nonlinear adaptive ship course controller, successfully solving a non-matched uncertain nonlinear control problem with unknown virtual control coefficient. Feed-forward neural network structure is applied in literature [4] to get a open-loop neural network controller through training, NN combined with closed-loop gain shaping algorithm is used to form a closed-loop control system to keep the ship course. Adaptability of NN, mapping ability of nonlinear function and robustness of closed-loop gain shaping algorithm is integrated in the NN based ship course-keeping program, the system has a better robust performance. Nussbaum function is introduced in literature [5], and approximation capability of fuzzy logic system is used to approximate the unknown nonlinear function in the model, multiple sliding mode control and adaptive fuzzy control is integrated to eliminating the effects of uncertainty of parameter, and singular value problem is also avoided in the controller design process. NN is used in literature [6] to modeling for both vessel identification and ship course-keeping controller. Fuzzy control is combined with NN in literature [7, 8] to design a fuzzy neural network controller.

On the basis of the literature [1-10], ship course-keeping is further improved in this paper, using the training ship "Yu long" as an example and utilizing control algorithm, ship course-keeping is achieved through adaptive neural network and the simulation results are analyzed.

2. Ship Course-Keeping Mathematical Model

Equation (1) gives linear first-order Nomoto model which is used for ship course-keeping [2].

$$\ddot{\psi} + \frac{1}{T_0}\dot{\psi} = \frac{K_0}{T_0}\delta, \tag{1}$$

Among these, ψ is the ship heading angle, δ is the rudder angle, K_0 is the steering gain index, T_0 is the ship following index. Reference [11] has summarized the results of previous studies, and presents a Nomoto model based responding type of nonlinear mathematical model, that is using a nonlinear item $\left(K_0/T_0\right)H\left(\dot{\psi}\right)$ to replace $\dot{\psi}/T_0$, and

$$H\left(\dot{\psi}\right) = \alpha\dot{\psi} + \beta\dot{\psi}^3, \tag{2}$$

where α, β represent the scale coefficient of the first and the third power of the rate of turning $\dot{\psi}$. Specific parameter value depends on factors like ship type, stowage, ship speed, etc. Taking ψ as ship heading angle, then $\dot{\psi} = r$; meanwhile, taking the frequently influence from uncertain interference such as wind, wave and current into consideration, the nonlinear dynamic equation of ship course-keeping system could be written as:

$$\begin{cases} \dot{\psi} = r \\ \dot{r} = -\dfrac{K_0}{T_0}(\alpha r + \beta r^3) + \dfrac{K_0}{T_0}\delta + \Delta \end{cases}, \tag{3}$$

where Δ is the uncertain interference. According to engineering practice, Δ is usually bounded disturbance, assuming there is an unknown constant could meet equation (1) on the basis of hypothesis.

$$\left\|\Delta\right\|_\infty \le \rho,\ \rho \text{ is a unknown positive constant}, \tag{4}$$

3. Control Design

Designing a nonlinear adaptive controller directed towards ship course-keeping system, targeting at making the actual course ψ track the expecting reference course ψ_r. In order to facilitate the derivation, one uses the symbol $e = \psi - \psi_r$ and $x_1 = \psi$, $x_2 = r = \dot{\psi}$, the corresponding nonlinear mathematical model could be transformed into the equation (5).

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_2) + bu + d \\ y = x_1 \end{cases}, \tag{5}$$

In equation (5), $y \in R$ is the system output, $b = K_0/T_0$, $u = \delta$, nonlinear function $f(x_2) = -b(\alpha x_2 + \beta x_2^3)$.

Step 1: Make $z_1 = x_1 - \psi_r$ one could get $\dot{z}_1 = x_2 - \dot{\psi}_r$. In the following, x_2 is considered as the virtual or intermediate control of z_1-subsystem and using $\alpha_1 \triangleq x_2$, the Lyapunov cost function is derived as $v_1 = \frac{1}{2}z_1^2$ and the corresponding differentiation is $\dot{v}_1 = z_1(x_2 - \dot{\psi}_r)$.

Then the desired intermediate control law is $\alpha_1^* = \dot{\psi}_r - c_1 z_1$.

