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基于自适应扰动观测器的自主船舶协同路径跟踪控制

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摘要: 为实现未知环境扰动下不确定欠驱动自主船舶的协同路径跟踪控制, 本文提出了一种基于自适应扰动观测器的鲁棒控制算法. 该算法采用径向基函数神经网络(RBFNNs)逼近模型参数不确定, 并利用最小学习参数化(MLP)技术对神经网络的权重及逼近误差进行压缩, 所设计观测器不需要环境扰动上界的精确信息. 进一步, 基于代数图论对船间通信进行建模, 设计了一种分散式协同控制律, 有效地降低了通信负载. 凭借Lyapunov稳定性理论证明了闭环系统内信号的有界性, 且能通过对设计参数的调节使跟踪误差的收敛界为任意小. 最后采用数值仿真试验验证了所提出算法的有效性和优越性.

关键词: 欠驱动船舶; 径向基函数神经网络; 自适应扰动观测器; 协同路径跟踪; 分散式控制

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Adaptive disturbance observer based cooperative path-following control for autonomous surface vessels

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Abstract: This paper proposed an adaptive disturbance observer based robust control algorithm to address the cooperative path following control of underactuated autonomous vessels under unknown time-varying environmental disturbance. In the algorithm, the radial basis function neural networks (RBFNNs) are employed to approximate the model parameter uncertainty. Based on the minimal learning parameterization (MLP) technique, both the weight and the approximation error of the neural networks are compressed. The disturbance observer is constructed without the information of the upper bound of the external disturbance. Furthermore, a decentralized cooperative control algorithm is presented on the basis of the algebraic graph theory, which reduce communication load between the autonomous vessels effectively. All signals in the closed-loop system are proved bounded by Lyapunov theory, and the bound of the error signal could be small enough by tuning the design parameters appropriately. Finally, numerical simulation is conducted to demonstrate the effectiveness and superiority of the proposed algorithm.

Key words: underactuated ship; radial basis function neural networks; adaptive disturbance observer; cooperative path-following; decentralized control

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1 引言

近年来, 随着各沿海国对海洋资源及海洋空间权益的争夺日趋激烈, 自主水面船舶的控制问题逐渐成为船舶运动控制领域的研究热点之一. 相对于单自主船有限的任务处理能力, 多自主船更加适用于复杂多样的海洋环境, 且具有效率高、灵活性强、容错性好等优点. 典型的多船问题包括集群态势感知、智能自主决策、协同编队控制等. 其中, 船舶协同编队控制指的是通过设计一种合理的控制器, 使一组网络化的自主船舶能够沿着预设路径航行, 并维持期望的几何队形以完成特定任务[1].

为了实现海洋环境下多自主船舶的编队控制, 国

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内外相关学者发展了一系列较为有效的控制策略. 如: 基于行为法[2–3]、虚拟结构法[4–5]、领航者–追随者法[6–8]、基于图论法[9–10]等. 文献[11]针对含有模型参数不确定及未知环境扰动的全驱动船舶编队控制问题, 提出了一种基于势能函数的自适应控制算法, 该算法不仅可以使船舶构建期望编队, 而且能够有效避免船间碰撞. 进一步, 针对欠驱动船舶的协同路径跟踪问题, 文献[12]提出了一种分散式同步控制律, 解决了通信延迟情况下的编队控制问题. 文献[13]通过将船舶编队系统解耦成路径跟踪回路和路径参数同步回路两个环节, 引入无源性理论框架对协同路径跟踪算法进行设计, 进一步增强了系统的鲁棒性和收敛性能. 文献[14]考虑了海底飞行节点的包含控制问题, 采用参数自适应技术对模型参数不确定及外部扰动的上界进行补偿, 使得追随者能够在有限时间内收敛到领航者形成的凸包内.

上述方法[10–13]虽然在不同条件下实现了船舶编队控制, 但是其对于不确定的处理都是建立在扰动上界及其一阶导数已知的前提下, 算法的应用具有一定的局限性. 为了增强系统的鲁棒性, 文献[15]构造了一种神经网络扰动观测器, 设计了一种基于观测器的领航者–追随编队算法, 该算法具有形式简捷、计算负载小的优点. 文献[16]基于终端滑模设计了一种自适应扰动观测器, 该观测器的构造不需要扰动上界的精确信息且具有更快的收敛速度. 文献[17]针对海洋环境扰动下的欠驱动多无人船控制问题, 设计了一种分散式观测器, 显著的增强了编队系统的鲁棒性. 这些方法都有效地处理模型不确定及环境扰动问题, 进一步保证了系统在动态环境中的控制性能.

