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Adaptive Fuzzy Control via Command Filtering and Backstepping for Ship Course-Keeping

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Abstract: With increasing marine transportation and logistics, the ship autopilot has become much more important not only to lower the seaman's operating intensions, but also to reduce the seaman's deployment. It is still a challenge to design ship course-keeping controller because of ship's uncertain dynamics and time-varying environmental disturbance. This study focuses on backstepping adaptive course-keeping controller design for ship autopilot. Takagi-Sugeno (T-S) fuzzy approximation can formulate ship motion's uncertainties. Therefore, the proposed controller has no need of a priori knowledge about ship's system dynamics. Command filtering can bypass the iterative differential manipulations in adaptive backstepping controller for conventional ship course. The design can guarantee the ultimate uniform boundedness of the signals in closed-loop system. Finally, simulation study verifies the efficiency of the ship course-keeping design.

Keywords: Backsteping control, strict-feedback nonlinear system, adaptive control, shipcourse-keeping control, fuzzy model control.

1. Introduction

Nowadays, the large and high-speed ships have become more and more popular because of the increasing marine transportation and logistics. Thus, traffic density also increases during the past decades. To promote the economic profits, it is expected not only to lower the seaman's operating intensions, but also to reduce the seaman's deployment. In 1920s, classic control theories were applied to ship's course-keeping controller design, and proportional-integral-derivative (PID) autopilot was invented. In 1970s, adaptive control theory was also applied. However, because of the complexities of ship's dynamics, the randomness and unpredictability in environmental disturbances, these methods can't handle the ship's course control problem completely [1, 2]. During recent years, kinds of the algorithms were applied to ship's course control, such as model reference adaptive control, self-tuning control with minimal variance, neural network control, fuzzy control, variable structure control, robust control, generalized predictive control, intelligent control, etc [3]. Some of these algorithms had become the theoretical bases of recently developed autopilot. Furthermore, some works had been published to study marine craft control [3].

On the other hand, a great deal of attention has been received in the field of nonlinear control [4, 5]. Many methods employ a synthesis approach where the controlled variable is chosen to make the time derivative of a negative definite Lyapunov candidate. A design methodology that has attracted much interest is "integrator backstepping" [6–9]. Particularly, the book [10] develops the backstepping approach to the point of a step-by-step design procedure. Backstepping is a technique to control the nonlinear systems with parameter uncertainty, particularly those systems in which the uncertainties do not satisfy matching conditions. Adaptive backsteping is a powerful tool for the design of controllers for nonlinear systems systems in or transformable to the parameter strict-feedback form, where $x \in \Re^n$ is the state, $u \in \Re$ is the control input, and $\theta \in \Re^p$ is an unknown constant vector. The adaptive backstepping approach utilizes stabilizing functions $\bar{\alpha}_i$ and tuning functions τ_i for $i = 1, \cdots, n$. Calculation of these quantities utilizes the partial derivatives $\partial\bar{\alpha}_{i-1}/\partial x_j$ and $\partial\bar{\alpha}_{i-1}/\partial\hat{\theta}_l$.

Motivated by the pioneering work [11], a novel backstepping adaptive tracking fuzzy controller strategy is proposed for ship steering. The ship dynamics is formulated into a class of nonlinear system in strict-feedback form. The control objective is to force the ship's course to track the output of the specified reference model. It is assumed that The ship motion's dynamics are unknown. We use fuzzy logic system to approximate the unknown system functions. The proposed algorithm can guarantee the boundedness of all the signals in the closed-loop ship steering system. The main differences between our strategy and aforementioned methods [8] are that, compensated tracking errors, not conventional tracking errors, are used to construct the course-keeping adaptive fuzzy controller. Then, the proposed design avoids the repeated differential of virtual control law completely, which make the controller structure quite simple and easy to implement in engineering. The simulation results demonstrate the effectiveness and usage of the proposed course-keeping controller.

