

带有输入死区的欠驱动水面船有限时间路径跟踪控制

王元慧, 王心玮[†], 邵兴超, 任哲达

(哈尔滨工程大学 智能科学与工程学院, 黑龙江 哈尔滨 150001)

摘要: 针对模型不确定、外界环境干扰和输入死区下的欠驱动水面船路径跟踪控制问题, 本文提出一种自适应有限时间路径跟踪控制方法. 首先, 设计有限时间视线制导律生成期望纵向速度和艏向角指令; 继而, 采用反步法分别设计有限时间纵向速度和艏向角控制器跟踪生成的期望信号, 其中结合径向基函数神经网络和最小学习参数算法逼近模型参数不确定性, 以及运用自适应技术补偿环境干扰、神经网络逼近误差和未知死区非线性组成的合成干扰; 此外, 为了避免复杂计算, 运用二阶跟踪微分器得到虚拟艏向控制律的导数, 基于李雅普诺夫稳定性理论, 证明整个闭环系统是实际有限时间稳定的; 最后, 仿真结果验证了所提方案的有效性.

关键词: 欠驱动水面船; 路径跟踪; 输入死区; 有限时间; 神经网络; 最小学习参数

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Finite-time path following control for underactuated surface vessels with input dead-zone

WANG Yuan-hui, WANG Xin-wei[†], SHAO Xin-chao, REN Zhe-da

(College of Intelligent Systems Science and Engineering, Harbin Engineering University, Harbin Heilongjiang 150001, China)

Abstract: This paper presents an adaptive finite-time path following control scheme for underactuated surface vessels in the presence of input dead-zone, model uncertainties and external environmental disturbances. Firstly, a finite-time surge-heading line-of-sight guidance law is designed to generate desired surge velocity and heading angle. Then, the adaptive finite-time surge and the heading controllers are developed to track reference signals via backstepping technique, where radial basis function neural network and minimum learning parameter algorithm are applied to approximate model uncertainties, and the adaptive technique is introduced to offset the lumped disturbances including unknown external environmental disturbances, approximation errors and input dead-zone. Besides, to reduce the computational burden inherent in backstepping technique, a second-order tracking differentiator is employed to generate derivative of the virtual heading control law. Based on the Lyapunov functions, it is proved that the closed-loop system is practical finite-time stable. Finally, simulation results are given to demonstrate the efficacy of the proposed scheme.

Key words: underactuated surface vessels; path following; input dead-zone; finite-time; neural network; minimum learning parameter algorithm

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1 引言

随着欠驱动水面船在海事工程的广泛应用, 欠驱动水面船的路径跟踪控制受到很多学者关注^[1-4]. 欠驱动水面船路径跟踪是指在不考虑时间约束的条件下, 设计一个控制方案使得船舶能够到达期望路径并

沿路径航行^[5]. 欠驱动水面船仅由螺旋桨和舵来控制其在水平面的运动, 而没有横向推进器, 容易受到海洋环境的影响, 影响跟踪性能. 因此, 欠驱动水面船路径跟踪控制研究具有重要的理论与工程意义.

路径跟踪控制可分成制导子系统和控制子系统,

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[†]通信作者. E-mail: s316040164@hrbeu.edu.cn.

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前者生成期望信号,后者跟踪生成的参考信号.视线(line-of-sight, LOS)制导方法由于简单有效而广泛应用于欠驱动水面船路径跟踪控制中.文献[6]基于LOS制导律设计期望艏向角,进而设计滑模控制器,保证了路径跟踪性能.文献[7]在传统LOS制导律中加入积分项,用于减少横向跟踪误差,改进跟踪效果.文献[8]提出了一种基于预测器的LOS制导律,对外界干扰引起的侧滑角进行补偿.文献[9]将滑模技术和LOS制导律结合,设计了鲁棒LOS制导律,提高了系统的鲁棒性.文献[10]设计了速度变化LOS制导律,同时,生成期望纵向速度和艏向角,提高了船舶的操纵性能.

在控制子系统中,外界环境干扰和模型不确定性会对船舶运动造成不利影响,需要在控制设计中进行处理.文献[11]采用降阶扩张状态观测器对环境干扰进行估计,然后基于反步法设计路径跟踪控制器.此外,神经网络具有万能逼近特性,常被用来处理船舶的不确定和环境干扰问题.文献[12]应用回声状态神经网络来估计模型不确定性.文献[13]运用径向基神经网络(radial basis function neural network, RBFNN)补偿系统的不确定性和环境干扰.文献[14]设计了一种自适应神经网络控制器,应用RBFNN逼近由模型不确定、环境干扰和输入饱和建模误差组成的合成干扰.然而,上述方法需要在线调整神经网络权值矩阵,导致学习时间变长.因此,文献[15]结合最小学习参数和神经网络来补偿系统的未知动态.此外,上述文献仅能证明在时间趋于无穷时系统是稳定的.为了提高系统的收敛速度,文献[16]基于反步法设计了自适应模糊有限时间控制器,并证明了系统是实际有限时间稳定的.文献[17]针对水面船轨迹跟踪问题设计了有限时间反步控制器,并运用有限时间干扰观测器估计外界干扰.然而,上述文献都未考虑输入死区问题.大多数物理系统都存在输入死区特性,特别是在船舶的执行机构中.在控制器设计过程中忽视死区问题会降低跟踪性能,甚至导致系统不稳定^[18].

受上述文献启发,本文研究具有输入死区特性的欠驱动水面船路径跟踪控制问题.在制导子系统中设计有限时间视线制导律生成期望信号,继而在控制子系统运用反步法设计有限时间控制器.结合神经网络技术和最小学习参数算法以及自适应技术处理系统的不确定项、环境干扰与死区非线性效果.本文的主要贡献如下:

1) 提出了一种有限时间视线制导律,能够生成纵向速度和艏向角期望信号,提高了跟踪性能和收敛速度;

2) 设计了自适应有限时间路径跟踪控制器,对输入死区进行补偿,证明了整个系统是实际有限时间稳定的;

3) 结合神经网络技术和最小学习参数算法对模型不确定性进行逼近,与传统的神经网络技术相比,设计参数显著减少,更容易应用于工程实际.并运用自适应技术补偿由环境干扰,逼近误差和死区非线性组成的合成干扰.

2 预备知识与问题描述

2.1 神经网络最小学习参数法

对于定义在紧集 Ω_x 上的未知连续函数 $f(\mathbf{x}) : \mathbb{R}^n \rightarrow \mathbb{R}$,其可以被RBFNN逼近^[19],即

$$f(\mathbf{x}) = \mathbf{W}^T \mathbf{h}(\mathbf{x}) + \chi, \quad (1)$$

式中: $\mathbf{x} \in \Omega_x$ 表示RBFNN的输入向量; χ 为估计误差,且 $|\chi| \leq \chi^*$, χ^* 为正常数; $\mathbf{W} = [w_1 \ w_2 \ \cdots \ w_m]^T \in \mathbb{R}^m$ 是RBFNN的最优权值,有 $\|\mathbf{W}\| \leq W^*$, W^* 为正常数, m 表示隐含层神经元的个数; $\mathbf{h}(\mathbf{x}) = [h_1(\mathbf{x}) \ h_2(\mathbf{x}) \ \cdots \ h_m(\mathbf{x})]^T$ 为RBFNN的基函数,一般为高斯函数,即

$$h_i(\mathbf{x}) = \exp\left(-\frac{\|\mathbf{x} - \mathbf{c}_i\|^2}{2b_i^2}\right), \quad i = 1, 2, \dots, m, \quad (2)$$

式中 \mathbf{c}_i 和 b_i 分别表示第 i 个高斯函数的中心向量和宽度.