受以上研究启发, 本文针对海洋环境扰动下含有模型参数不确定的欠驱动自主船舶协同路径跟踪问题, 设计了一种基于自适应神经网络扰动观测器的鲁棒控制算法. 同时, 引入代数图论对船间通信进行建模, 提出了一种分散式的协同控制律, 实现了欠驱动自主船舶的编队控制. 与已有的研究结果相比, 本文的主要贡献有: 1) 构造了一种自适应扰动观测器, 该观测器可以有效观测海洋环境扰动且不需要扰动上界的精确信息; 2) 采用径向基函数神经网络(radial basis function neural networks, RBFNNs)对模型参数不确定进行逼近. 同时, 由于观测器和路径跟踪控制器采用同一套神经网络, 有效地降低了计算负载; 3) 利用多自主船舶的局部信息, 设计了一种分散式协同控制律, 降低了船间通信量, 实现了多自主船舶对参数化路径的跟踪.

2 预备知识与问题描述

2.1 符号定义

在本文中, $|\cdot|$表示绝对值, $\|\cdot\|$表示Euclidean范数, $\hat{(\cdot)}$表示$(\cdot)$的估计值且$\tilde{(\cdot)}=(\cdot)-\hat{(\cdot)}$. $(\cdot)^{\theta_i}=\dfrac{\partial(\cdot)}{\partial\theta_i}$为$(\cdot)$对$\theta_i$的一阶偏导数, $(\cdot)^{\theta_i^2}=\dfrac{\partial^2(\cdot)}{\partial\theta_i^2}$为$(\cdot)$对$\theta_i$的二阶偏导数.

2.2 代数图论

考虑一组含有n艘欠驱动自主水面船舶的网络化多船系统. 采用无向图$G=G(V,E)$对船间的信息交换情况进行建模, 其中$V=\{\upsilon_1,\upsilon_2,\cdots,\upsilon_n\}$表示包含有$n$个节点的有限集, E表示基本元素为$e_{i,j}=(\upsilon_i,\upsilon_j)$的边集, 边$e_{i,j}$对应编队节点之间的通信关系, 且满足$e_{i,j}\in E\Leftrightarrow e_{j,i}\in E$. 若$G$中节点$\upsilon_i$和$\upsilon_j$之间存在路径相连, 则称这两个节点是连通的. 若$G$中任意两个节点是连通的, 则该图为连通图. 若$\upsilon_i$和$\upsilon_j$处于同一条边上, 则称这两个节点为邻接. 图$G$的邻接矩阵记为$A=[a_{i,j}]\in\mathbb{R}^{n\times n}$, 若节点$\upsilon_i,\upsilon_j$是邻接的, 则$a_{i,j}=1$, 否则$a_{i,j}=0$. 在图$G$中, 与节点$\upsilon_i$相关联的边的数量称为度, 其组成的矩阵为度矩阵, 记为$D\in\mathbb{R}^{n\times n}$. 则图$G$的Laplacian矩阵记为$L=D-A$, L为对称矩阵且满足$L1_n=0$, 因此0是L对应于特征向量1的特征值.

2.3 欠驱动自主船舶模型

考虑n艘由两种独立执行器(螺旋桨、舵机)驱动的欠驱动自主船舶, 其具体配置参数详见文献[18–20]. 由于此类型的船舶只有前进和艏摇方向的运动可以被直接控制, 故船舶模型具有欠驱动特性. 定义编队系统中第i艘船舶的运动学方程为

$$\begin{cases}\dot{x}_i=u_i\cos\psi_i-v_i\sin\psi_i,\\ \dot{y}_i=u_i\sin\psi_i+v_i\cos\psi_i,\\ \dot{\psi}_i=r_i,\end{cases}\tag{1}$$

其中: (x_i,y_i), ψ_i表示惯性坐标系中第i艘自主船的位置及艏向角, u_i,v_i,r_i表示附体坐标系中自主船舶的纵向、横向及艏摇角速度, $i=1,2,3,\cdots,n$.

第i艘自主船舶的动力学模型为

$$\begin{cases}\dot{u}_i=\dfrac{f_{\mathrm{u}_i}}{m_{\mathrm{u}_i}}+\dfrac{d_{\mathrm{wu}_i}}{m_{\mathrm{u}_i}}+\dfrac{\tau_{\mathrm{u}_i}}{m_{\mathrm{u}_i}},\\ \dot{v}_i=\dfrac{f_{\mathrm{v}_i}}{m_{\mathrm{v}_i}}+\dfrac{d_{\mathrm{wv}_i}}{m_{\mathrm{v}_i}},\\ \dot{r}_i=\dfrac{f_{\mathrm{r}_i}}{m_{\mathrm{r}_i}}+\dfrac{d_{\mathrm{wr}_i}}{m_{\mathrm{r}_i}}+\dfrac{\tau_{\mathrm{r}_i}}{m_{\mathrm{r}_i}},\end{cases}\tag{2}$$