The remainder of this paper is organized as follows: Section 2 describes ship course-keeping control system modeling, some useful preliminaries and Takagi-Sugeno fuzzy system. Section 3 presents design procedures of model-reference adaptive fuzzy controller law. Some simulation results are given in Section 4. Finally, Section 5 concludes the paper.

2. Problem Formulation & Preliminary

A. Ship Control System Modeling

Japanese scholar Nomoto [2] had put forward the 2nd-order linear mathematical model between ship's rudder and course as follows

$$T\ddot{\psi} + \dot{\psi} = K\delta \tag{1}$$

where ψ is ship course, δ is ship rudder angle,the constant T is the ship's straight-line stability index, the constant K is the ship's turning ability index. From the linearization theory of nonlinear system, only under the condition of small perturbations of ship's motion state variables from its basis states can this linear model (1) be applied to. The basis states refers to that of constant forward speed from longitudinally middle section. If ship motion's amplitude is very large or large rudder angle is utilized, nonlinear ship course control model should be used. Based on the Nomoto's ship's 2nd-order nonlinear model, Norrbin[2] gavethe following 2nd-order nonlinear model

$$T\ddot{\psi} + H_{Non}(\dot{\psi}) = K\delta \tag{2}$$

$$H_{Non}(\dot{\psi}) = \alpha_3\dot{\psi}^3 + \alpha_2\dot{\psi}^2 + \alpha_1\dot{\psi} + \alpha_0 \tag{3}$$

where α_0, α_1, α_2 and α_3 are the uncertain coefficients. In this paper, we will research the more general case, namely, it is assumed uncertain nonlinear part $H_{Non}(\dot{\psi})$ in (2) is completely unknown. For the convenience, we introduce $x_1 = \psi$, $x_2 = \dot{\psi}$, and $u = \delta$. Then, the Norrbin model can be transformed into a class of nonlinear system in strict-feedback form as follows

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + g(x)u \end{cases} \tag{4}$$

where $x = [x_1, x_2]^T$, $f(x) = H_{Non}(\dot{\psi})/T$, $f(x)$ denotes the system's unknown dynamics, $g(x) = K/T$. In this paper, we will design ship's course-keeping adaptive fuzzy controller for the uncertain nonlinear system in the strict-feedback form in (4).

B. Definition and Useful Lemmas

The proposed adaptive fuzzy controller will guarantee ultimate uniform boundedness of the closed-loop system. Therefore, the definition of stability of systems is given as follows. Given a nonlinear system

$$\dot{x}(t) = f(x,t), \quad y = h(x,t), \quad x(t) \in \mathbb{R}^n, \quad t \le t_0 \tag{5}$$

if there exists a compact $U \in \mathbb{R}^n$ such that for all $x(t_0) = x_0 \in U$, and there exists an $\varepsilon > 0$ and a number $T(\varepsilon, x_0)$ such that $\|x(t)\| < \varepsilon$ for all $t \ge t_0 + T(\varepsilon, x_0)$, it is said that the solution of (5) is ultimately uniformly bounded (UUB) [12].

To proceed, the following definition and simple lemmas play an important role in the manipulation of our main results on adaptive fuzzy controller design.

Lemma 1 (Young's inequality) [13] For scalar time functions $x(t) \in \mathbb{R}$ and $y(t) \in \mathbb{R}$, it holds that

$$2xy \le \frac{1}{\omega}x^2 + \omega y^2 \tag{6}$$

for any $\omega > 0$.

Lemma 2 (Cauchy's inequality)[13] The inequality is given by

$$\left|x^T y\right| \le |x||y| \tag{7}$$

Lemma 3 (Completing squares)[13] For scalar time functions $x(t) \in \mathbb{R}$ and $y(t) \in \mathbb{R}$,

$$-x^2+2xy=-x^2+2xy-y^2+y^2\le y^2 \tag{8}$$

Lemma 4[14] The following inequality holds for any $\varepsilon>0$ and for any $x\in\mathbb{R}$

$$0\le |x|-x\tanh(\frac{x}{\varepsilon})\le \kappa\varepsilon \tag{9}$$

where κ satisfies $\kappa=e^{-(\kappa+1)}$, i.e. $\kappa=-0.2785$.