然而,在实际应用中,最优权值 \mathbf{W} 是未知的,需要对其进行估计,这增加了控制器的计算负担,导致学习时间变长.因此,为了减少学习时间,提出了神经网络最小学习参数方法.定义正常数 $\varphi = \|\mathbf{W}\|^2$,通过对 φ 进行估计可以实现最小学习参数的自适应估计.定义 $\hat{\varphi}$ 是 φ 的估计值, $\tilde{\varphi} = \hat{\varphi} - \varphi$ 是估计误差.

2.2 定义与引理

引理 1^[20] 对于系统 $\dot{x} = f(x)$,若存在正的连续可微函数 $V(x)$ 、正实数 $g_1, g_2, 0 < a_1 < 1$ 和 $g_3 > 0$ 使得

$$\dot{V}(x) \leq -g_1 V(x) - g_2 V^{a_1}(x) + g_3, \quad (3)$$

那么这个系统是实际有限时间稳定的,对于常数 $0 < \mu < g_1$,有 $V(x) \leq \frac{g_3}{g_1 - \mu}$,其调节时间满足

$$T \leq \frac{1}{\mu(1 - a_1)} \ln\left(\frac{\mu V^{1-a_1}(0) + g_2}{g_2}\right), \quad (4)$$

式中 $V(0)$ 为 $V(x)$ 的初始值.

引理 2^[21] 对任意实数 $x_i, i = 1, \dots, n$,以及 $0 < b < 1$,有以下不等式成立:

$$(|x_1| + \cdots + |x_n|)^b \leq |x_1|^b + \cdots + |x_n|^b. \quad (5)$$

引理 3^[22] 对任意正常数 ϵ 和 $x \in \mathbb{R}$,有

$$0 \leq |x| - x \tanh \frac{x}{\epsilon} \leq \kappa \epsilon, \quad (6)$$

式中 $\kappa = 0.2785$.

2.3 船舶数学模型

欠驱动水面船在水平面的三自由度数学模型可描述为^[23]

$$\begin{cases} \dot{x} = u \cos \psi - v \sin \psi, \\ \dot{y} = u \sin \psi + v \cos \psi, \\ \dot{\psi} = r, \end{cases} \quad (7)$$

$$\begin{cases} m_{11}\dot{u} = m_{22}vr - d_{11}u + \delta_1 + \tau_1, \\ m_{22}\dot{v} = -m_{11}ur - d_{22}v + \delta_2, \\ m_{33}\dot{r} = (m_{11} - m_{22})uv - d_{33}r + \delta_3 + \tau_2, \end{cases} \quad (8)$$

式中: x, y, ψ 分别表示船舶在北东坐标下的位置和艏向角; u, v, r 分别表示船舶在船体坐标系下的线速度和角速度; $m_{ii}, i = 1, 2, 3$ 为船舶的惯性参数; $d_{ii}, i = 1, 2, 3$ 为船舶的水动力阻尼系数; $\delta_1, \delta_2, \delta_3$ 表示时变海洋环境; τ_1 和 τ_2 为船舶控制输入。

由于船舶执行机构具有死区非线性, 控制输入可表示为^[24]

$$\tau_i = DZ(\tau_{ci}) = \begin{cases} \tau_{ci} - b_{ri}, & \tau_{ci} \geq b_{ri}, \\ 0, & b_{li} \leq \tau_{ci} < b_{ri}, \\ \tau_{ci} - b_{li}, & \tau_{ci} < b_{li}, \end{cases} \quad (9)$$

式中: $i = 1, 2$; τ_{ci} 为控制输入指令; b_{li}, b_{ri} 为执行机构死区的折点。

控制输入可重写为

$$\tau_i = \tau_{ci} + \rho_i, \quad i = 1, 2, \quad (10)$$

式中

$$\rho_i = \begin{cases} -b_{ri}, & \tau_{ci} \geq b_{ri}, \\ -\tau_{ci}, & b_{li} \leq \tau_{ci} < b_{ri}, \\ -b_{li}, & \tau_{ci} < b_{li}, \end{cases} \quad i = 1, 2, \quad (11)$$

于是, 有 $|\rho_i| \leq \bar{\rho}_i = \max\{b_{ri}, -b_{li}\}, i = 1, 2$; $\bar{\rho}_i, i = 1, 2$ 为未知正常数。

欠驱动水面船的动力学模型可以写为

$$\begin{cases} m_{11}\dot{u} = m_{22}vr - d_{11}u + \delta_1 + \rho_1 + \tau_{c1}, \\ m_{22}\dot{v} = -m_{11}ur - d_{22}v + \delta_2, \\ m_{33}\dot{r} = (m_{11} - m_{22})uv - d_{33}r + \delta_3 + \rho_2 + \tau_{c2}. \end{cases} \quad (12)$$

2.4 路径跟踪误差动态

如图1所示, 船舶跟踪一条参数化路径, 在路径上选择一参考点 $(x_p(\theta), y_p(\theta))$ 定义 Serret-Frenet(SF) 坐标系, θ 为路径参数, 纵轴 X_p 沿该点在路径上的切线方向, 横轴 Y_p 沿该点的法线方向. 东北坐标系的纵轴与 X_p 之间的夹角为

$$\gamma_p = \arctan \frac{y'_p(\theta)}{x'_p(\theta)}, \quad (13)$$

式中: $x'_p(\theta) = \frac{\partial x_p}{\partial \theta}, y'_p(\theta) = \frac{\partial y_p}{\partial \theta}$.

在 SF 坐标系中, 船舶位置 (x, y) 与参考点 (x_p, y_p) 的跟踪误差为

$$\begin{bmatrix} x_e \\ y_e \end{bmatrix} = \begin{bmatrix} \cos \gamma_p & -\sin \gamma_p \\ \sin \gamma_p & \cos \gamma_p \end{bmatrix}^T \begin{bmatrix} x - x_p \\ y - y_p \end{bmatrix}, \quad (14)$$

式中: x_e 是前向跟踪误差, y_e 为横向跟踪误差。

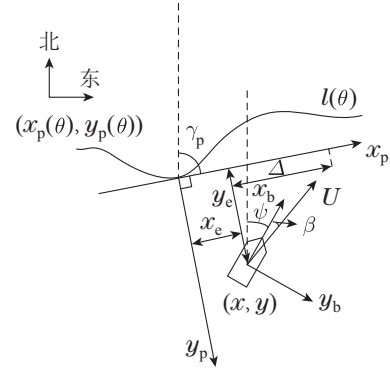


图1 路径跟踪几何图示

Fig. 1 The geometrical illustration of path following

对跟踪误差求导, 得到

$$\begin{cases} \dot{x}_e = U \cos(\psi - \gamma_p + \beta) + \dot{\gamma}_p y_e - u_x, \\ \dot{y}_e = U \sin(\psi - \gamma_p + \beta) - \dot{\gamma}_p x_e, \end{cases} \quad (15)$$

式中: $U = \sqrt{u^2 + v^2}$ 是欠驱动水面船的合速度, $\beta = \arctan \frac{v}{u}$ 为侧滑角, $u_x = \dot{\theta} \sqrt{x'_p{}^2(\theta) + y'_p{}^2(\theta)}$ 为期望路径上虚拟参考点的速度。

为了避免侧滑角 β 在 u, v 同时为 0 时存在奇点的情况, 定义期望侧滑角 $\beta_d = \arctan \frac{v}{u_d}$, u_d 为下文设计的期望纵向速度. 跟踪误差动态可写成

$$\begin{cases} \dot{x}_e = U_d \cos(\psi + \beta_d - \gamma_p) + \dot{\gamma}_p y_e - u_x + u_e \cos(\psi - \gamma_p), \\ \dot{y}_e = U_d \sin(\psi + \beta_d - \gamma_p) - \dot{\gamma}_p x_e + u_e \sin(\psi - \gamma_p) + U \omega \psi_e, \end{cases} \quad (16)$$

式中: $U_d = \sqrt{u_d^2 + v^2}, u_e = u - u_d, \psi_e = \psi - \psi_d, \psi_d$ 为期望艏向角, 且 $\omega = \frac{\cos \psi_e - 1}{\psi_e} \sin(\psi_d + \beta_d - \gamma_p) + \frac{\sin \psi_e}{\psi_e} \cos(\psi_d + \beta_d - \gamma_p)$.