By the virtue of the approximation capability of RBF NN, one obtains the approximation equation, i.e. $-\dot{\psi}_r = \boldsymbol{\theta}_1^{*T}\boldsymbol{s}_1 + \varepsilon_1$ [12]. Thus,

$$\alpha_1 = -c_1 z_1 - \hat{\boldsymbol{\theta}}_1^T \boldsymbol{s}_1 \quad \tilde{\boldsymbol{\theta}} = \hat{\boldsymbol{\theta}} - \boldsymbol{\theta}^*$$

Furthermore, the Lyapunov function is added as

$$v_1 = \frac{1}{2}z_1^2 + \frac{1}{2}\tilde{\boldsymbol{\theta}}_1^T\tilde{\boldsymbol{\theta}}_1$$

And the corresponding derivative of v_1 is obtained as follows.

$$\begin{aligned} \dot{v}_1 &= z_1\dot{z}_1 + \tilde{\boldsymbol{\theta}}_1^T\dot{\hat{\boldsymbol{\theta}}}_1 \\ &= z_1 z_2 - c_1 z_1^2 + z_1\varepsilon_1 + \tilde{\boldsymbol{\theta}}_1^T(-z_1\boldsymbol{s}_1 + \dot{\hat{\boldsymbol{\theta}}}_1) \end{aligned}$$

The adaptive law is selected as

$$\dot{\hat{\boldsymbol{\theta}}}_1 = z_1\boldsymbol{s}_1 + \rho_1\hat{\boldsymbol{\theta}}_1,\ \ \rho_1 < 0$$

According to the inequality $\left|D_1 Z_1\right| - D_1 Z_1 \tanh\left(D_1 Z_1/s\right) < 0.2785s$ [10], the actual α_1 is formulated as equation (6).

$$\begin{aligned} &\alpha_1 = -c_1 z_1 - \hat{\boldsymbol{\theta}}_1^T\boldsymbol{s}_1 - \varepsilon_1^* \tanh\left|\frac{z_1\varepsilon_1^*}{s}\right| \\ &\dot{v}_1 \le z_1 z_2 - c_1 z_1^2 + 0.2785s + \rho\tilde{\boldsymbol{\theta}}_1^T\hat{\boldsymbol{\theta}}_1, \end{aligned} \tag{6}$$

Step 2: One use $z_2 = x_2 - \alpha_1$ and derive

$$\dot{z}_2 = f(x_2) + bu + d - \dot{\alpha}_1$$

Select $\dfrac{f(x_2)}{b} - \dfrac{\dot{\alpha}_1}{b} = \boldsymbol{\theta}_2^{*T}\boldsymbol{s}_2 + \varepsilon_2$

$$\dot{z}_2 = b(u + \boldsymbol{\theta}_2^{*T}\boldsymbol{s}_2 + \varepsilon_2 + \frac{d_2}{b})$$

The final control law is derived as (7).

$$u = -c_2 z_2 - \hat{\boldsymbol{\theta}}_2^T\boldsymbol{s}_2 - (\varepsilon_2^* + \frac{d_2^*}{b})\tanh\left|\frac{z_2(\varepsilon_2^* + d_2^*)}{s}\right| - z_1, \quad (7)$$

The further Lyapunov function is

$$v_2 = \frac{z_2^2}{2b} + \frac{1}{2}\tilde{\boldsymbol{\theta}}_2^T\tilde{\boldsymbol{\theta}}_2 + v_1$$

$$\begin{aligned}
\dot{v}_2 &= \frac{z_2\dot{z}_2}{b} + \frac{1}{2}\tilde{\boldsymbol{\theta}}_2{}^T\dot{\hat{\boldsymbol{\theta}}}_2 + \dot{v}_1 \\
&= -c_2 z_2^2 - z_1 z_2 + z_2(\varepsilon_2 + \frac{d_2}{b_2}) \\
&\quad - z_2(\varepsilon_2^* + \frac{d_2^*}{b_2})\tanh\left(\frac{z_2(\varepsilon_2^* + \frac{d_2^*}{b_2})}{s}\right) \\
&\quad + \hat{\boldsymbol{\theta}}_2^T(\hat{\boldsymbol{\theta}}_2 - z_2\boldsymbol{s}_2) + \dot{v}_1 \\
&\le -z_1 z_2 + c_2 z_2^2 + 0.2785s + \hat{\boldsymbol{\theta}}_2^T(\hat{\boldsymbol{\theta}}_2 - z_2\boldsymbol{s}_2) + \dot{v}_1
\end{aligned}$$

The corresponding adaptive law is

$$\dot{\hat{\boldsymbol{\theta}}}_2 = z_2\boldsymbol{s}_2 + \rho_2\hat{\boldsymbol{\theta}}_2, \quad \rho_2 < 0$$

one get

$$\begin{aligned}
\dot{v}_2 &\le -c_1 z_1^2 - c_2 z_2^2 + \rho_1\tilde{\boldsymbol{\theta}}_1^T\hat{\boldsymbol{\theta}}_1 + \rho_2\tilde{\boldsymbol{\theta}}_2^T\hat{\boldsymbol{\theta}}_2 + 0.2785s \times 2 \\
&= -cv_2 + d
\end{aligned}, \quad (8)$$

It is obvious that all states in the closed-loop system is uniformly ultimately bounded. v_2 could convergence to zero by selecting the parameters appropriately.

