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Brief paper

Robust dynamic positioning of ships with disturbances under input saturation[☆]

Jialu Du[a], Xin Hu[a], Miroslav Krstić[b], Yuqing Sun[c]

[a] School of Information Science and Technology, Dalian Maritime University, Dalian, Liaoning, 116026, China
[b] Department of Mechanical and Aerospace Engineering, University of California, San Diego, La Jolla, CA 92093-0411, USA
[c] School of Marine Engineering, Dalian Maritime University, Dalian, Liaoning, 116026, China

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A B S T R A C T

In the presence of unknown time-varying disturbances and input saturation, this paper develops a robust nonlinear control law for the dynamic positioning (DP) system of ships using a disturbance observer, an auxiliary dynamic system, and the dynamic surface control (DSC) technique. The disturbance observer is constructed to provide the estimates of unknown time-varying disturbances, the auxiliary dynamic system is employed to handle input saturation, and the DSC technique makes the designed DP control law be simple and easy to implement in practice. It is proved that the designed DP robust nonlinear control law can maintain ship's position and heading at desired values, while guaranteeing the uniform ultimate boundedness of all signals in the DP closed-loop control system. Finally, simulations on a supply ship are carried out to demonstrate the effectiveness of the developed DP control law.

1. Introduction

A dynamic positioning (DP) system aims at regulating the horizontal position and heading of the vessel exclusively by means of its own propulsion system (Sørensen, 2011). Compared with the traditional anchor moored positioning, the DP mode has the advantages of working in the deep sea, high positioning accuracy, and avoiding damaging the seabed (Fossen, 2011). With the ocean exploration and exploitation moving into the deep and distant sea, the DP system has been increasingly used in offshore operations, such as offshore oil and gas drilling, underwater cable and pipe laying, and wreck investigation (Hassani, Sørensen, & Pascoal, 2013).

With the advances of the nonlinear control, the DP nonlinear control has gradually gained much attention. In 1990s, the DP nonlinear control laws were developed by using the backstepping method (Krstić, Kanellakopoulos, & Kokotović, 1995) in component form in Grøvlen and Fossen (1996) and in vector setting in Fossen and Grøvlen (1998), respectively, where disturbances due to waves, currents and wind were neglected. In Fossen and Strand (1999), Fossen and Strand proposed a passive observer with wave filtering for the DP system to estimate low-frequency positions and velocities of ships from noisy position measurements and bias states (environmental disturbances). Combining the passive observer and a proportional–derivative control law, Loria et al. presented a globally asymptotically stable controller for the DP system, the effectiveness of which was demonstrated by experimentation with a 1:70 scale model of a supply ship (Loria, Fossen, & Panteley, 2000). Benetazzo et al. presented a DP discrete variable-structure controller with Kalman filters estimating the disturbances, which exhibits better performance than the proportional–integral–derivative (PID) controller with the passive observer (Benetazzo, Ippoliti, Longhi, & Raspa, 2012). Considering the variations of sea states, Hassani et al. designed a bank of Kalman filters for the DP system to adapt to sea state variations using the multiple model adaptive estimate techniques (Hassani, Sørensen, Pascoal, & Aguiar, 2012). Nguyen et al. proposed a hybrid controller for the DP system using the supervisory switching control so that different controllers can be switched online according to sea state variations (Nguyen, Sørensen, & Quek, 2007). Considering unknown time-varying disturbances, Du et al. proposed a robust adaptive neural controller for the DP system, where ship unknown model dynamics and

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E-mail addresses: dujl66@163.com (J. Du), hxljy123@sina.com (X. Hu), krstic@ucsd.edu (M. Krstić), sunyq@dlmu.edu.cn (Y. Sun).

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time-varying disturbances are compensated for by adaptive radial basis function (RBF) neural networks (Du, Yang, Wang, & Guo, 2013). In the presence of ship unknown dynamic parameters, unavailable velocities, and unknown time-varying disturbances, Du et al. developed an adaptive robust output feedback controller for the DP system by incorporating adaptive RBF neural networks and the high-gain observer into the vectorial backstepping method (Du, Hu, Liu, & Chen, 2015).

All aforementioned control design for the DP system did not take into account input saturation. Input saturation is a potential problem for the DP system since the commanded control inputs calculated by the DP controller are possibly constrained by the maximum forces and moment that the propulsion system can produce. This would give rise to degraded performance and even instability of the DP control system. Input saturation puts a challenge on the DP control design. In the presence of unknown constant disturbances and input saturation, Veksler et al. developed model predictive control (MPC) for the DP system combining DP control design with thrust allocation, where actuator saturation was handled in the optimization problem of MPC (Veksler, Johansen, Borrelli, & Realfsen, 2016); Perez and Donaire proposed DP proportional–integral control, where disturbances and input saturation were handled by the integral action with anti-windup scheme (Perez & Donaire, 2009); and Donaire and Perez proposed DP passivity-based control, where disturbances and input saturation were handled by using the integral action and anti-windup compensator in the port-Hamiltonian framework (Donaire & Perez, 2012).