由于 $|\frac{\cos \psi_e - 1}{\psi_e}| < 0.73, |\frac{\sin \psi_e}{\psi_e}| \leq 1$, 可知 ω 是有界的, 即存在一正常数 d_1 , 有 $|\omega| \leq d_1$.

为了下文的控制方案设计, 现提出以下假设:

假设 1 欠驱动水面船的惯性参数和水动力阻尼系数是未知的;

假设 2 环境干扰 $\delta_i, i = 1, 2, 3$ 是有界的, 即

$|\delta_i| \leq \bar{\delta}_i, \bar{\delta}_i, i = 1, 2, 3$ 为未知正常数.

注1 在实际工程中, 欠驱动水面船的惯性参数和水动力阻尼系数随着船舶工况而变化, 且由于辨识技术或成本原因而难以精确获得, 因此, 本文假设惯性参数和水动力阻尼系数未知是合理的. 船舶受到的环境干扰能量是有限的, 因此, 假设2是合理的.

本文的控制目标: 对于存在输入死区、模型不确定和未知环境干扰的欠驱动水面船, 设计有限时间制导律和控制律使得船舶能够跟踪一条期望路径.

3 制导律设计

为了跟踪期望路径以及镇定前向和横向跟踪误差, 设计有限时间制导律如下:

$$u_x = k_1 x_e + k_2 \text{sig}^a(x_e) + U_d \cos(\psi + \beta_d - \gamma_p), \quad (17)$$

$$u_d = k_3 \sqrt{(y_e + \text{sig}^a(y_e))^2 + \Delta^2}, \quad (18)$$

$$\psi_d = \gamma_p - \beta_d - \arctan \frac{y_e + \text{sig}^a(y_e)}{\Delta}, \quad (19)$$

式中: k_1, k_2, k_3 为设计的正常数, Δ 为前向距离. $\text{sig}^a(\cdot) = |\cdot|^a \text{sign}(\cdot), 0 < a < 1$.

注2 与文献[5-9]中的LOS制导律相比, 本文设计的制导律能够同时生成期望纵向速度和艏向角, 提高了船舶操纵性能. 与文献[10]中的制导律相比, 在制导律设计中加入 $\text{sig}^a(\cdot)$ 项, 提高了制导子系统的收敛速度. 此外, 由式(18)可知 $u_d > 0$, 避免了侧滑角的奇异问题.

将制导律(17)-(19)代入式(16), 可得

$$\begin{cases} \dot{x}_e = -k_1 x_e - k_2 \text{sig}^a(x_e) + \dot{\gamma}_p y_e + \\ \quad u_e \cos(\psi - \gamma_p), \\ \dot{y}_e = -\frac{k_3}{\cos \beta_d} y_e - \frac{k_3}{\cos \beta_d} \text{sig}^a(y_e) - \\ \quad \dot{\gamma}_p x_e + u_e \sin(\psi_d - \gamma_p) + U \omega \psi_e. \end{cases} \quad (20)$$

构造李雅普诺夫函数如下:

$$V_1 = \frac{1}{2} x_e^2 + \frac{1}{2} y_e^2. \quad (21)$$

对 V_1 求导, 得

$$\begin{aligned} \dot{V}_1 &= x_e \dot{x}_e + y_e \dot{y}_e = \\ & -k_1 x_e^2 - k_2 x_e \text{sig}^a(x_e) - \frac{k_3}{\cos \beta_d} y_e^2 - \\ & \frac{k_3}{\cos \beta_d} y_e \text{sig}^a(y_e) + x_e u_e \cos(\psi - \gamma_p) + \\ & y_e u_e \sin(\psi_d - \gamma_p) + U \omega y_e \psi_e \leq \\ & -k_1 x_e^2 - k_3 y_e^2 - k_2 |x_e|^{1+a} - \\ & k_3 |y_e|^{1+a} + x_e u_e \cos(\psi - \gamma_p) + \\ & y_e u_e \sin(\psi_d - \gamma_p) + U \omega y_e \psi_e. \end{aligned} \quad (22)$$

4 控制律设计

本节将结合反步法, 最小学习参数法以及自适应技术分别设计有限时间纵向和艏向控制器.

4.1 纵向速度控制器

对纵向速度误差 u_e 求导, 根据式(12)可得

$$\begin{aligned} m_{11} \dot{u}_e &= m_{22} v r - d_{11} u + \delta_1 + \rho_1 + \\ & \tau_{c1} - m_{11} \dot{u}_d = \\ & f_1 + \delta_1 + \rho_1 + \tau_{c1}, \end{aligned} \quad (23)$$

式中 $f_1 = m_{22} v r - d_{11} u - m_{11} \dot{u}_d$.

选取李雅普诺夫函数如下:

$$V_2 = \frac{m_{11}}{2} u_e^2, \quad (24)$$

对 V_2 求导得

$$\begin{aligned} \dot{V}_2 &= m_{11} u_e \dot{u}_e = \\ & u_e (f_1 + \delta_1 + \rho_1 + \tau_{c1}). \end{aligned} \quad (25)$$

由于 f_1 是未知的, 因此, 运用RBFNN对其进行估计, 有

$$f_1 = \mathbf{W}_1^T \mathbf{h}(\mathbf{x}_1) + \chi_1, \quad (26)$$

式中: \mathbf{W}_1 为最优权值; $\mathbf{x}_1 = [u \ v \ r \ \dot{u}_d]$; χ_1 为估计误差, 有 $|\chi_1| \leq \chi_1^*, \chi_1^*$ 为正常数.

此外, 为了补偿由环境干扰, 神经网络逼近误差和死区非线性组成的合成干扰, 定义纵向合成干扰的上界为 $D_1 = \bar{\delta}_1 + \bar{\rho}_1 + \chi_1^*, \hat{D}_1$ 为其估计值, 估计误差为 $\tilde{D}_1 = \hat{D}_1 - D_1$.

根据杨氏不等式可得

$$u_e \mathbf{W}_1^T \mathbf{h}(\mathbf{x}_1) \leq \frac{1}{2} u_e^2 \varphi_1 \mathbf{h}^T(\mathbf{x}_1) \mathbf{h}(\mathbf{x}_1) + \frac{1}{2}, \quad (27)$$

式中 $\varphi_1 = \|\mathbf{W}_1\|^2$.