式中: $m_{\mathrm{u}_i},m_{\mathrm{v}_i},m_{\mathrm{r}_i}$为惯性系数,

$$f_{\mathrm{u}_i}=-c_{13}^ir_i-d_{11}^iu_i-g_{\mathrm{u}_i},$$
$$f_{\mathrm{v}_i}=-c_{23}^ir_i-d_{22}^iv_i-d_{23}^ir_i-g_{\mathrm{v}_i},$$
$$f_{\mathrm{r}_i}=-c_{31}^iu_i-c_{32}^iv_i-d_{32}^iv_i-d_{33}^ir_i-g_{\mathrm{r}_i}$$

为非线性函数, $c_{13}^i,c_{23}^i,c_{31}^i,c_{32}^i$为科氏力和离心力, $d_{11}^i,d_{22}^i,d_{23}^i,d_{32}^i,d_{33}^i$为水动力阻尼系数, $g_{\mathrm{u}_i},g_{\mathrm{v}_i},g_{\mathrm{r}_i}$

为未建模动态, $\tau_{\mathrm{u}_i}, \tau_{\mathrm{r}_i}$为螺旋桨及舵机在船舶纵向及艏摇方向上的控制输入量, $d_{\mathrm{wu}_i}, d_{\mathrm{wv}_i}, d_{\mathrm{wr}_i}$为由风、浪、流在船舶纵向、横向及艏摇方向上引起的环境扰动力或力矩.

假设 1 海洋环境扰动$d_{\mathrm{wu}_i}, d_{\mathrm{wv}_i}, d_{\mathrm{wr}_i}$满足

$$|d_{\mathrm{wu}_i}| \leqslant \xi_{\mathrm{u}i},\ |d_{\mathrm{wv}_i}| \leqslant \xi_{\mathrm{v}i},\ |d_{\mathrm{wr}_i}| \leqslant \xi_{\mathrm{r}i},$$

其中$\xi_{\mathrm{u}i}, \xi_{\mathrm{v}i}, \xi_{\mathrm{r}i}$为未知扰动的上界.

2.4 RBFNNs逼近

作为一种通用逼近器, 神经网络通常用于逼近未知非线性函数. 由于RBFNNs的简洁性及其强大的逼近能力, 本文采用RBFNNs对自主船舶动力学回路中的非线性不确定项进行逼近[21–22].

引理 1 对于任意给定的连续光滑函数$f(\boldsymbol{Z})$, $f(0)=0$, 利用RBFNNs可以在紧集$\Omega_{\mathrm{Z}} \subset \mathbb{R}^q$上以任意精度逼近$f(\boldsymbol{Z})$

$$f(\boldsymbol{Z}) = \boldsymbol{W}^{\mathrm{T}}\boldsymbol{S}(\boldsymbol{Z}) + \varepsilon,\ \forall \boldsymbol{Z} \in \Omega_{\mathrm{Z}}, \tag{3}$$

式中$\boldsymbol{W} = [w_1\ \ \cdots\ \ w_N]^{\mathrm{T}}$为理想参数权重, ε为有界函数的逼近误差且满足$|\varepsilon| < \varepsilon^*$, $\varepsilon^* > 0$为未知常数, $\boldsymbol{S}(\boldsymbol{Z}) = [s_1(\boldsymbol{Z})\ \ \cdots\ \ s_N(\boldsymbol{Z})]^{\mathrm{T}}$, $s_j(\boldsymbol{Z})$通常为如下形式的高斯函数:

$$s_j(\boldsymbol{Z}) = \exp(-\frac{\|\boldsymbol{Z} - \mu_j\|^2}{2h_j^2}),\ j = 1, \cdots, N, \tag{4}$$

式中$\mu_j \in \mathbb{R}^q$为接受域的中心, h_j为高斯函数的宽度.

2.5 控制目标

如图1所示, 定义$\eta_i = [x_i\ \ y_i\ \ \psi_i]^{\mathrm{T}} \in \mathbb{R}^3$为第$i$艘自主船舶在惯性坐标系中的位置变量,

$$\eta_{\mathrm{d}_i}(\theta_i) = [x_{\mathrm{d}_i}(\theta_i)\ \ y_{\mathrm{d}_i}(\theta_i)\ \ \psi_{\mathrm{d}_i}(\theta_i)]^{\mathrm{T}} \in \mathbb{R}^3$$

为预设的参数化路径, $(x_{\mathrm{d}_i}(\theta_i), y_{\mathrm{d}_i}(\theta_i))$为预设参考位置, ψ_{d_i}为预设参考航向, $\theta_i \in \mathbb{R}$为路径参数. 本文的控制目标: 针对未知海洋环境扰动下的不确定多欠驱动自主水面船舶系统, 设计一种分散式的协同路径跟踪算法, 使得各自主船舶能够跟踪其预设参考位置, 并通过合理地选择设计参数, 使得路径跟踪误差, 速度跟踪误差及路径协同误差为任意小. 即

a) $\lim\limits_{t\to\infty} \|\eta_i - \eta_{\mathrm{d}_i}\| \leqslant \delta_{1i}$;

b) $\lim\limits_{t\to\infty} |\dot{\theta}_i - \upsilon_{\mathrm{d}_i}| \leqslant \delta_{2i}$;

c) $\lim\limits_{t\to\infty} |\theta_i - \theta_j| \leqslant \delta_{3i}$;

其中υ_{d_i}为期望速度, $\delta_{1i}, \delta_{2i}, \delta_{3i} \in \mathbb{R}$为较小的正常数.

