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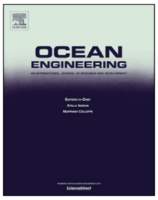

Nonlinear adaptive fuzzy output-feedback controller design for dynamic positioning system of ships

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ABSTRACT

This paper develops a nonlinear adaptive fuzzy output feedback controller for dynamic positioning (DP) system of ships in the presence of unmeasured states of ships, unknown dynamic model parameters, unknown time varying environment disturbances and input saturation. It is the first time that all the conditions above are simultaneously dealt with in the DP control design. By combining adaptive fuzzy system and auxiliary dynamic system, a control scheme with high-gain observer is developed via vectorial backstepping method. It is proved that the proposed nonlinear adaptive fuzzy output feedback controller can maintain the ship at desired position and heading with arbitrary accuracy, while guaranteeing the uniform ultimate boundedness of all closed loop signals in the DP system. Finally, simulations are carried on a supply ship to demonstrate the effectiveness of the proposed control approach.

1. Introduction

Dynamic positioning (DP) system enable the ship automatically to maintain at the desired position and heading by means of its thrusters and propellers (Sørensen, 2011), (Tannuri and Morishita, 2006). Compared with the traditional anchor moored positioning, the DP system has the strength of working in the deep ocean, high positioning accuracy, and avoiding damaging the seabed (Fossen, 2011). With the development of the ocean exploration and exploitation, the DP system has been increasingly used in offshore operations, such as offshore oil and gas drilling, underwater cable and pipe laying, and dredging (Hassani et al., 2013).

The first DP system was designed by proportional integrator derivative (PID) controllers cascaded with low pass or notch filters in the early 1960's. In the middle of 1970's, all kinds of control methodologies based on optimal control theory of linear Kalman filter were introduced into the DP system (Balchen and Jenssen, 1980). The main disadvantages of these methods were that the kinetic equations of motions must be linearized under certain conditions. With the progress of the nonlinear control theory, the DP nonlinear control gradually gained a lot attention. In 1990's the DP controller with nonlinear observer were developed by the vectorial backstepping methology, where the disturbances were neglected (Fossen and Grøvlen, 1998). Subsequently, the study in (Fossen and Strand, 1999), a passive observer with wave filtering was proposed for the DP system to estimate low-frequency positions and velocities of ships from noisy position measurements and environment disturbances. Combining the passive observer and proportional-derivative (PD) control law, a globally asymptotically stable controller was presented for the DP system in (Loria et al., 2000), where the slowly varying environmental disturbances and the unmeasured states were considered. And then, to deal with the problem of dynamic uncertainties and the disturbances acting on the ship, a class of feedforward approximators in (Tee and Ge, 2006) and a radial basis function (RBF) networks in (Du et al., 2013) were employed to compensate for these. Furthermore, in the presence of unknown dynamic parameters of the ship, unmeasured velocities and unknown time-varying disturbances, an adaptive robust output feedback controller was developed for the DP system by merging adaptive RBF neural networks and high-gain observer into the vectorial backstepping method (Du et al., 2015).

Unfortunately, it should be pointed out that all aforementioned control methods for the DP system did not take into account input saturation. Input saturation is a potential problem for the DP system as the commanded control inputs computed by the DP controller are probably constrained by the maximum forces and moment that the propulsion system can provide. This would degrade the control system performance and even lead to instability of the DP system. In recent years, many approaches have been put into use in order to resolve the input saturation problem for the DP control system. For example, a model

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predictive control (MPC) was introduced for the DP system combining DP control design with thruster allocation, where the unknown disturbance and input saturation problem were addressed by the optimization problem of MPC (Veksler et al., 2016). Also, a DP proportional-integral (PI) controller was proposed in (Perez and Donaire, 2009), where the disturbances and input saturation were settled by integral control with anti-windup scheme. In addition, a DP passivity-based control design was proposed in (Donaire and Perez, 2012), where disturbances and input saturation were handled by using anti-windup compensator in the port-Hamiltonian. However, in (Veksler et al., 2016), (Perez and Donaire, 2009) and (Donaire and Perez, 2012), the disturbance acting on the ship was unknown constant, it is restrictive in practice. In the latest literature, a robust nonlinear control law for the DP system has been given in (Du et al., 2016), where a disturbance observer was constructed to estimate unknown time-varying disturbance and an auxiliary dynamic system was employed to resolve input saturation, but the unmeasured states of the ship were not considered.

With the development of fuzzy control theory, adaptive fuzzy control scheme provides an effective control approach for the nonlinear system. An adaptive fuzzy tracking controller was designed for uncertain non-strict feedback nonlinear systems with unknown nonlinear functions or model uncertain for the case of the states measurable and the states immeasurable (Tong et al., 2016a). Also, an adaptive fuzzy output feedback controller was developed for the switched systems under the consideration of unknown nonlinearities, unmeasured states and unknown dead zones (Tong et al., 2016b). Subsequently, considering unstructured uncertainties, unmodeled dynamics and unavailable states, a novel robust adaptive fuzzy output feedback stabilization control approach was proposed in (Tong and Li, 2017). In addition, the problem of adaptive fuzzy output feedback control was investigated for a class of output constrained uncertain nonlinear systems with input saturation, unmeasured states and unknown disturbance in (Li et al., 2014). To be specific, using backstepping control and approximation-based adaptive technique to accommodate certain faults in the plant and the controller itself in the tracking control of surface vessels, yet only the time-varying hydrodynamic disturbances were considered (Chen and Tan, 2013). However, all aforementioned fuzzy control theory for the nonlinear system did not take into account unmeasured states, unknown dynamic model parameters, dynamic disturbance and input saturation, simultaneously.