设计纵向速度控制律如下:

$$\begin{aligned} \tau_{c1} &= -k_u u_e - k_{u1} \text{sig}^a(u_e) - \\ & \frac{1}{2} u_e \hat{\varphi}_1 \mathbf{h}^T(\mathbf{x}_1) \mathbf{h}(\mathbf{x}_1) - \tanh \frac{u_e}{\epsilon_1} \hat{D}_1, \end{aligned} \quad (28)$$

式中: k_u, k_{u1}, ϵ_1 是设计的正常数, $0 < a < 1, \hat{\varphi}_1$ 为 φ_1 的估计值.

设计自适应律为

$$\dot{\hat{\varphi}}_1 = \frac{1}{2} \gamma_{u1} u_e^2 \mathbf{h}^T(\mathbf{x}_1) \mathbf{h}(\mathbf{x}_1) - \gamma_{u1} \lambda_1 (\hat{\varphi}_1 - p_1), \quad (29)$$

$$\dot{\hat{D}}_1 = \gamma_{u2} u_e \tanh \frac{u_e}{\epsilon_1} - \gamma_{u2} \lambda_2 (\hat{D}_1 - p_2), \quad (30)$$

式中 $\gamma_{u1}, \gamma_{u2}, \lambda_1, \lambda_2, p_1, p_2$ 为设计的正常数.

构造李雅普诺夫函数如下:

$$V_{2a} = \frac{m_{11}}{2} u_e^2 + \frac{1}{2\gamma_{u1}} \tilde{\varphi}_1^2 + \frac{1}{2\gamma_{u2}} \tilde{D}_1^2, \quad (31)$$

式中 $\tilde{\varphi}_1 = \hat{\varphi}_1 - \varphi_1$.

对 V_{2a} 求导得

$$\begin{aligned} \dot{V}_{2a} = & m_{11}u_e\dot{u}_e + \frac{1}{\gamma_{u1}}\tilde{\varphi}_1\dot{\hat{\varphi}}_1 + \frac{1}{\gamma_{u2}}\tilde{D}_1\dot{\hat{D}}_1 = \\ & u_e(\mathbf{W}_1^T\mathbf{h}(\mathbf{x}_1) + \chi_1 + \delta_1 + \rho_1 + \tau_{c1}) + \\ & \frac{1}{2}u_e^2\tilde{\varphi}_1\mathbf{h}^T(\mathbf{x}_1)\mathbf{h}(\mathbf{x}_1) - \lambda_1\tilde{\varphi}_1(\hat{\varphi}_1 - p_1) + \\ & u_e\tilde{D}_1 \tanh\frac{u_e}{\epsilon_1} - \lambda_2\tilde{D}_1(\hat{D}_1 - p_2) \leq \\ & -k_u u_e^2 - k_{u1}|u_e|^{1+a} - \lambda_1\tilde{\varphi}_1(\hat{\varphi}_1 - p_1) - \\ & \lambda_2\tilde{D}_1(\hat{D}_1 - p_2) + D_1\epsilon_1\kappa + \frac{1}{2}. \end{aligned} \quad (32)$$

4.2 艏向控制器

第1步 对艏向角跟踪误差 ψ_e 求导得

$$\dot{\psi}_e = r - \dot{\psi}_d. \quad (33)$$

设计虚拟艏向控制律

$$\alpha_{r0} = -k_\psi\psi_e - k_{\psi1}\text{sig}^a(\psi_e) + \dot{\psi}_d, \quad (34)$$

式中: $k_\psi, k_{\psi1}$ 为设计的正常数, $0 < a < 1$.

让 α_{r0} 通过二阶跟踪微分器

$$\begin{cases} \dot{\alpha}_r = p, \\ \dot{p} = -l_1^2(l_2(\alpha_r - \alpha_{r0}) + \frac{l_3 p}{l_1}), \end{cases} \quad (35)$$

式中: l_1, l_2, l_3 为设计参数, $p = \dot{\alpha}_r$ 为跟踪微分器的状态. 根据文献[25]可知,当 $l_1 \rightarrow +\infty$ 时,跟踪误差的估计误差趋于零. 这说明 $y_1 = \alpha_r - \alpha_{r0}$ 是有界的,即存在一正常数 d_2 ,有 $|y_1| \leq d_2$.

第2步 定义艏向角速度跟踪误差为

$$r_e = r - \alpha_r, \quad (36)$$

对其求导得

$$\begin{aligned} m_{33}\dot{r}_e = & (m_{11} - m_{22})uv - d_{33}r + \delta_3 + \rho_2 + \\ & \tau_{c2} - m_{33}\dot{\alpha}_r = \\ & f_2 + \delta_3 + \rho_2 + \tau_{c2}, \end{aligned} \quad (37)$$

式中 $f_2 = (m_{11} - m_{22})uv - d_{33}r - m_{33}\dot{\alpha}_r$.

选取李雅普诺夫函数如下:

$$V_3 = \frac{1}{2}\psi_e^2 + \frac{m_{33}}{2}r_e^2, \quad (38)$$

对 V_3 求导得

$$\begin{aligned} \dot{V}_3 = & \psi_e\dot{\psi}_e + m_{33}r_e\dot{r}_e = \\ & \psi_e\dot{\psi}_e + r_e(f_2 + \delta_3 + \rho_2 + \tau_{c2}). \end{aligned} \quad (39)$$

由于 f_2 是未知的,因此运用RBFNN对其进行估计,得

$$f_2 = \mathbf{W}_2^T\mathbf{h}(\mathbf{x}_2) + \chi_2, \quad (40)$$

式中: \mathbf{W}_2 为最优权值; $\mathbf{x}_2 = [u \ v \ r \ \dot{r}_d]$; χ_2 为估计误差,有 $|\chi_2| \leq \chi_2^*$, χ_2^* 为正常数.

定义艏向合成干扰的上界为 $D_2 = \bar{\delta}_3 + \bar{\rho}_2 + \chi_2^*$,

\hat{D}_2 为其估计值,估计误差为 $\tilde{D}_2 = \hat{D}_2 - D_2$.

根据杨氏不等式可得

$$r_e\mathbf{W}_2^T\mathbf{h}(\mathbf{x}_2) \leq \frac{1}{2}r_e^2\varphi_2\mathbf{h}^T(\mathbf{x}_2)\mathbf{h}(\mathbf{x}_2) + \frac{1}{2}, \quad (41)$$

式中 $\varphi_2 = \|\mathbf{W}_2\|^2$.

设计艏向控制律如下:

$$\begin{aligned} \tau_{c2} = & -k_r r_e - k_{r1}\text{sig}^a(r_e) - \psi_e - \\ & \frac{1}{2}r_e\hat{\varphi}_2\mathbf{h}^T(\mathbf{x}_2)\mathbf{h}(\mathbf{x}_2) - \tanh\frac{r_e}{\epsilon_2}\hat{D}_2, \end{aligned} \quad (42)$$

式中: k_r, k_{r1}, ϵ_2 是设计的正常数, $0 < a < 1$, $\hat{\varphi}_2$ 为 φ_2 的估计值.

设计自适应律为

$$\dot{\hat{\varphi}}_2 = \frac{1}{2}\gamma_{r1}r_e^2\mathbf{h}^T(\mathbf{x}_2)\mathbf{h}(\mathbf{x}_2) - \gamma_{r1}\lambda_3(\hat{\varphi}_2 - p_3), \quad (43)$$

$$\dot{\hat{D}}_2 = \gamma_{r2}r_e \tanh\frac{r_e}{\epsilon_2} - \gamma_{r2}\lambda_4(\hat{D}_2 - p_4), \quad (44)$$

式中 $\gamma_{r1}, \gamma_{r2}, \lambda_3, \lambda_4, p_3, p_4$ 为设计的正常数.