In this paper, simultaneously considering unknown time-varying disturbances and input saturation, we develop a robust nonlinear control law for the DP system. To the best of the authors' knowledge, it is the first time in the literature that unknown time-varying disturbances and input saturation are simultaneously dealt with in the DP control design. A disturbance observer is constructed to estimate unknown time-varying disturbances and an auxiliary dynamic system is employed to handle input saturation, on the basis of which the DP control law is designed by using the DSC technique.

2. Problem formulation

Two right-hand coordinate frames are defined as indicated in Fig. 1. The earth-fixed frame $OX_0Y_0Z_0$ is an inertial coordinate frame. The origin O of the earth-fixed frame can be chosen as any point on the earth's surface. The axis OX_0 is directed to the north, OY_0 is directed to the east, and OZ_0 points towards the center of the earth. The body-fixed frame $AXYZ$ is a moving coordinate frame which is fixed to the ship. The origin A of the body-fixed frame is located at the gravity center of the ship. The axis AX is directed from aft to fore, AY is directed to starboard, and AZ is directed from top to bottom. Both the X_0Y_0 and the XY planes are parallel to the still water surface. The nonlinear motion mathematical model of a ship in DP mode is expressed as (Fossen & Strand, 1999)

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

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

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. $\nu = [u, v, r]^T$ is the velocity vector in the body-fixed frame, consisting of the surge velocity u, the sway velocity v, and the yaw rate r of the ship. $J(\psi)$ is the rotation matrix given by

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

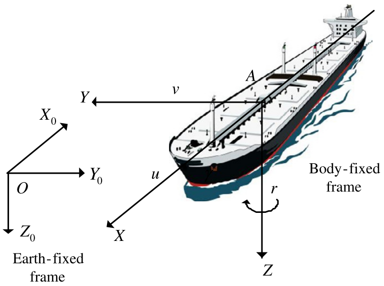

Fig. 1. Earth-fixed frame and body-fixed frame (Fossen, 2011).

with the property $\|J(\psi)\| = 1$. Here, $\|\cdot\|$ denotes the two-norm of a vector or a matrix. M is the inertia matrix including added mass, which is invertible, symmetric and positive definite. D is the damping matrix. $\tau = [\tau_1, \tau_2, \tau_3]^T$ is the control vector produced by the propulsion system, consisting of control forces τ_1 in surge and τ_2 in sway, and moment τ_3 in yaw. In practice, the control forces and moment are subject to saturation nonlinearities due to the physical limitations of thrusters and can be described as follows:

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

where $\tau_{i\max}$ and $\tau_{i\min}$ are the maximum and the minimum control forces or moments that the ship's propulsion system can produce, respectively. $\tau_c = [\tau_{c1}, \tau_{c2}, \tau_{c3}]^T$ is the commanded control vector calculated by the DP control law, consisting of commanded control forces τ_{c1} in surge and τ_{c2} in sway, and moment τ_{c3} in yaw. $d(t) = [d_1(t), d_2(t), d_3(t)]^T$ is the disturbance vector, consisting of disturbance forces $d_1(t)$ in surge and $d_2(t)$ in sway, and moment $d_3(t)$ in yaw.

Assumption 1. The disturbances $d_i(t), i = 1, 2, 3$ are unknown time-varying yet bounded and there exists an unknown positive constant ρ such that

$$\|\dot{d}(t)\| \le \rho. \tag{5}$$

Remark 1. Since the ocean environment is constantly changing and has finite energy, the disturbances acting on the ship can be viewed as the unknown time-varying yet bounded signals with the finite changing rates. Therefore, Assumption 1 is reasonable.

Remark 2. The environmental disturbances acting on ships can be separated into low-frequency components induced by second-order waves, wind and currents and wave-frequency components induced by first-order waves. The low-frequency disturbances cause the ship to drift and the wave-frequency disturbances cause the ship's oscillatory motions. Compensating for the wave-frequency components of the wave forces would cause power consumption and potential wear and tear of the actuators. On the other hand, it is not necessary to compensate for them, since they essentially rock the ship back and forth (Veksler et al., 2016). These motions should be discarded from the position and heading measurements before they are sent to the DP system, which is known as wave filtering. Several wave filtering methods have been proposed (Fossen & Strand, 1999; Hassani et al., 2012). Therefore, we accomplish DP control compensating only for the low-frequency components of environmental disturbances.

The control objective in this paper is to design a DP robust nonlinear control law τ_c for the ship with unknown time-varying disturbances and input saturation under Assumption 1, so that the ship's position (x, y) and heading ψ are maintained at the desired values $\eta_d = [x_d, y_d, \psi_d]^T$ with arbitrarily small errors, while all signals in the DP closed-loop control system are uniformly ultimately bounded.