Lemma 5[15]Let $V:[0,\infty)\to\mathbb{R}$ satisfies the inequality

$$\dot V\le -2a_0V+b_0,\quad t\ge 0, \tag{10}$$

where a_0 and b_0 are positive constants. Then

$$V(t)\le V(t_0)\exp[-2a_0(t-t_0)]+\frac{b_0}{2a_0} \tag{11}$$

C. Descriptions of Takagi-Sugeno Fuzzy System

In this section, we introduce the structure of the Takagi-Sugeno (T-S) fuzzy model [16] in order to approximate unknown ship's dynamics. T-S fuzzy rules are a set of linguistic statements in the following form

R_j: IF x_1 is F_1^j and x_2 is F_2^j and $\cdots$ and x_n is F_n^j,

THEN $y_j=a_0^j+a_1^jx_1+\cdots+a_n^jx_n,\quad j=1,2,\cdots,K,$

where $a_i^j, i=0,1,\cdots,n$ are the unknown constants to be adapted, y_j is the output variable of the fuzzy system. In this paper, it's assumed that singleton fuzzifier and center-average defuzzifier are chosen. Then, $f(x)$ can be expressed as the following

$$f(x)=\frac{\sum_{j=1}^{K}y_j\left[\prod_{i=1}^{n}\mu_{F_i}^j(x_i)\right]}{\sum_{j=1}^{K}\left[\prod_{i=1}^{n}\mu_{F_j}^j(x_i)\right]}=\sum_{j=1}^{K}\zeta_j(x)y_j \tag{12}$$

where

$$y_j=a_0^j+a_1^jx_1+\cdots a_n^jx_n, \tag{13}$$

$$\zeta_j(x)=\frac{\prod_{i=1}^{n}\mu_{F_i}^i(x_i)}{\sum_{j=1}^{K}\left[\prod_{i=1}^{n}\mu_{F_i}^j(x_i)\right]}, \tag{14}$$

which is called fuzzy basis function. To proceed, the following lemma plays an important role on adaptive fuzzy controller design.

Lemma 6 (Universal Approximation Theorem) [17] Let the input universal of discourse U be a compact set in $\mathbb{R}^r$. Then, for any given real continuous function $h(x)$ on U and arbitrary $\forall d>0$, there exists a fuzzy system in the form of (12) such that $\sup_{x\in U}|h(x)-f(x)|\le d$.

Based on Lemma 6, it is well known that the aforementioned T-S fuzzy logic system is capable of uniformly approximating any well-defined nonlinear function over a compact set U_c to any degree of accuracy with triangular or Gaussian membership function.

The membership function $\mu_{F_i}^j(x_i)$ in $f(x)$ is denoted by some type of membership function, $\zeta_j(x)$ is a known continuous function. So (12) can be restructured into as follows

$$f(x)=\zeta(x)A_Z^0+\zeta(x)A_Z^1x+d, \tag{15}$$

where

$$\zeta(x)=[\zeta_1(x),\zeta_2(x),\cdots,\zeta_K(x)],$$
$$x=[x_1,x_2,\cdots,x_n]^T,$$
$$A_Z^0=\left[a_0^1,a_0^2,\cdots,a_0^K\right]^T,$$
$$A_Z^1=\begin{pmatrix} a_1^1 & a_2^1 & \cdots & a_n^1\\ a_1^2 & a_2^2 & \cdots & a_n^2\\ \vdots & \vdots & \ddots & \vdots\\ a_1^K & a_2^K & \cdots & a_n^K\end{pmatrix}.$$

3. Ship Course-Keeping Adaptive Fuzzy Controller Design

The control objective is to steer ship course x_{1c} to track the output of the prescribed reference model, and guarantee the ultimate uniform boundness for all the signals in the close-loop system.