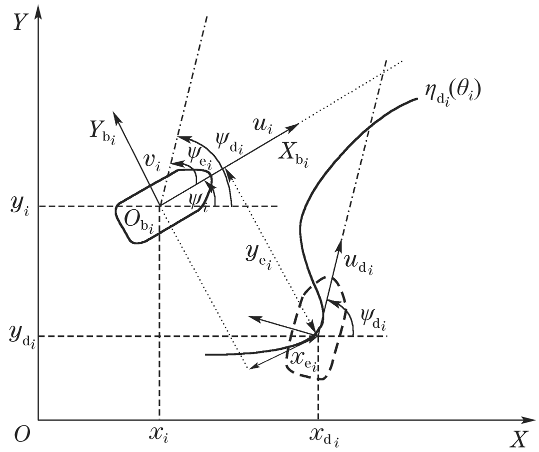


图 1 自主船舶路径跟踪原理图

Fig. 1 General framework of path following control for the autonomous vessel

3 控制器设计与稳定性分析

如图2所示, 控制器的设计分为3个部分.

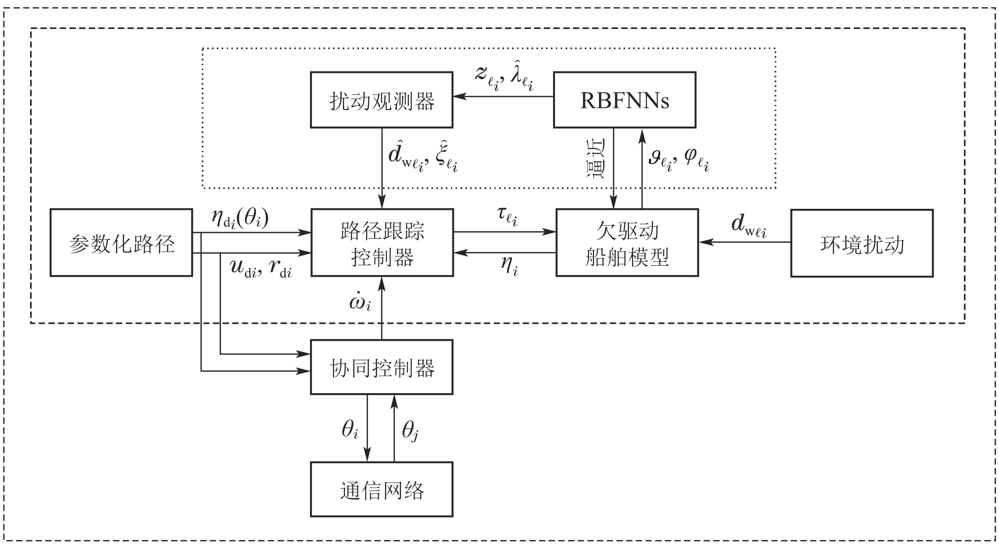


图 2 自主船舶协同路径跟踪流程图

Fig. 2 Flow chart of cooperative path following control for autonomous vessels

首先, 采用RBFNNs逼近船舶模型参数不确定, 针对未知环境扰动构造自适应扰动观测器; 其次, 针对单艘自主水面船舶设计路径跟踪控制器, 使得各自主船舶能够跟踪其对应的预设参数化路径; 最后, 基于代数图论对船间通信进行建模, 设计路径参数协同控制器, 使得多自主船舶能够以期望的几何队形编队航行.

3.1 自适应扰动观测器设计

为了增强船舶编队系统的鲁棒性, 采用RBFNNs和最小学习参数化(minimal learning parameterization, MLP)技术设计了一种形式简捷的自适应扰动观测器. 相对于传统的扰动观测器, 该观测器不需要船舶模型参数及环境扰动上界的精确信息, 更加易于算法在海洋工程领域的推广.

由引理1, 采用RBFNNs对第i艘自主船舶动力学模型中的非线性项f_{ℓ_i}, $\ell_i=u_i,v_i,r_i$进行逼近

$$f_{\ell_i}=\boldsymbol{A}_{\ell_i}^{\mathrm{T}}\boldsymbol{S}_{\ell_i}(\boldsymbol{v})+\varepsilon_{\ell_i},\tag{5}$$

则

$$\|f_{\ell_i}\|_2=\|\boldsymbol{A}_{\ell_i}^{\mathrm{T}}\boldsymbol{S}_{\ell_i}(\boldsymbol{v})+\varepsilon_{\ell_i}\|_2\leqslant\vartheta_{\ell_i}\varphi_{\ell_i},\tag{6}$$

式中: $\vartheta_{\ell_i}=\max\{\|\boldsymbol{A}_{\ell_i}\|,\varepsilon_{\ell_i}\},\varphi_{\ell_i}=1+\|\boldsymbol{S}_{\ell_i}\|,\ell_i=u_i,v_i,r_i$.