构造李雅普诺夫函数如下:

$$V_{3a} = \frac{1}{2}\psi_e^2 + \frac{m_{33}}{2}r_e^2 + \frac{1}{2\gamma_{r1}}\tilde{\varphi}_2^2 + \frac{1}{2\gamma_{r2}}\tilde{D}_2^2, \quad (45)$$

式中 $\tilde{\varphi}_2 = \hat{\varphi}_2 - \varphi_2$.

对 V_{3a} 求导得

$$\begin{aligned} \dot{V}_{3a} = & \psi_e\dot{\psi}_e + m_{33}r_e\dot{r}_e + \frac{1}{\gamma_{r1}}\tilde{\varphi}_2\dot{\hat{\varphi}}_2 + \frac{1}{\gamma_{r2}}\tilde{D}_2\dot{\hat{D}}_2 = \\ & \psi_e(r_e + y_1 + \alpha_{r0} - \dot{\psi}_d) + \\ & r_e(\mathbf{W}_2^T\mathbf{h}(\mathbf{x}_2) + \chi_2 + \delta_3 + \rho_2 + \tau_{c2}) + \\ & \frac{1}{2}r_e^2\tilde{\varphi}_1\mathbf{h}^T(\mathbf{x}_2)\mathbf{h}(\mathbf{x}_2) - \lambda_3\tilde{\varphi}_2(\hat{\varphi}_2 - p_3) + \\ & r_e\tilde{D}_2 \tanh\frac{r_e}{\epsilon_2} - \lambda_4\tilde{D}_2(\hat{D}_2 - p_4) \leq \\ & -k_\psi\psi_e^2 - k_{\psi1}|\psi_e|^{1+a} - k_r r_e^2 - k_{r1}|r_e|^{1+a} - \\ & \lambda_3\tilde{\varphi}_2(\hat{\varphi}_2 - p_3) - \lambda_4\tilde{D}_2(\hat{D}_2 - p_4) + \\ & \frac{1}{2} + \psi_e y_1 + D_2\epsilon_2\kappa. \end{aligned} \quad (46)$$

5 稳定性分析

定理1 对于欠驱动水面船数学模型(7)–(8),在满足假设1–2的条件下,由设计的制导律(17)–(19)、控制律(28)(42)和更新律(29)(30)(43)(44)组成的制导和控制能够实现本文的控制目标,且闭环系统是实际有限时间稳定的.

证 选取如下的李雅普诺夫函数:

$$\begin{aligned} V = & V_1 + V_{2a} + V_{3a} = \\ & \frac{1}{2}x_e^2 + \frac{1}{2}y_e^2 + \frac{m_{11}}{2}u_e^2 + \frac{1}{2\gamma_{u1}}\tilde{\varphi}_1^2 + \frac{1}{2\gamma_{u2}}\tilde{D}_1^2 + \\ & \frac{1}{2}\psi_e^2 + \frac{m_{33}}{2}r_e^2 + \frac{1}{2\gamma_{r1}}\tilde{\varphi}_2^2 + \frac{1}{2\gamma_{r2}}\tilde{D}_2^2. \end{aligned} \quad (47)$$

对 V 求得

$$\begin{aligned} \dot{V} \leq & -k_1 x_e^2 - k_3 y_e^2 - k_2 |x_e|^{1+a} - k_3 |y_e|^{1+a} + \\ & x_e u_e \cos(\psi - \gamma_p) + y_e u_e \sin(\psi_d - \gamma_p) + \\ & U \omega y_e \psi_e - k_u u_e^2 - k_{u1} |u_e|^{1+a} - \\ & \lambda_1 \tilde{\varphi}_1 (\hat{\varphi}_1 - p_1) - \lambda_2 \tilde{D}_1 (\hat{D}_1 - p_2) + D_1 \epsilon_1 \kappa + \\ & \frac{1}{2} - k_\psi \psi_e^2 - k_{\psi 1} |\psi_e|^{1+a} - k_r r_e^2 - k_{r1} |r_e|^{1+a} - \\ & \lambda_3 \tilde{\varphi}_2 (\hat{\varphi}_2 - p_3) - \lambda_4 \tilde{D}_2 (\hat{D}_2 - p_4) + \\ & \frac{1}{2} + \psi_e y_1 + D_2 \epsilon_2 \kappa. \end{aligned} \quad (48)$$

根据杨氏不等式, 有

$$x_e u_e \cos(\psi - \gamma_p) \leq \frac{1}{2} x_e^2 + \frac{1}{2} u_e^2, \quad (49)$$

$$y_e u_e \sin(\psi_d - \gamma_p) \leq \frac{1}{2} y_e^2 + \frac{1}{2} u_e^2, \quad (50)$$

$$U \omega y_e \psi_e \leq \frac{1}{2} y_e^2 + \frac{1}{2} U^2 d_1^2 \psi_e^2, \quad (51)$$

$$\begin{aligned} -\tilde{\varphi}_1 (\hat{\varphi}_1 - p_1) & \leq \\ -\frac{1}{2} \tilde{\varphi}_1^2 + \frac{1}{2} (\varphi_1 - p_1)^2 & = \\ -\frac{1}{4} \tilde{\varphi}_1^2 - \frac{1}{4} (\tilde{\varphi}_1 - \sqrt{|\tilde{\varphi}_1|})^2 + \\ \frac{1}{4} \tilde{\varphi}_1 - \frac{1}{2} \tilde{\varphi}_1^{\frac{3}{2}} + \frac{1}{2} (\varphi_1 - p_1)^2 & \leq \\ -\frac{1}{8} \tilde{\varphi}_1^2 - \frac{1}{2} |\tilde{\varphi}_1|^{\frac{3}{2}} + \frac{1}{2} (\varphi_1 - p_1)^2, \end{aligned} \quad (52)$$

$$\begin{aligned} -\tilde{\varphi}_2 (\hat{\varphi}_2 - p_3) & \leq \\ -\frac{1}{8} \tilde{\varphi}_2^2 - \frac{1}{2} |\tilde{\varphi}_2|^{\frac{3}{2}} + \frac{1}{2} (\varphi_2 - p_3)^2, \end{aligned} \quad (53)$$

$$\begin{aligned} -\tilde{D}_1 (\hat{D}_1 - p_2) & \leq \\ -\frac{1}{8} \tilde{D}_1^2 - \frac{1}{2} |\tilde{D}_1|^{\frac{3}{2}} + \frac{1}{2} (D_1 - p_2)^2, \end{aligned} \quad (54)$$

$$\begin{aligned} -\tilde{D}_2 (\hat{D}_2 - p_4) & \leq \\ -\frac{1}{8} \tilde{D}_2^2 - \frac{1}{2} |\tilde{D}_2|^{\frac{3}{2}} + \frac{1}{2} (D_2 - p_4)^2, \end{aligned} \quad (55)$$