Step 1: Define two tracking errors for the state x_1

$$\tilde x_1=x_1-x_{1c} \tag{16}$$

$$\bar x_1=\tilde x_1-\xi_1 \tag{17}$$

where x_{1c} is the desired ship course, $\tilde x_1$ is ship course tracking error, and $\bar x_1$ is the ship course's compensated tracking errors. In this paper, it is assumed that x_{1c} is continuous and has 1-order derivative.

$$\dot\xi_1=-k_1\xi_1+(x_{2c}-x_{2c}^0) \tag{18}$$

$$x_{2c}^0=\alpha_1-\xi_2 \tag{19}$$

where ξ_2 will be defined in the step 2, x_{2c} and $\dot x_{2c}$ are obtained after the filtering of x_{2c}^0, α_1 is virtual control input, $k_1 > 0$ is the constant to be chosen by the designer. Then, we obtain

$$\dot{\bar{x}}_1 = \bar{x}_2 + \alpha_1 + k_1\xi_1 - \dot{x}_{1c} \tag{20}$$

Choose the following Lyapunov candidate function

$$V_1(t) = \frac{1}{2}\bar{x}_1^2 \tag{21}$$

Then, the derivative of Lyapunov candidate function (21) is given by

$$\dot{V}(t) = \bar{x}_1\bar{x}_2 + \bar{x}_1\alpha_1 + k_1\bar{x}_1\xi_1 + \bar{x}_1\dot{x}_{1c} \tag{22}$$

We construct the following virtual control input α_1 as follows

$$\alpha_1 = -k_1\tilde{x}_1 - \dot{x}_{1c} \tag{23}$$

Substituting the virtual control input (23) into (22) results in

$$\dot{V}_1(t) = -c_1V_1(t) + \bar{x}_1\bar{x}_2 \tag{24}$$

where $c_1 = 2k_1$.

Step 2: Similar to Step 1, two tracking errors for x_2 is defined as follows

$$\tilde{x}_2 = x_2 - x_{2c} \tag{25}$$

$$\bar{x}_2 = \tilde{x}_2 - \xi_2 \tag{26}$$

where $\tilde{x}_2$ is tracking error, ξ_2 will be defined in the subsequent descriptions, $\bar{x}_2$ is compensated tracking error, x_{2c} is generated by the following filter

$$x_{2c}(t) = \frac{K_2}{K_2 + s}\left[x_{2c}^0(t)\right] \tag{27}$$

where $K_2 > 0$ is the constant to be chosen by the designer. Generally, there should be $K_2 \gg k_2$.

T-S fuzzy system (12) is used to approximate the unknown dynamics $f(x)$ in ship course control system. Then we obtain

$$\begin{aligned} f(x) &= \zeta(x)Q_1\bar{x} + \zeta(x)(Q_0 + Q_1x_c) \\ &\quad + \zeta(x)Q_1\xi + d \end{aligned} \tag{28}$$

where $\bar{x} = [\bar{x}_1 \quad \bar{x}_2]^T$, $x_c = [x_{1c} \quad x_{2c}]^T$, $\xi = [\xi_1 \quad \xi_2]^T$. From (4) and (28), we obtain

$$\begin{aligned} \dot{\bar{x}}_1 &= g(x)u + \zeta(\bar{x})Q_1\bar{x} + \zeta(x)(Q_0 + Q_1\bar{x}_c) \\ &\quad + \zeta(\bar{x})Q_1\xi + d - \dot{x}_{2c} \\ &= g(x)u + \zeta(x)Q_1x + \Omega \end{aligned} \tag{29}$$

