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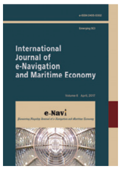

Original article

Robust Adaptive Fuzzy Design for Ship Linear-tracking Control with Input Saturation☆

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Abstract

A robust adaptive control approach is proposed for underactuated surface ship linear path-tracking control system based on the backstepping control method and Lyapunov stability theory. By employing T-S fuzzy system to approximate nonlinear uncertainties of the control system, the proposed scheme is developed by combining "dynamic surface control" (DSC) and "minimal learning parameter" (MLP) techniques. The substantial problems of "explosion of complexity" and "dimension curse" existed in the traditional backstepping technique are circumvented, and it is convenient to implement in applications. In addition, an auxiliary system is developed to deal with the effect of input saturation constraints. The control algorithm avoids the singularity problem of controller and guarantees the stability of the closed-loop system. The tracking error converges to an arbitrarily small neighborhood. Finally, MATLAB simulation results are given from an application case of Dalian Maritime University training ship to demonstrate the effectiveness of the proposed scheme.

Keywords: Underactuated surface ship, Path- tracking control, Fuzzy Control, DSC, MLP, Input Saturation

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1. Introduction

When a ship is travelling via way-points at a constant cruise speed, ship linear-path tracking control is of great importance to saving travelling time, distance and fuel in practice. So the path-following control is very suitable for practical engineering. Actually, ship motion control has always received considerable attention. Sutton et al. (1991, p. 35) applied the fuzzy theory to the field of ship course control. Due to strong approximation ability, the Fuzzy System is mainly used to approximate the unknown nonlinear uncertainties. The application of the Fuzzy system has promoted the development of ship motion control. Yang (2004, p.406) presented novel robust adaptive fuzzy control algorithms based on backstepping and small-gain approach.

However, with the increasing orders of control systems, the repeated derivatives of control laws in the design cause the problem of "computational expansion". Fortunately, Swaroop (1997, p. 3028) and Yip (1998, p.959) proposed the dynamic surface control (DSC) technique. By introducing the first order filter into traditional backstepping method, it simplifies the complexity of the controller. After that, the literatures (Wang, 2005, p. 195) and (Wang, 2009, p.16) applied this technique to nonlinear systems and uncertain nonlinear systems.

In practical application, the controller will inevitably be affected by the control input saturation and uncertain nonlinear characteristics. Aiming at nonlinear system, Hu (2001) proposed a nonlinear saturation compensation design algorithm. And then, the introduction of an auxiliary design in Chen (2009, p. 85), Li (2009) and Chwa (2011, p.1357) compensated the impact of input saturation constraints that existed in the ship's adaptive rudder input control. Li (2014, p.2299) considered input saturation in composite adaptive fuzzy control design for uncertain nonlinear strict-feedback systems. The well-known "dimension curse" is a substantial problem, which imposes that many parameters need to be tuned in the adaptive control schemes based on fuzzy or neural networks system. As we move to high dimensional systems, the learning time tends to become unacceptably large. In order to serve this problem, the paper (Li, 2011, p.2277) utilized MLP approach to reduce learning parameters and computation load, which is convenient to be implemented in applications.

In this paper, the dynamic surface control technique and MLP algorithm are combined to apply to ship's path-tracking control system with unknown nonlinear items. An adaptive fuzzy tracking control algorithm is proposed considering input saturation based on Lyapunov method, and guarantees the stability of the closed loop system.

2. Preliminaries

In this part, we briefly describe the structure of the T-S type fuzzy logic system. Generally, there are N rules in the fuzzy system, and each rule has the following form:

R_{j} : If x_1 is h_1^j, AND x_2 is h_2^j, AND $\cdots$ AND x_n is h_n^j,

then y_j is $a^j x$,which is the function of $a_1^j x_1 + a_2^j x_2 + \cdots a_n^j x_n$.

a_i^j , $j = 1,2,\cdots N$, $i = 1,2,\cdots n$ are unknown constants, h_i^j is input variable, $a^j x$ is output variable.

The product fuzzy inference is used to evaluate the ANDs of the fuzzy rules. After being defuzzified by a typical center average defuzzifier, the output of the T-S fuzzy system is in the following vector form:

$$\hat{f}(x, A_x) = \xi(x) A_x x \tag{1}$$

where $\xi(x) = [\xi_1(x), \xi_2(x) \cdots \xi_N(x),]$.

The Fuzzy basis function $\xi_j(x)$ and vector A_x are as follows:

$$\xi(x) = \frac{\prod_{i=1}^{n} \mu_{h_i^j}(x_i)}{\sum_{j=1}^{N} \prod_{i=1}^{n} \mu_{h_i^j}(x_i)}, \quad A_x = \begin{bmatrix} a_{11} a_{12} \cdots a_{1n} \\ a_{21} a_{22} \cdots a_{2n} \\ \vdots \; \vdots \; \vdots \; \vdots \\ a_{N1} a_{N2} \cdots a_{Nn} \end{bmatrix} \tag{2}$$

where $\mu_{h_i^j}(x_i)$ is membership function.

The step steering operation is unable to realize in the actual process of handling the ship, so it is necessary to consider the rudder actuator dynamics, otherwise it will affect the performance of heading control.

The mathematical steering model is added to nonlinear ship mathematical model and can be expressed as follows:

$$T_E \dot{\delta} + \delta = K_E \delta_E \tag{3}$$

where δ_E is the command rudder angle, δ is the actual rudder angle, T_E is the time delay constant, and K_E is the control gain.

The ship course cannot be arbitrarily changed in the actual course control. Rudder angle and steering speed