Trajectory Tracking Control of Nonlinear Full Actuated Ship with Disturbances

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***Abstract*—Based on backstepping technique, this paper presents a design of any reference trajectory tracking controller for marine surface vessels under unknown time-variant environmental disturbances. The mathematical model of nonlinear surface ship movement includes Coriolis and centripetal matrix and nonlinear damp term. The observer is constructed for providing an estimation of unknown disturbances. It is proved that the designed ship trajectory tracking control law can make the resulting closed loop trajectory tracking system of ship be the globally uniformly ultimately bounded and achieve the object of trajectory tracking, while guarantee the global uniform boundedness of all signals of system. The simulation results on a model ship show that the control force and control torque are reasonable, and the transient state and steady-state performances are satisfactory. The effectiveness of the designed control law is verified.**

Keywords-ship trajectory tracking control; disturbance observer; backsteping; nonlinear;

I. INTRODUCTION

Controlling of surface marine vessels to track a given trajectory has been a representative control problem for marine applications and it has attracted considerable attention from the control community for many years[1]. It is of great significance for navigation in safety, energy- saving and emission-reduction to implement trajectory tracking of ship. The conventional course autopilot cann't meet the requirements for ship steering because track bias is not directly controlled. Along with the development of science and technology, especially the appearance of high accuracy DGPS, it becomes possible to solve the problem of trajectory tracking of ship. On the other hand, the ship motion dynamics are characterized by large inertia, large delay and strong nonlinear, and the ship during navigation is easily influenced by environment such as wind, waves and currents, all of which make the ship trajectory tracking control more complicated. Therefore, the research on the problem of the ship trajectory tracking control has received a lot of attention both in theory and in practice.

A ship trajectory tracking controller was designed to make the system be local asymptotical stable combining LQG method with the feed forward control in [2]. In [3], the fuzzy logic control combined with PID control achieved the semi-global exponential stability of the ship trajectory tracking error system. In [4], taking the advantage of the neural networks of the model free adaptive, a novel ship trajectory tracking controller with self-learning and self-tuning functions was developed. The models used in all above references are the simplified linear form. Along with the development of the theory of control and the higher requirements for control performance, this is an inevitable trend to use more accurate nonlinear mathematical model to describe the dynamics characteristics of ship maneuvering. In recent years, a good number of nonlinear design techniques have been developed for the tracking control problem for under-actuated ship. Jiang proposed two global tracking control laws for underactuated vessels based on Lyapunov's direct method[5]. Do et al. extended Jiang's work and developed a robust control law to environmental disturbances such as wave, wind, and ocean currents for ships on a linear course[6]. In [7], Petterson and Nijmeijer provided a semi-global exponential stabilization of the tracking error for any desired trajectory using an integrator backstepping approach. In [8], furthermore, they improved the control law in [7] and attained the exponential stability of the closed-loop trajectory tracking system, which was validated by the experimental results with a small model ship. The approach in [8] was further improved to obtain a globally exponentially convergent control law in [9], which was tested with the same vessel and on the same trajectory as the one presented in [8]. [10] introduced a design of global smooth controllers that achieved the practical stabilization of arbitrary reference trajectories. For the full-actuated ships, based on passive theory, in [11] the output feedback controller was designed for the nonlinear ship motion mathematical model containing linear damping only, which achieved the semi-global exponentially stability of the closed loop system of ship trajectory tracking. Du et.al designed a nonlinear trajectory tracking control law for full-actuated ship including Coriolis and centripetal matrix and nonlinear damp term under constant disturbances based on backstepping design tool with integrator in [12]. However, the sea state during navigation of ships always changes. Therefore, assuming the disturbances induced by wind, waves and currents are unknown time-variant, this paper proposes a robust trajectory tracking controller of ship based on disturbance observer, backstepping technique and Lyapunov direct method. The disturbance observer is introduced in the controller design process to provide an estimation of unknown external disturbances.

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The rest of this paper is organized as follows. In section Ⅱ, the 3 DOF nonlinear mathematical model of a surface ship motion under disturbances due to wind, waves and ocean currents is presented. In Section Ⅲ, the trajectory tracking control law of ship is derived based on backstepping design tool and a disturbance observer. The simulation results are provided to validate the designed controller in Section Ⅳ, followed by the conclusions in Section Ⅴ.