构造如下形式自适应观测器:

$$\hat{d}_{\mathrm{w}\ell_i}=k_{\mathrm{d}\ell_i}z_{\ell_i}+\hat{\xi}_{\ell_i}\frac{z_{\ell_i}}{\|z_{\ell_i}\|}.\tag{7}$$

设计自适应律

$$\begin{cases}\dot{\hat{\lambda}}_{\ell_i}=\Gamma_{1\ell_i}(z_{\ell_i}\varPhi_{\ell_i}-\sigma_{1\ell_i}(\hat{\lambda}_{\ell_i}-\hat{\lambda}_{\ell_i}(0))),\\ \dot{\hat{\xi}}_{\ell_i}=\Gamma_{2\ell_i}(\|z_{\ell_i}\|-\sigma_{2\ell_i}(\hat{\xi}_{\ell_i}-\hat{\xi}_{\ell_i}(0))).\end{cases}\tag{8}$$

式(7)–(8)中: $k_{\mathrm{d}\ell_i},\Gamma_{1\ell_i},\Gamma_{2\ell_i},\sigma_{1\ell_i},\sigma_{2\ell_i}$均为大于零的设计参数; $\hat{d}_{\mathrm{w}\ell_i}$为$d_{\mathrm{w}\ell_i}$的估计值; $z_{\ell_i}=m_{\ell_i}\ell_i-m_{\ell_i}\hat{\ell}_i$为辅助状态; $\lambda_{\ell_i}=\vartheta_{\ell_i}^2$, $\varPhi_{\ell_i}=\dfrac{\varphi_i^2}{4b_{\ell_i}}$, b_{ℓ_i}为正常数.

根据式(2), 第i艘欠驱动自主船舶的动力学模型可表示为如下形式:

$$m_{\ell_i}\dot{\ell}_i=f_{\ell_i}+\tau_{\ell_i}+d_{\mathrm{w}\ell_i},\ \ell_i=u_i,v_i,r_i.\tag{9}$$

定义

$$m_{\ell_i}\dot{\hat{\ell}}_{\ell_i}=k_{\mathrm{d}\ell_i}z_{\ell_i}+\hat{\lambda}_{\ell_i}\varPhi_{\ell_i}+\hat{\xi}_{\ell_i}\frac{z_{\ell_i}}{\|z_{\ell_i}\|}+\tau_{\ell_i}.\tag{10}$$

根据式(9)–(10), 由杨氏不等式得

$$\begin{aligned}&z_{\ell_i}\dot{z}_{\ell_i}=\\&z_{\ell_i}(m_{\ell_i}\dot{\ell}_i-m_{\ell_i}\dot{\hat{\ell}}_i)=\\&z_{\ell_i}(f_{\ell_i}+d_{\mathrm{w}\ell_i}-k_{d\ell_i}z_{\ell_i}-\hat{\lambda}_{\ell_i}\varPhi_{\ell_i}-\hat{\xi}_{\ell_i}\frac{z_{\ell_i}}{\|z_{\ell_i}\|})\leqslant\\&-k_{\mathrm{d}\ell_i}z_{\ell_i}^2+\|f_{\ell_i}\|z_{\ell_i}+\|d_{\mathrm{w}\ell_i}\|\|z_{\ell_i}\|-\\&\hat{\lambda}_{\ell_i}\varPhi_{\ell_i}z_{\ell_i}-\hat{\xi}_{\ell_i}\frac{z_{\ell_i}^2}{\|z_{\ell_i}\|}\leqslant\\&-k_{\mathrm{d}\ell_i}z_{\ell_i}^2+\vartheta_{\ell_i}\varphi_{\ell_i}z_{\ell_i}+\xi_{\ell_i}\|z_{\ell_i}\|-\\&\hat{\lambda}_{\ell_i}\varPhi_{\ell_i}z_{\ell_i}-\hat{\xi}_{\ell_i}\frac{z_{\ell_i}}{\|z_{\ell_i}\|}\leqslant\\&-k_{\mathrm{d}\ell_i}z_{\ell_i}^2+(\frac{\vartheta_{\ell_i}^2\varphi_{\ell_i}^2}{4b_{\ell_i}}+b_{\ell_i})z_{\ell_i}+\xi_{\ell_i}\|z_{\ell_i}\|-\\&\hat{\lambda}_{\ell_i}\varPhi_{\ell_i}z_{\ell_i}-\hat{\xi}_{\ell_i}\frac{z_{\ell_i}}{\|z_{\ell_i}\|}\leqslant\\&-k_{\mathrm{d}\ell_i}z_{\ell_i}^2+(\lambda_{\ell_i}-\hat{\lambda}_{\ell_i})\varPhi_{\ell_i}z_{\ell_i}+\\&z_{\ell_i}b_{\ell_i}+\tilde{\xi}_{\ell_i}\frac{z_{\ell_i}^2}{\|z_{\ell_i}\|}=\\&-k_{\mathrm{d}\ell_i}z_{\ell_i}^2+z_{\ell_i}\tilde{\lambda}_{\ell_i}\varPhi_{\ell_i}+z_{\ell_i}b_{\ell_i}+\tilde{\xi}_{\ell_i}\|z_{\ell_i}\|.\end{aligned}\tag{11}$$