where Ω is introduced for the reason of the convenience, and

$$\begin{aligned} \Omega &= \zeta(x)(Q_0 + Q_1x_c) + \zeta(x)Q_1\xi + d - \dot{x}_{2c} \\ &\le \|\zeta(x)\|\|Q_0 + Q_1x_c\| + \|\zeta(x)\|\|Q_1\|\|\xi\| \\ &\quad + |d| + |\dot{x}_{2c}| \\ &\le \|Q_0\| + |\theta|\|Q_U\|\|x_c\| + |\theta|\|Q_U\|\|\zeta(x)\|\|\xi\| \\ &\quad + |d| + |\dot{x}_{2c}| \\ &\le \chi^*\beta(x) \end{aligned} \tag{30}$$

where $\|\bullet\|$ denotes the vector's Eulidean norm or matrix's induced 2-norm, $Q_1 = \theta Q_U$, $\|Q_U\| = 1$, θ is the unknown constant, whose accurate value is necessarily known, d is the maximal approximate error for T-S fuzzy system, namely $d \le \Delta$,

$$\chi^* = \max\left\{\|Q_1^0\| + |\theta|\|x_c\|, |\theta|, |\Delta| + |\dot{x}_{2c}|\right\}$$

$$\beta(x) = 1 + \|\zeta(x)\| + \|\zeta(x)\|\|\xi\|$$

Next, we introduce the definition

$$\dot{\xi}_2 = -k_2\xi_2 + g(x)(u_c - u_c^0) \tag{31}$$

where $k_2 > 0$ is the constant to be chosen by the designer, u_c^0 is filtered to output u_c, $u_c = u$. Generally, we choose $u_c^0 = u_c = u$.

Combining (25), (26), (29) and (30) yields

$$\dot{\bar{x}}_2 = \zeta(x)Q_1\bar{x} + \Omega + g(x)u + k_2\xi_2 \tag{32}$$

Formulate the following Lyapunov candidate function

$$V_2(t) = V_1(t) + \frac{1}{2}\bar{x}_2^2 + \frac{1}{2}\Gamma_1^{-1}\tilde{\gamma}^2 + \frac{1}{2}\Gamma_2^{-1}\tilde{\chi}^2 \tag{33}$$

where $\tilde{\gamma} = \gamma^* - \hat{\gamma}$, $\tilde{\chi} = \chi^* - \hat{\chi}$, $\hat{\gamma}$ and $\hat{\chi}$ are the estimated value of the adapted parameters γ^* and χ^*, $\Gamma_1 > 0$ and $\Gamma_2 > 0$ are chosen by the designer. The derivative of the Lyapunov candidate function is given by

$$\begin{aligned} \dot{V}_2(t) &\le \dot{V}_1(t) + \bar{x}_2\zeta(x)Q_1\bar{x} + \bar{x}_2\chi\beta(x) + \bar{x}_2g(x)u \\ &\quad + \bar{x}_2k_2\xi_2 + \Gamma_1^{-1}\tilde{\gamma}\dot{\hat{\gamma}} + \Gamma_2^{-1}\tilde{\chi}\dot{\hat{\chi}} \end{aligned} \tag{34}$$

The items $\bar{x}_2\zeta(x)Q_1\bar{x}$ and $\bar{x}_2\chi\beta(x)$ in (34) are discussed as follows, respectively. By use of Young's inequality in Lemma 1, we obtain

$$\begin{aligned} \bar{x}_2\zeta(x)Q_1\bar{x} &\le \frac{\theta^2}{2w}\bar{x}_2^2\zeta(x)\zeta^T(x) + \frac{w}{2}\bar{x}^TQ_U^TQ_U\bar{x} \\ &\le \gamma^*\frac{1}{2w}\bar{x}_2^2\zeta(x)\zeta^T(x) + \frac{w}{2}\bar{x}^T\bar{x} \end{aligned}$$

$$= \tilde{\gamma}\frac{1}{2w}\bar{x}_2^2\zeta(x)\zeta^T(x) + \frac{w}{2}\bar{x}^T\bar{x} + \hat{\gamma}\frac{1}{2w}\bar{x}_2^2\zeta(x)\zeta^T(x) \quad (35)$$

where $w > 0$ is chosen by the designer.