II. Problem Statements

The 3 DOF nonlinear motion equations of a ship can be expressed as [13][14]

$$\dot{\eta} = R(\psi)\upsilon \tag{1}$$

$$M\dot{\upsilon} + C(\upsilon)\upsilon + D(\upsilon)\upsilon = \tau + b \tag{2}$$

where $\eta = [x, y, \psi]^T$. x, y is the position variables of the ship and $\psi \in [0, 2\pi]$ is the yaw angle of the ship in the earth-fixed frame. $\upsilon = [u, v, r]^T$ is the ship velocity vector. u, v and r are respectively the velocities in the surge, sway and yaw of ship in the body-fixed frame. $\tau = [\tau_1, \tau_2, \tau_3]^T$ is the control input vector consisting of the surge force τ_1, the sway force τ_2 and the yaw torque τ_3. $b = [b_1, b_2, b_3]^T$ is the vector representing unknown and time-variant external disturbances due to waves, wind and ocean currents in the body-fixed frame. And it is assumed that $\|\dot{b}(t)\| \le C_d$, where C_d is a nonnegative known constant. The rotation matrix $R(\psi)$, inertia matrix M, hydrodynamic Coriolis and centripetal matrix $C(\upsilon)$, and damping matrix $D(\upsilon)$ are given by

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

$$M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{23} & m_{33} \end{bmatrix} \tag{4}$$

$$C(\upsilon) = \begin{bmatrix} 0 & 0 & -m_{22}v - m_{23}r \\ 0 & 0 & m_{11}u \\ m_{22}v + m_{23}r & -m_{11}u & 0 \end{bmatrix} \tag{5}$$

$$D(\upsilon) = D_L + D_{NL} = \begin{bmatrix} d_{11}(u) & 0 & 0 \\ 0 & d_{22}(v,r) & d_{23}(v,r) \\ 0 & d_{32}(v,r) & d_{33}(v,r) \end{bmatrix} \tag{6}$$

where

$m_{11} = m - X_{\dot{u}}$, $m_{22} = m - Y_{\dot{v}}$, $m_{23} = mx_g - Y_{\dot{r}}$, $m_{33} = I_z - N_{\dot{r}}$,

$d_{11}(u) = -X_u - X_{u|u|}|u|$, $d_{22}(v,r) = -Y_v - Y_{v|v|}|v| - Y_{|r|v}|r|$,

$d_{23}(v,r) = -Y_r - Y_{|v|r}|v| - Y_{|r|r}|r|$, $d_{32}(v,r) = -N_v - N_{|v|v}|v| - N_{|r|v}|r|$,

$d_{33}(v,r) = -N_r - N_{|v|r}|v| - N_{|r|r}|r|$,

where m is the mass of the ship, I_z is the moment of inertia about the yaw rotation, and the other symbols are referred as the Society of Naval Architects and Marine Engineers (SNAME) notation in [15]. It is noted that M is a positive definite matrix.

The control objective in this paper is to design a feedback control law τ for the system (1)-(2) such that $\eta(t)$ tracks a reference trajectory $\eta_d(t)$, while the closed-loop system of ship trajectory tracking is globally uniformly ultimately bounded.

III. Controller Design

In this section, a disturbance observer is constructed to provide an estimation of the time-variant external disturbances of the ship and the backstepping technique is introduced to design the controller for trajectory tracking.

A. Disturbance Observer Design

For the disturbance vector, the observer is constructed as follows [9]

$$\hat{b}(t) = \beta + K_0 M\upsilon \tag{7}$$

$$\dot{\beta} = -K_0\beta - K_0\left[-C(\upsilon)\upsilon - D(\upsilon)\upsilon + \tau + K_0 M\upsilon\right] \tag{8}$$

where K_0 is a positive definite symmetric design matrix and β is an intermediate auxiliary vector.

Define the observer estimation error as:

$$\tilde{b} = b - \hat{b} \tag{9}$$

Differentiating both sides of (9) results in

$$\begin{aligned} \dot{\hat{b}} &= \dot{\beta} + K_0 M\dot{\upsilon} \\ &= -K_0\beta - K_0\left[-C(\upsilon)\upsilon - D(\upsilon)\upsilon + \tau + K_0 M\upsilon\right] \\ &\quad + K_0 M \cdot M^{-1}\left[-C(\upsilon)\upsilon - D(\upsilon)\upsilon + \tau + b\right] \\ &= -K_0\left(\beta + K_0 M\upsilon - b\right) \\ &= K_0\left[b - \left(\beta + K_0 M\upsilon\right)\right] \\ &= K_0\left[b(t) - \hat{b}\right] \end{aligned} \tag{10}$$

Then

$$\begin{aligned} \dot{\tilde{b}} &= \dot{b} - \dot{\hat{b}} \\ &= \dot{b} - K_0\left[b(t) - \hat{b}\right] \\ &= \dot{b} - K_0\tilde{b} \end{aligned} \tag{11}$$