$$\psi_e y_1 \leq \frac{1}{2} \psi_e^2 + \frac{1}{2} d_2^2. \quad (56)$$

将式(50)–(56)代入式(48), 可得

$$\begin{aligned} \dot{V} \leq & -k_1 x_e^2 - k_3 y_e^2 - k_2 |x_e|^{1+a} - k_3 |y_e|^{1+a} + \\ & \frac{1}{2} x_e^2 + u_e^2 + \frac{1}{2} y_e^2 + \frac{1}{2} U^2 d_1^2 \psi_e^2 + \frac{1}{2} y_e^2 - \\ & k_u u_e^2 - k_{u1} |u_e|^{1+a} - \frac{\lambda_1}{8} \tilde{\varphi}_1^2 - \frac{\lambda_1}{2} |\tilde{\varphi}_1|^{\frac{3}{2}} + \\ & \frac{\lambda_1}{2} (\varphi_1 - p_1)^2 - \frac{\lambda_2}{8} \tilde{D}_1^2 - \frac{\lambda_2}{2} |\tilde{D}_1|^{\frac{3}{2}} + \\ & \frac{\lambda_2}{2} (D_1 - p_2)^2 + D_1 \epsilon_1 \kappa + \frac{1}{2} - k_\psi \psi_e^2 - \\ & k_{\psi 1} |\psi_e|^{1+a} - k_r r_e^2 - k_{r1} |r_e|^{1+a} - \\ & \frac{\lambda_3}{8} \tilde{\varphi}_2^2 - \frac{\lambda_3}{2} |\tilde{\varphi}_2|^{\frac{3}{2}} + \frac{\lambda_3}{2} (\varphi_2 - p_3)^2 - \end{aligned}$$

$$\begin{aligned} & \frac{\lambda_4}{8} \tilde{D}_2^2 - \frac{\lambda_4}{2} |\tilde{D}_2|^{\frac{3}{2}} + \frac{\lambda_4}{2} (D_2 - p_4)^2 + \\ & D_2 \epsilon_2 \kappa + \frac{1}{2} + \frac{1}{2} \psi_e^2 + \frac{1}{2} d_2^2 \leq \\ & -(k_1 - \frac{1}{2}) x_e^2 - (k_3 - 1) y_e^2 - (k_u - 1) u_e^2 - \\ & \frac{\lambda_1}{8} \tilde{\varphi}_1^2 - \frac{\lambda_2}{8} \tilde{D}_1^2 - (k_\psi - \frac{1}{2} U^2 d_1^2 - \frac{1}{2}) \psi_e^2 - \\ & k_r r_e^2 - \frac{\lambda_3}{8} \tilde{\varphi}_2^2 - \frac{\lambda_4}{8} \tilde{D}_2^2 - k_2 |x_e|^{\frac{1+a}{2}} - \\ & k_3 |y_e|^{\frac{1+a}{2}} - k_{u1} |u_e|^{\frac{1+a}{2}} - \frac{\lambda_1}{2} |\tilde{\varphi}_1|^{\frac{3}{4}} - \\ & \frac{\lambda_2}{2} |\tilde{D}_1|^{\frac{3}{4}} - k_{\psi 1} |\psi_e|^{\frac{1+a}{2}} - k_{r1} |r_e|^{\frac{1+a}{2}} - \\ & \frac{\lambda_3}{2} |\tilde{\varphi}_2|^{\frac{3}{4}} - \frac{\lambda_4}{2} |\tilde{D}_2|^{\frac{3}{4}} + \frac{\lambda_1}{2} (\varphi_1 - p_1)^2 + \\ & \frac{\lambda_2}{2} (D_1 - p_2)^2 + \frac{\lambda_3}{2} (\varphi_2 - p_3)^2 + D_1 \epsilon_1 \kappa + \\ & \frac{\lambda_4}{2} (D_2 - p_4)^2 + \frac{1}{2} d_2^2 + D_2 \epsilon_2 \kappa + 1 \leq \\ & -K_1 V - K_2 V^g + C, \end{aligned} \quad (57)$$

式中: $K_1 = \min\{2(k_1 - \frac{1}{2}), 2(k_3 - 1), 2(k_u - 1), \frac{\lambda_1 \gamma_{u1}}{4}, \frac{\lambda_2 \gamma_{u2}}{4}, 2(k_\psi - \frac{1}{2} U^2 d_1^2 - \frac{1}{2}), 2k_r, \frac{\lambda_3 \gamma_{r1}}{4}, \frac{\lambda_4 \gamma_{r1}}{4}\}$, $K_2 = \min\{2^{\frac{1+a}{2}} k_2, 2^{\frac{1+a}{2}} k_3, 2^{\frac{1+a}{2}} k_{u1}, 2^{-\frac{1}{4}} \lambda_1 \gamma_{u1}^{\frac{3}{4}}, 2^{-\frac{1}{4}} \lambda_2 \gamma_{u2}^{\frac{3}{4}}, 2^{\frac{1+a}{2}} k_{\psi 1}, 2^{\frac{1+a}{2}} k_{r1}, 2^{-\frac{1}{4}} \lambda_3 \gamma_{r1}^{\frac{3}{4}}, 2^{-\frac{1}{4}} \lambda_4 \gamma_{r2}^{\frac{3}{4}}\}$, $g = \min\{\frac{1+a}{2}, \frac{3}{4}\}$, $C = \frac{\lambda_1}{2} (\varphi_1 - p_1)^2 + \frac{\lambda_2}{2} (D_1 - p_2)^2 + \frac{\lambda_3}{2} (\varphi_2 - p_3)^2 + \frac{\lambda_4}{2} (D_2 - p_4)^2 + \frac{1}{2} d_2^2 + D_1 \epsilon_1 \kappa + D_2 \epsilon_2 \kappa + 1$.

通过选取合适的参数, 使得 $K_1 > 0$, $K_2 > 0$, 根据引理1可知, 系统是实际有限时间稳定的. 在有限的时间 T 内, 对于 $t \geq T$ 和 $0 < \mu < K_1$, V 将收敛到区域 $V_2 \leq \frac{C}{K_1 - \mu}$, 且其调节时间 T 为

$$T = \frac{1}{\mu(1-g)} \ln\left(\frac{\mu V^{1-g}(0) + K_2}{K_2}\right), \quad (58)$$

式中 $V(0)$ 为 V 的初值. 证毕.

6 仿真研究

为验证本文设计方法的有效性, 以文献[26]的船舶模型进行仿真研究. 船舶模型参数为: $m_{11} = 25.8 \text{ kg}$, $m_{22} = 33.8 \text{ kg}$, $m_{33} = 2.76 \text{ kgm}^2$, $d_{11} = 0.93 \text{ kg/s}$, $d_{22} = 2.89 \text{ kg/s}$, $d_{33} = 0.5 \text{ kg} \cdot \text{m}^2/\text{s}$. 船舶执行机构的死区参数为: $b_{r1} = b_{r2} = 1$, $b_{11} = b_{12} = -1$. 时变环境干扰设置为: $\delta_1 = 0.7 \times \sin(0.1t) + 0.3 \sin(0.2t) + 0.4$, $\delta_2 = 0.4 \cos(0.5t) + 0.1\pi + 0.1 \sin(0.2t) + 0.1$, $\delta_3 = 0.4 \cos(0.5t) + 0.2\pi + 0.2 \sin(0.1t) + 0.2$.

跟踪的期望路径如下:

$$\begin{cases} x_p(\theta) = 5 \sin(0.2\theta) + \theta, \\ y_p(\theta) = \theta. \end{cases} \quad (59)$$

船舶初始状态设为 $[x \ y \ \psi]^T = [4 \ 0 \ \frac{\pi}{4}]^T$ 以及 $[u \ v \ r]^T = [0 \ 0 \ 0]^T$. 控制参数设置为: $k_1 = 1, k_2 = 1, k_3 = 0.2, \Delta = 1, a = 0.8, k_u = 10, k_{u1} = 1, k_\psi = 1, k_{\psi1} = 0.1, k_r = 10, k_{r1} = 1, \gamma_{u1} = 5, \lambda_1 = 0.2, p_1 = 10, \gamma_{u2} = 20, \epsilon_1 = 0.05, \lambda_2 = 0.01, p_2 = 100, \gamma_{r1} = 5, \lambda_3 = 0.2, p_3 = 10, \gamma_{r2} = 5, \epsilon_2 = 0.05, \lambda_4 = 0.01, p_4 = 100, l_1 = 10, l_2 = 1, l_3 = 1$.