By use of Lemma 4, we obtain

$$\begin{aligned} \bar{x}_2\chi^*\beta(x) &\le \chi^*|\bar{x}_2||\beta(x)| \\ &= \tilde{\chi}|\bar{x}_2||\beta(x)| + \hat{\chi}|\bar{x}_2||\beta(x)| \\ &\le \tilde{\chi}|\bar{x}_2||\beta(x)| + 0.2785\upsilon \\ &\quad + \hat{\chi}\bar{x}_2\beta(x)\tanh\left(\frac{\hat{\chi}\bar{x}_2\beta(x)}{\upsilon}\right) \end{aligned} \quad (36)$$

We choose the following ship course-keeping control law

$$u = \frac{1}{g(x)}\left[-k_2\tilde{x}_2 - \frac{1}{2w}\hat{\gamma}\bar{x}_2\zeta(x)\zeta^T(x) - \bar{x}_1 - \hat{\chi}\beta(x)\tanh\left(\frac{\bar{x}_2\hat{\chi}\beta(x)}{\upsilon}\right)\right] \quad (37)$$

and adaptive law

$$\dot{\hat{\gamma}} = \Gamma_1\left[\frac{1}{2w}\bar{x}_2^2\zeta(x)\zeta^T(x) - \sigma_1(\hat{\gamma} - \gamma_0)\right] \quad (38)$$

$$\dot{\hat{\chi}} = \Gamma_2\left[|\bar{x}_2|\beta(x) - \sigma_2(\chi - \chi_0)\right] \quad (39)$$

where $\sigma_1 > 0$, $\sigma_2 > 0$, $\gamma_0 > 0$ and $\chi_0 > 0$ are chosen by the designer.

By completion of squares, we obtain

$$2\tilde{\gamma}(\hat{\gamma} - \gamma^0) \le -\tilde{\gamma}^2 - (\hat{\gamma} - \gamma^0)^2 + (\gamma^* - \gamma^0)^2 \quad (40)$$

$$2\tilde{\chi}(\hat{\chi} - \chi^0) \le -\tilde{\chi}^2 - (\hat{\chi} - \chi^0)^2 + (\chi^* - \chi^0)^2 \quad (41)$$

For the convenience, we introduce the following definition

$$c_2 := \min\{2k_1 - w, 2k_2 - w, \Gamma_1\sigma_1, \Gamma_2\sigma_2\} \quad (42)$$

$$\varpi := \frac{\sigma_1}{2}(\gamma^* - \gamma^0)^2 + \frac{\sigma_2}{2}(\chi^* - \chi^0)^2 + 0.2785\upsilon \quad (43)$$

Combining (34), (35), (36)-(41) results in

$$\dot{V}_2(t) \le -cV_2(t) + \varpi \quad (44)$$

From (44) and Lemma 5, we obtain

$$V_2(t) \le V(t_0)\exp\left[-c(t - t_0)\right] + c/\varpi, \quad t \ge t_0 \quad (45)$$

Then we know $\bar{x}_i (i = 1,2)$, $\tilde{\chi}$, $\tilde{\gamma}$ belong to the following compact sets

$$\left\{(\bar{x}_i, \tilde{\gamma}, \tilde{\chi}) \middle| V_2(t) \le V(0) + \varpi/c\right\} \quad (46)$$

This also indicates that $\bar{x}_i$, $\tilde{\chi}$, $\tilde{\gamma}$ in the closed-loop system is ultimate uniform bounded. Furthermore, it can be concluded from (18) and (31) that $x_{ic} \to x_{ic}^0$ can be arbitrarily small through appropriate choice of the filter's parameters. Then, we obtain $\xi_i \to 0$ and $\bar{x}_i$, $\to$, $\tilde{x}_i$. Hence, course tracking error $\tilde{x}_i$ is UUB, and may be arbitrarily small by reasonably choosing design parameters. From (27), the filter's output is also bounded. From the aforementioned, the control law (37) can ensure the UUB of all the signals in the closed-loop system.