4. Simulation Examples

Take the training ship "Yu Long" of Dalian Maritime University as an example, the main parameters of the ship are shown in Table 1.

The parameters of the responding type of nonlinear mathematical model based on the above parameters are: $K_0 = 0.48$, $T_0 = 216.58$, $\alpha = 9.16$, $\beta = 10814.0$. The parameters of the controller design are: $c_1 = c_2 = 7.4$, $\rho_1 = 1.2$, $\rho_2 = 2.0$.

Table 1. The main data and dimensions of vessel Yu Long.

Elements	Values
Length between perpendiculars	126 m
Breadth	20.8 m
Bow draft	8.0 m
Stern draft	8.0 m
Displacement volume	14635 t
Height of the initial stability	1.45 m
Block coefficient	0.681
Gravity coordinate	0.63 m
Rudder area	18.8 m^2
Rudder height	6.1 m
Aspect ratio	1.72
Max. rudder angle	30 deg.
Max. rudder rate	2.5 deg./s
Propeller diameter	4.6 m
Propeller pitch	3.66 m
Area radio	0.67
Propeller blade	4

The results of simulation are shown in Fig. 1 and Fig. 2. As is illustrated in Fig. 1, without considering the environment interference, course is stable at around 10 degs after 100 s, deviation is 0, rudder angle returned to 0 after steering. As is illustrated in Fig. 2, under the level No. 5 sea state, the heading angle is also stable at around 10 degs after 100 s, deviation is around +1 deg. Meanwhile, the action of rudder is always chattering a ±3 deg small rudder angle around −3 deg. All the above description illustrates that the adaptive neural control scheme has a good control performance.

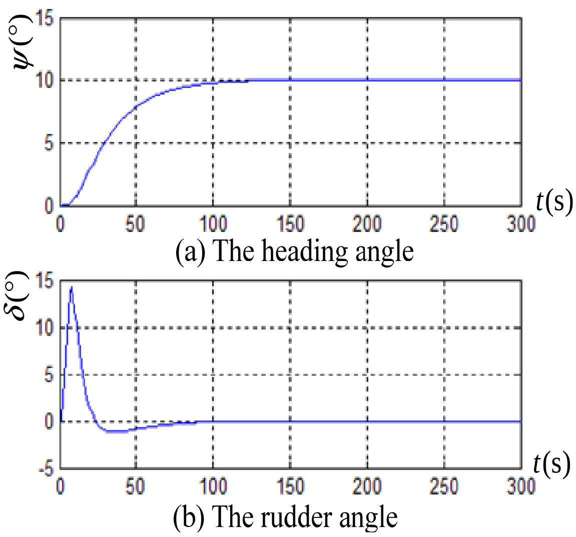

Fig. 1. The control performance without considering the environment interference.

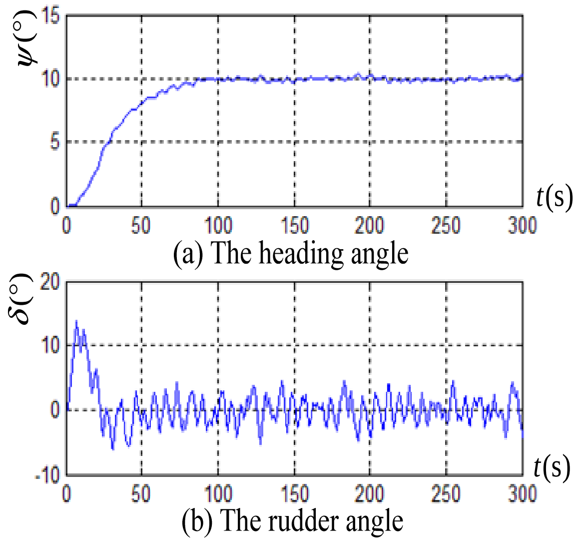

Fig. 2. The control performance under the level No. 5 sea state.

5. Conclusion

This paper presents a deep analysis and proof of adaptive neural network approximation algorithm used for ship course-keeping. The simulation research is carried out based on the training ship "Yu long" as an example. The control effects of ship course-keeping under the sea state No. 0 is simulated and is compared with that under the sea state No. 5, the experiment proves that good control effect is able to achieve.

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