为了验证本文方法的有效性,将进行2组仿真对比. 第1组,在考虑输入死区的情况下,将本文设计的有限时间视线制导律与文献[9]中的鲁棒视线制导律以及文献[10]中的纵向速度变化视线制导律进行对比;第2组,将进行死区补偿与不考虑输入死区的情况进行对比.

6.1 制导律性能验证

为了验证本文提出的有限时间视线制导律的有效性,将其与文献[9]中的鲁棒视线制导律以及文献[10]中的纵向速度变化视线制导律进行对比,本文制导律与文献[9-10]中的制导律分别定义为有限时间纵向速度和艏向角 (finite-time surge-heading LOS, FTSH-LOS)制导律、鲁棒视线(robust LOS, RLOS)制导律和纵向速度变化视线 (surge varying LOS, SVLOS) 制导律,仿真结果如图2-9所示.

由图2可知,在各个制导律下,欠驱动水面船均能到达期望路径,并沿路径航行.

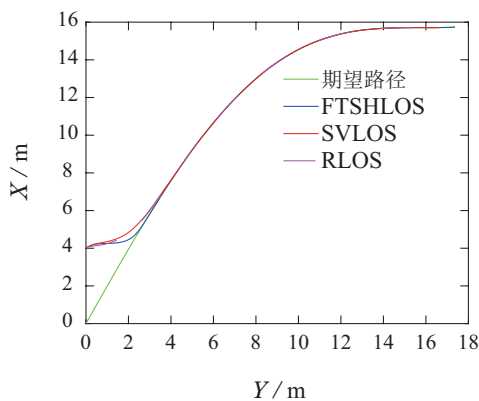


图2 不同制导律下的路径跟踪效果

Fig. 2 Path following performance under different guidance laws

从图3可以看出,基于FTSHLOS制导律的船舶跟踪误差有着更好的稳态性能,船舶能更快到达期望路径,这是因为本文设计了有限时间制导律,船舶跟踪误差收敛速度比RLOS和SVLOS快.

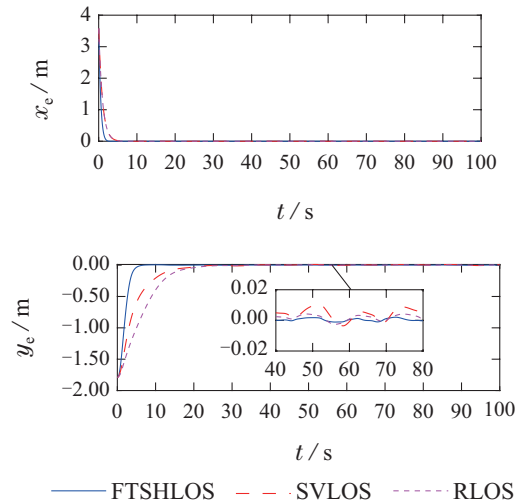


图3 不同制导律下的路径跟踪误差

Fig. 3 Path following errors under different guidance laws

图4-5分别是欠驱动水面船的艏向角和纵向速度跟踪曲线,可以看出其跟踪效果良好.

图6-7分别是纵向和艏向上神经网络权值范数平方以及合成干扰的估计值,表明这些参数总是有界的,且在输入死区存在的情况下实现稳定.

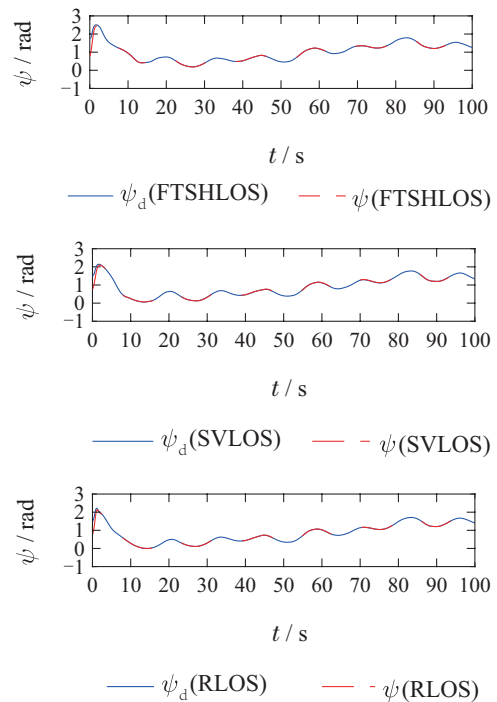
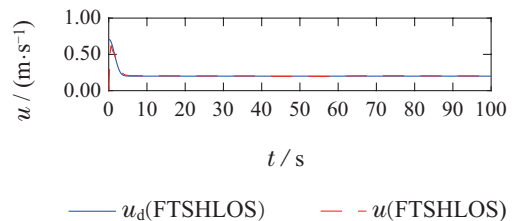