4. Simulation Experiment

We takes Dalian Maritime University's training ship "Yulong" as example. By use of Simulink Toolbox in Matlab 7.2, simulation experiments are carried out for the ship course controller design. Ship Yulong's main particulars are as follows: design speed 14 knots, length between main particulars 126 meters, breadth 20.8 meters, draft 8 meters, cubic coefficient 0.681, buoyant center position 0.25 meter, rudder area 18.8 meters. From these parameters, K = 0.4343, T = 238.7592 could be calculated. The control objective is to force the ship course x_1 to track a reference signal x_{1c}, where is the output of the following transfer function

$$x_{1c}(t) = \frac{0.0025}{s^2 + 0.08s + 0.0025}\left[x_{1c,r}(t)\right] \quad (47)$$

whose input $x_{1r,c}(t)$ is square wave with period 200 seconds, and amplitude 30°.

We use total 9 IF-THEN rules to approximate the nonlinear system function f (x) in the ship steering control system. We select membership functions for ship course x_1 and rate-of-turn x_2 as follows

$$\mu_{\text{positive}}(x_i) = \frac{1}{1 + \exp\left[-4(x_i - \pi/4)\right]} \quad (48)$$

$$\mu_{\text{zero}}(x_i) = \frac{1}{\exp(-x_i^2)} \quad (49)$$

$$\mu_{\text{positive}}(x_i) = \frac{1}{1 + \exp\left[-4(x_i - \pi/4)\right]} \quad (50)$$

We choose the virtual control input

$$\alpha_1 = -0.1\tilde{x}_1 - \dot{x}_{1c} \quad (51)$$

We use the following filter

$$x_{2c}(t) = \frac{10}{10+s}\left[x_{2c}^{0}(t)\right] \quad (52)$$

We choose the ship course's adaptive fuzzy controller as follows

$$u = \frac{T}{K}\Big[-4\tilde{x}_2 - 20\hat{\gamma}\bar{x}_2\zeta(x)\zeta^T(x) - \bar{x}_1 - \hat{\chi}\beta(x)\tanh\left(\frac{\bar{x}_2\hat{\chi}\beta(x)}{10}\right)\Big] \quad (53)$$

equipped with adaptive laws

$$\dot{\hat{\gamma}} = 2\left[20\bar{x}_2^2\zeta(x)\zeta^T(x) - 0.05(\hat{\gamma} - 0.01)\right] \quad (54)$$

$$\dot{\hat{\chi}} = 2\left[|\bar{x}_2|\beta(x) - 0.2(\hat{\chi} - 0.1)\right] \quad (55)$$