定义如下Lyapunov函数:

$$V_{\mathrm{d}_i}=\sum_{\ell_i=u_i,r_i}(\frac{1}{2}z_{\ell_i}^2+\frac{1}{2\Gamma_{1\ell_i}}\tilde{\lambda}_{\ell_i}^2+\frac{1}{2\Gamma_{2\ell_i}}\tilde{\xi}_{\ell_i}^2).\tag{12}$$

根据式(8)(11), 沿着时间t对式(12)求导得

$$\begin{aligned}&\dot{V}_{\mathrm{d}_i}\leqslant\\&\sum_{\ell_i=u_i,r_i}(z_{\ell_i}\dot{z}_{\ell_i}-\Gamma_{\ell_i}^{-1}\tilde{\lambda}_{1\ell_i}\dot{\hat{\lambda}}_{\ell_i}-\Gamma_{2\ell_i}^{-1}\tilde{\xi}_{\ell_i}\dot{\hat{\xi}}_{\ell_i})=\\&\sum_{\ell_i=u_i,r_i}(-k_{\mathrm{d}\ell_i}z_{\ell_i}^2+z_{\ell_i}b_{\ell_i}-\frac{\sigma_{1\ell_i}}{2}\tilde{\lambda}_{\ell_i}^2-\frac{\sigma_{2\ell_i}}{2}\tilde{\xi}_{\ell_i}^2+\\&\frac{\sigma_{1\ell_i}}{2}(\lambda_{\ell_i}-\hat{\lambda}_{\ell_i}(0))^2+\frac{\sigma_{2\ell_i}}{2}(\xi_{\ell_i}-\hat{\xi}_{\ell_i}(0))^2)=\\&\sum_{\ell_i=u_i,r_i}(-(k_{\mathrm{d}\ell_i}-1)z_{\ell_i}^2-\frac{\sigma_{1\ell_i}}{2}\tilde{\lambda}_{\ell_i}^2-\frac{\sigma_{2\ell_i}}{2}\tilde{\xi}_{\ell_i}^2+\frac{1}{4}b_{\ell_i}^2+\\&\frac{\sigma_{1\ell_i}}{2}(\lambda_{\ell_i}-\hat{\lambda}_{\ell_i}(0))^2+\frac{\sigma_{2\ell_i}}{2}(\xi_{\ell_i}-\hat{\xi}_{\ell_i}(0))^2).\end{aligned}\tag{13}$$

定理 1　针对欠驱动自主船舶(1)–(2), 假设1成立, 利用扰动观测器(7)及其自适应律(8), 存在

$$a_{\mathrm{d}_i}=\min_{\ell_i=u_i,r_i}\{(k_{\mathrm{d}\ell_i}-1),\Gamma_{1\ell_i}\frac{\sigma_{1\ell_i}}{2},\Gamma_{2\ell_i}\frac{\sigma_{2\ell_i}}{2}\}>0,$$

可以实现对海洋环境扰动$d_{\mathrm{w}\ell_i}$的有效观测.

证　根据式(13), 选取$k_{\mathrm{d}\ell_i}>1$, 则$\dot{V}_{\mathrm{d}_i}$可以转化为如下形式:

$$\dot{V}_{\mathrm{d}_i}\leqslant-2a_{\mathrm{d}_i}V_{\mathrm{d}_i}+\sigma_{\mathrm{d}_i},\tag{14}$$

其中$a_{\mathrm{d}_i},\sigma_{\mathrm{d}_i}>0$为常数且满足

$$\begin{aligned}&a_{\mathrm{d}_i}=\min_{\ell_i=u_i,r_i}\{(k_{\mathrm{d}\ell_i}-1),\Gamma_{1\ell_i}\frac{\sigma_{1\ell_i}}{2},\Gamma_{2\ell_i}\frac{\sigma_{2\ell_i}}{2}\},\\&\sigma_{\mathrm{d}_i}=\sum_{\ell_i=u_i,r_i}(\frac{1}{4}b_{\ell_i}^2+\frac{\sigma_{1\ell_i}}{2}(\lambda_{\ell_i}-\hat{\lambda}_{\ell_i}(0))^2+\\&\qquad\frac{\sigma_{2\ell_i}}{2}(\xi_{\ell_i}-\hat{\xi}_{\ell_i}(0))^2).\end{aligned}$$