图4 不同制导律下的艏向角跟踪

Fig. 4 The heading angle tracking performance under different guidance laws



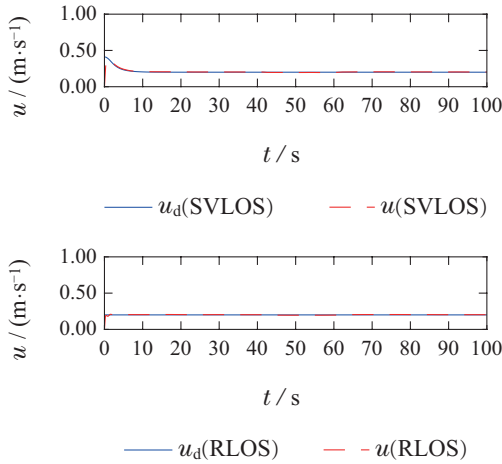


图5 不同制导律下的纵向速度跟踪

Fig. 5 The surge speed tracking performance under different guidance laws

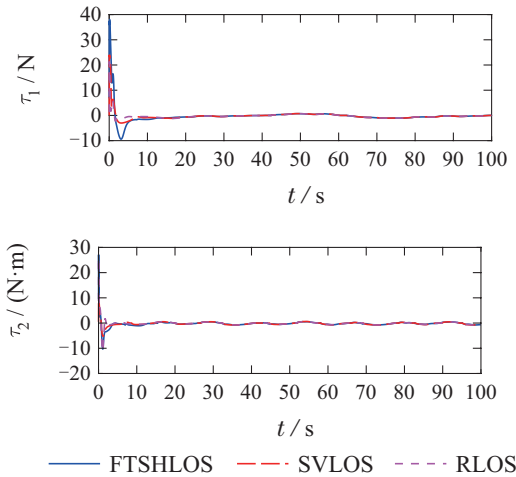


图8 不同制导律下的控制输入

Fig. 8 The control inputs under different guidance laws

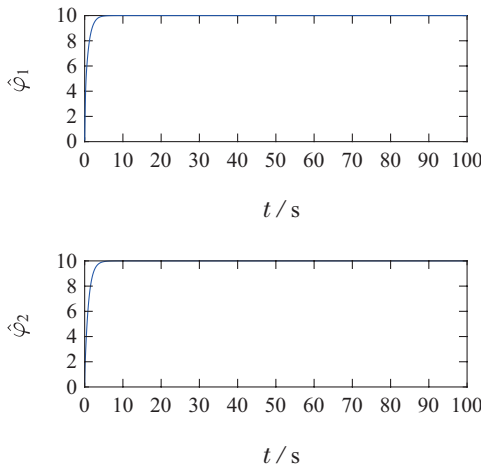


图6 φ_1 和 φ_2 的估计值

Fig. 6 The estimations of φ_1 and φ_2

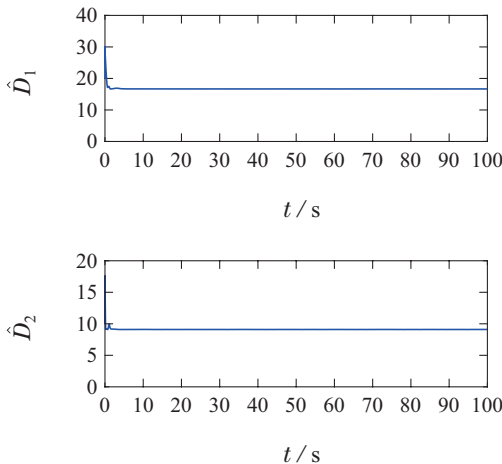


图7 D_1 和 D_2 的估计值

Fig. 7 The estimations of D_1 and D_2

图8为欠驱动水面船的实际控制输入。

基于以上结果,可以得出本文设计的有限时间制导律使得船舶在一定时间内跟踪上期望路径,且跟踪误差波动范围小。

6.2 控制器性能验证

为了验证本文设计控制器对死区非线性进行处理的有效性,将其与文献[17]中不考虑输入死区情况下设计的控制器进行对比,本文控制器与文献[17]中的控制器分别定义为考虑死区与未考虑死区。仿真结果如图9-12所示。

由图9可知,在两种控制方法下,欠驱动水面船均能跟踪期望路径。

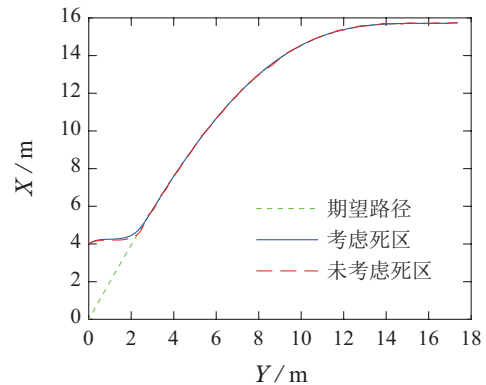


图9 不同控制器下的路径跟踪效果

Fig. 9 Path following performance under different controllers

从图10可以看出,本文控制器有着更好的稳态性能,而忽视死区导致横向跟踪误差存在波动。

图11给出了欠驱动水面船的艏向角和纵向速度误差变化曲线,明显看出死区非线性对跟踪性能造成的不利影响。在忽视输入死区的情况下,设计的控制命令没有超出死区界限,导致船舶控制输入为0,因此,纵向速度和艏向角不能及时跟踪期望值,跟踪误差波动较大。

图12是欠驱动水面船的实际控制输入,可以看出在不考虑输入死区情况下设计的控制器所得到的控制输入在一些时刻为0,这会影响船舶的路径跟踪性能,导致较大的路径跟踪误差。从仿真结果可以得出,

本文对死区非线性进行补偿所设计的控制方案更符合实际情况, 且有着更好的跟踪性能.

7 结论

本文提出了一种神经自适应有限时间路径跟踪控制方法, 解决了欠驱动水面船在输入死区约束下的路径跟踪问题. 在制导子系统中, 设计的有限时间视线制导律能够同时制导纵向速度和艏向角. 在控制器设计中, 结合径向基神经网络和最小学习参数算法以及自适应技术补偿环境干扰、模型参数不确定以及未知死区非线性, 并运用反步法设计有限时间控制器. 通过稳定性分析证明了系统是实际有限时间稳定的, 仿真结果也说明了控制方案的有效性. 然而, 本文没有考虑输出受限问题, 且船舶速度是已知的, 后续可进一步研究在速度未知情况下船舶路径跟踪输出受限问题, 提高欠驱动水面船路径跟踪性能并保障航行安全.

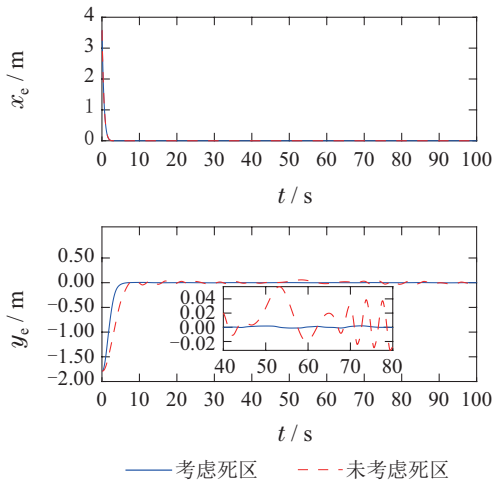


图 10 不同控制器下的路径跟踪误差

Fig. 10 Path following errors under different controllers

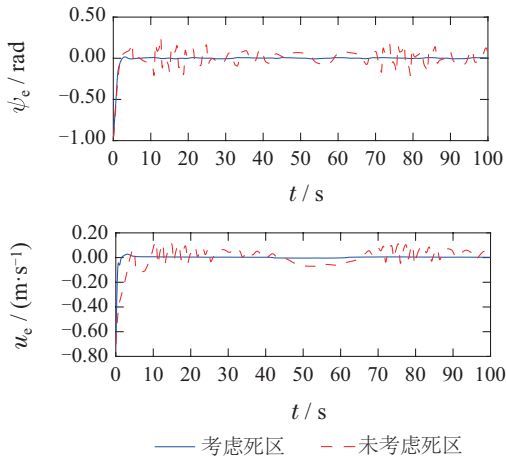


图 11 不同控制器下的艏向角和纵向速度跟踪误差

Fig. 11 Heading angle and surge velocity tracking errors under different controllers

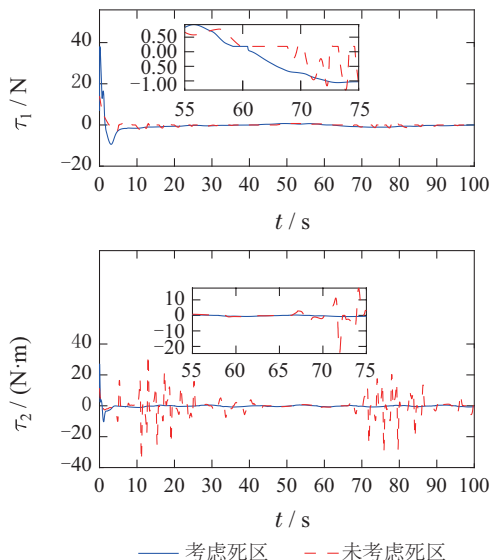


图 12 不同控制器下的控制输入

Fig. 12 The control inputs under different controllers

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作者简介:

王元慧 博士, 教授, 博士生导师, 目前研究方向为船舶运动控制、海洋机器人自主控制, E-mail: wangyuanhui@hrbeu.edu.cn;

王心玮 博士研究生, 目前研究方向为船舶路径跟踪控制、智能控制、有限时间控制, E-mail: s316040164@hrbeu.edu.cn;

邵兴超 博士, 讲师, 目前研究方向为船舶运动控制、船舶动力定位控制, E-mail: shaoxingchao@163.com;

任哲达 博士研究生, 目前研究方向为船舶协同控制, E-mail: renzheda@hrbeu.edu.cn.