It is known that the problem of unmeasured states, unknown dynamic model parameters, dynamic disturbance and input saturation is unavoidable for the DP control system design, yet the above literature exist theoretical obstruction or engineering practical shortcoming. Motivated by the above considerations, a nonlinear adaptive fuzzy output feedback controller is developed for the DP system considering the unmeasured states of the ship, unknown dynamic model parameters, unknown time-varying environment disturbances and input saturation simultaneously in this paper. To the best of authors' knowledge, it is the first time in the literature that all the conditions above are simultaneously dealt with in the DP control design. On one hand, a high-gain observer is used to estimate unmeasured state and the estimated states are fed back to the control system. On the other hand, an adaptive fuzzy system is employed to approximate the uncertain term induced by unknown dynamic model parameters and the unknown time varying environment disturbances without the need for explicit knowledge of the bounds in the control law. In particularly, an auxiliary dynamic system is exploited to deal with the input saturation. On the basis of above, the DP control law is developed by vectorial backstepping method. The main contributions of this paper can be summarized as follows: (1) The established adaptive fuzzy output feedback control method can solve the problems of unmeasured states, unknown dynamic model parameters, unknown time-varying environment disturbances and input saturation simultaneously. (2)The proposed DP control scheme is simple and easy to implement in practice due to applying adaptive fuzzy control. (3) The boundedness of the closed-loop system is guaranteed.

The rest of the paper is organized as follows. In section 2, the problem formulation and preliminaries are provided for preparation. The nonlinear adaptive fuzzy output feedback control design is presented for the DP system of ships with unmeasured states, unknown dynamic model parameters, unknown time-varying environment disturbances and input saturation in section 3. Simulation studies and comparations on a supply ship are given in section 4 to illustrate the effective of the proposed control approach. Finally, the conclusion is drawn in section 5.

2. Problem formulation and preliminaries

2.1. Problem formulation

The nonlinear motion mathematical model of a ship in the DP mode is expressed as (Fossen and Strand, 1999)

$$\dot{\eta} = J(\psi)\nu \tag{1}$$

$$M\dot{\nu} + D\nu = \tau + d(\eta, \nu, t) \tag{2}$$

where $\eta = [x, y, \psi]^T$ is the position vector in the earth-fixed frame, consisting of the surge position x, the sway position y, and the heading $\psi \in [0, 2\pi]$ of the ship. $\nu = [u, \upsilon, r]^T$ is the velocity vector in the body-fixed frame, consisting of the surge velocity u, the sway velocity υ, the yaw rate r of the ship. $J(\psi)$ is the rotation matrix given by

$$J(\psi) = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

with the property $J^{-1}(\psi) = J^T(\psi)$ and $\| J(\psi) \| = 1$. Here, $\| \cdot \|$ stands for the determinant of a matrix. M denotes the inertial matrix including added mass effects, which is invertible, and positive definite. D denotes the linear damping matrix. $\tau = [\tau_1, \tau_2, \tau_3]^T$ represents the control input vector produced by propeller and thruster system, consisting of force τ_1 in surge, force τ_2 in sway and moment τ_3 in yaw. In practice, the control forces and moment are limited to saturation nonlinearities due to the physical limitations of thrusters and can be described as follows:

$$\tau_i = \begin{cases} \tau_{i\max}, & if \quad \tau_{ci} > \tau_{i\max} \\ \tau_{ci}, & if \quad \tau_{i\min} \le \tau_{ci} \le \tau_{i\max} \quad i = 1, 2, 3 \\ \tau_{i\min}, & if \quad \tau_{ci} < \tau_{i\min} \end{cases} \tag{4}$$

where $\tau_{i\max}$ and $\tau_{i\min}$ are the maximum and minimum control forces or moments that the ship's propulsion system can provide, respectively. $\tau_c = [\tau_{c1}, \tau_{c2}, \tau_{c3}]^T$ is the commanded control vector calculated by the DP control law, including commanded control forces τ_{c1} in surge and τ_{c2} in sway, and moment τ_{c3} in yaw. $d(\eta, \nu, t) \in R^3$ is unknown time-varying environmental disturbance depends on η and ν due to wind, waves and currents and unmodeled dynamics.

Assumption 1. The parameters M and D are unknown, yet $M = M^T$ and D is positive definite. The ship's velocity vector is not available for the feedback.

Remark 1. The parameters M and D are related to ship's operation and sea states, which are constantly changing. Besides, the ship's velocities are unmeasured for most ships. Hence, the Assumption 1 is reasonable.

Lemma 1. (Tee and Ge, 2006) *For the continuous disturbance function* $d_i(\eta, \nu, t) \in R, i = 1, 2, 3$ *, there exists positive, smooth, nondecreasing functions* $p_i(\eta, \upsilon) \in R^+$ *and* $q_i(t) \in R^+$ *such that* $|d_i(\eta, \upsilon, t)| \le p_i(\eta, \upsilon) + q_i(t)$.

Remark 2. Since the ocean environment is constantly changing and has finite energy, the disturbance acting on ship can be deemed to be the unknown time-varying yet bounded signals. Lemma 1 allows one to separate the multivariable disturbance term $d_i(\eta, \upsilon, t), i = 1, 2, 3$ into a bounding function in terms of the internal states of the ship η, υ and a