对式(14)两边进行积分可得

$$V_{\mathrm{d}_i}\leqslant\frac{\sigma_{\mathrm{d}_i}}{2a_{\mathrm{d}_i}}+(V_{\mathrm{d}_i}(0)-\frac{\sigma_{\mathrm{d}_i}}{2a_{\mathrm{d}_i}})\mathrm{e}^{-2a_{\mathrm{d}_i}t}.\tag{15}$$

由式(15)可得$\lim\limits_{t\to\infty}V_{\mathrm{d}_i}(t)=\dfrac{\sigma_{\mathrm{d}_i}}{2a_{\mathrm{d}_i}}$, 故$V_{\mathrm{d}_i}$可以指

数收敛于半径为$\dfrac{\sigma_{\mathrm{d}_i}}{2a_{\mathrm{d}_i}}$的球域. 则系统状态$z_{\ell_i}$及误差信号$\tilde{\lambda}_{\ell_i},\tilde{\xi}_{\ell_i}$可以指数收敛于半径为$\sqrt{\dfrac{\sigma_{\mathrm{d}_i}}{2a_{\mathrm{d}_i}}}$的球域. 同时, 通过调节设计参数的$\alpha_{\ell_i},\Gamma_{1\ell_i},\Gamma_{2\ell_i},\sigma_{1\ell_i},\sigma_{2\ell_i}$的大小, 可以使收敛半径$\sqrt{\dfrac{\sigma_{\mathrm{d}_i}}{2a_{\mathrm{d}_i}}}$任意小.

根据式(7)(9)–(10)得

$$\begin{aligned}\tilde{d}_{\ell_i}=&d_{\ell_i}-\hat{d}_{\ell_i}=\\&m_{\ell_i}\dot{\ell}_i-f_{\ell_i}-\tau_{\ell_i}-(m_{\ell_i}\dot{\hat{\ell}}_i-\hat{\lambda}_{\ell_i}\Phi_{\ell_i}-\tau_{\ell_i})=\\&\dot{z}_{\ell_i}+\tilde{\lambda}_{\ell_i}\Phi_{\ell_i}+b_{\ell_i}.\end{aligned}\tag{16}$$

由式(16)可知, $z_{\ell_i},\tilde{\lambda}_{\ell_i}$在紧集上指数收敛于原点附近任意小的邻域, 且$b_{\ell_i}$可选取为任意小的正数, 则可得$\tilde{d}_{\ell_i}$收敛于原点附近任意小的邻域, 即$\hat{d}_{\ell_i}$可以以任意精度逼近环境扰动$d_{\ell_i}$. 证毕.

3.2 路径跟踪控制器设计

针对单艘自主船舶设计基于自适应扰动观测器的路径跟踪算法, 使欠驱动自主船舶能够以期望速度跟踪其对应的预设参考路径. 设计过程分为两步: 1) 通过构造位置误差设计运动学回路的虚拟控制器; 2) 构造速度误差信号并基于自适应扰动观测器设计船舶路径跟踪控制器.

步骤 1 定义如下运动学回路误差:

$$\begin{bmatrix}x_{\mathrm{e}i}\\y_{\mathrm{e}i}\\\psi_{\mathrm{e}i}\end{bmatrix}=J^{\mathrm{T}}(\psi)\begin{bmatrix}x_{\mathrm{d}_i}-x_i\\y_{\mathrm{d}_i}-y_i\\\psi_{\mathrm{d}_i}-\psi_i\end{bmatrix},\tag{17}$$

其中:

$$\psi_{\mathrm{d}_i}=\arctan\frac{y^{\theta_i}_{\mathrm{d}_i}}{x^{\theta_i}_{\mathrm{d}_i}};$$

$J(\psi)\in\mathbb{R}^3$为附体坐标系和惯性坐标系之间的旋转变换矩阵:

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

根据式(1), 沿着时间t对式(17)求导得

$$\begin{bmatrix}\dot{x}_{\mathrm{e}i}\\\dot{y}_{\mathrm{e}i}\\\dot{\psi}_{\mathrm{e}i}\end{bmatrix}=\begin{bmatrix}r_iy_{\mathrm{e}i}-u_i+u_{\mathrm{d}_i}\cos\psi_{\mathrm{e}i}\\-r_ix_{\mathrm{e}i}-v_i+u_{\mathrm{d}_i}\sin\psi_{\mathrm{e}i}\\-r_i+r_{\mathrm{d}_i}\end{bmatrix},\tag{18}$$

式中$u_{\mathrm{d}_i},r_{\mathrm{d}_i}$为第$i$艘自主船在其对应的参数化路径$\eta_{\mathrm{d}_i}(\theta_i)$上的期望速度, 该速度的大小由参数变化率$\dot{\theta}_i$进行调节, 且有

$$\begin{cases}u_{\mathrm{d}_i}(\theta_i)=\bar{u}_{\mathrm{d}_i}(\theta_i)\dot{\theta}_i,\\r_{\mathrm{d}_i}(\theta_i)=\bar{r}_{\mathrm{d}_i}(\theta_i)\dot{\theta}_i,\end{cases}\tag{19}$$