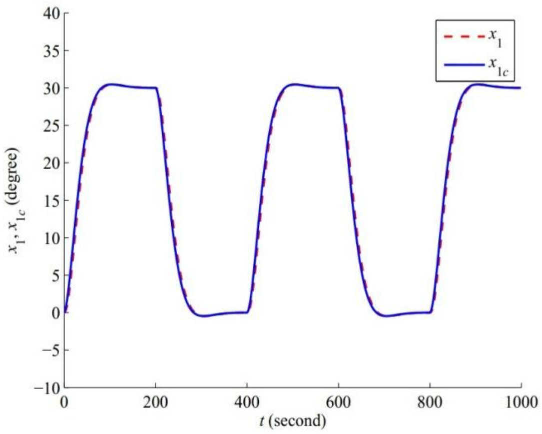

Figure4.1 Comparison of the state x_1 and the desired trajectory x_{1c}

During simulation experiment, we use separate-type model as platform, where hydrodynamic characteristics of hull, propeller and rudder are taken into consideration. Figures 1-4 illustrate the simulation results. Figure4.1 shows the time response of actual course and desired trajectory, where real line represents actual course x_1, and dotted line denotes desired trajectory x_{1c}. Figure4.2 is control input, or rudder angle. Figures 3 and 4 are adaptive parameters $\hat{\chi}$ and $\hat{\gamma}$, respectively. From Figures 1-4, the performance of the design controller is satisfactory, and all the signals in the closed-loop system is UUB. Furthermore, fine tuning of k_1, k_2, Γ_1, Γ_2 can achieve more precise tracking error, but with larger control input.

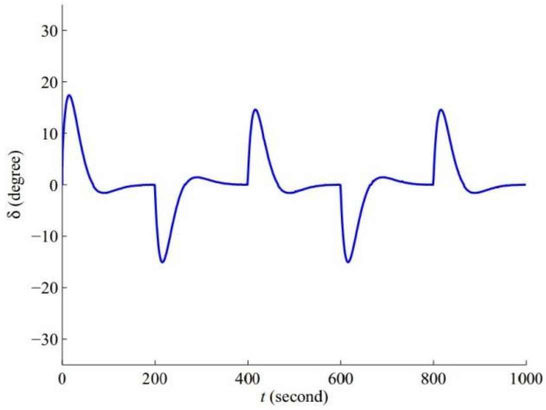

Figure4.2 Control input

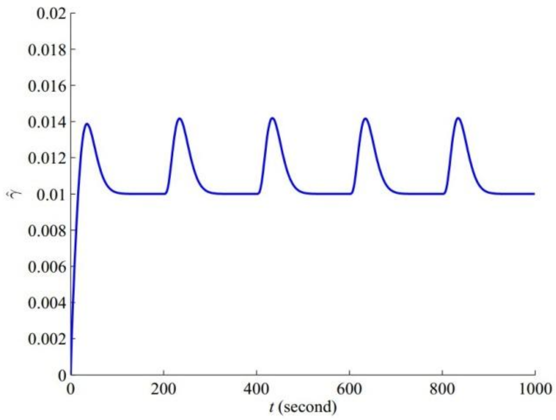

Figure4.3 Adaptive law: $\hat{\gamma}$

5. Conclusions

In this paper, adaptive tracking fuzzy control scheme for ship course-keeping is proposed in the framework of the nonlinear system in strict-feedback form. T-S fuzzy system is employed to approximate the unknown dynamics. The proposed algorithm can guarantee the boundedness of all signals in the closed-loop system. Compensated tracking errors and no tracking errors are used to construct the controller. Based on compensated tracking error which is not the traditional tracking error, the proposed design avoids the repeated differential of virtual control law completely, which make the controller structure quite simple and easy to implement. Simulation experiment is implemented to demonstrate the effectiveness of the course-keeping control algorithm.

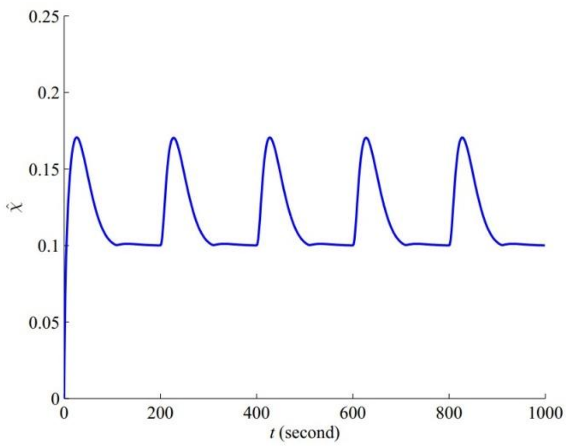

Figure4.4 Adaptive law: $\hat{\chi}$

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