其中$\bar{u}_{\mathrm{d}_i}(\theta_i),\bar{r}_{\mathrm{d}_i}(\theta_i)$的具体形式如下:

$$\begin{cases}\bar{u}_{\mathrm{d}_i}(\theta_i)=\sqrt{x^{\theta_i}_{\mathrm{d}_i}(\theta_i)^2+y^{\theta_i}_{\mathrm{d}_i}(\theta_i)^2},\\\bar{r}_{\mathrm{d}_i}(\theta_i)=\dfrac{x^{\theta_i}_{\mathrm{d}_i}(\theta_i)y^{\theta_i^2}_{\mathrm{d}_i}-x^{\theta_i^2}_{\mathrm{d}_i}(\theta_i)y^{\theta_i}_{\mathrm{d}_i}(\theta_i)}{x^{\theta_i}_{\mathrm{d}_i}(\theta_i)^2+y^{\theta_i}_{\mathrm{d}_i}(\theta_i)^2}.\end{cases}\tag{20}$$

为使多自主船能够沿着参数化路径同步运动, 引入如下误差变量:

$$\omega_i=\dot{\theta}_i-v_{\mathrm{d}_i}(\theta_i).\tag{21}$$

定义动力学回路的速度误差信号$u_{\mathrm{e}i}=\alpha_{\mathrm{u}_i}-u_i,\tilde{\psi}_{\mathrm{e}i}=\alpha_{\psi_{\mathrm{e}i}}-\psi_{\mathrm{e}i},r_{\mathrm{e}i}=\alpha_{\mathrm{r}_i}-r_i,\alpha_{\mathrm{u}_i},\alpha_{\psi_{\mathrm{e}i}},\alpha_{\mathrm{r}_i}$为待设计的虚拟控制律.

将式(19)代入式(18)得

$$\begin{bmatrix}\dot{x}_{\mathrm{e}i}\\\dot{y}_{\mathrm{e}i}\\\dot{\psi}_{\mathrm{e}i}\end{bmatrix}=\begin{bmatrix}r_iy_{\mathrm{e}i}+u_{\mathrm{e}i}-\alpha_{\mathrm{u}_i}+\bar{u}_{\mathrm{d}_i}\dot{\theta}_i\cos\psi_{\mathrm{e}i}\\-r_ix_{\mathrm{e}i}-v_i+\bar{u}_{\mathrm{d}_i}\dot{\theta}_i\sin\psi_{\mathrm{e}i}\\r_{\mathrm{e}i}-\alpha_{\mathrm{r}_i}+\bar{r}_{\mathrm{d}_i}\dot{\theta}_i\end{bmatrix}.\tag{22}$$

设计如下虚拟控制律:

$$\begin{cases}\alpha_{\mathrm{u}_i}=k_{1i}x_{\mathrm{e}i}+\bar{u}_{\mathrm{d}_i}v_{\mathrm{d}_i}\cos\psi_{\mathrm{e}i},\\\alpha_{\psi_{\mathrm{e}i}}=\arctan(\dfrac{v_i-k_{2i}y_{\mathrm{e}i}-\dfrac{\bar{u}^2_{\mathrm{d}_i}v^2_{\mathrm{d}_i}y_{\mathrm{e}i}}{4}}{\bar{u}_{\mathrm{d}_i}v_{\mathrm{d}_i}}),\\\alpha_{\mathrm{r}_i}=-k_{3i}\tilde{\psi}_{\mathrm{e}i}+\bar{r}_{\mathrm{d}_i}v_{\mathrm{d}_i}-\dot{\alpha}_{\psi_{\mathrm{e}i}},\end{cases}\tag{23}$$

其中k_{1i},k_{2i},k_{3i}为大于零的设计参数.

选取如下形式Lyapunov函数:

$$V_{1i}=\frac{1}{2}(x^2_{\mathrm{e}i}+y^2_{\mathrm{e}i}+\tilde{\psi}^2_{\mathrm{e}i}).\tag{24}$$

根据式(22), 对式(24)求导得

$$\begin{aligned}\dot{V}_{1i}=&x_{\mathrm{e}i}(r_iy_{\mathrm{e}i}+u_{\mathrm{e}i}-\alpha_{\mathrm{u}_i}+\bar{u}_{\mathrm{d}_i}v_{\mathrm{d}_i}\cos\psi_{\mathrm{e}i})+\\&y_{\mathrm{e}i}(-r_ix_{\mathrm{e}i}-v_i+\bar{u}_{\mathrm{d}_i}v_{\mathrm{d}_i}\sin(\alpha_{\psi_{\mathrm{e}i}}-\tilde{\psi}_{\mathrm{e}i}))+\\&\tilde{\psi}_{\mathrm{e}i}(\dot{\alpha}_{\psi_{\mathrm{e}i}}+\alpha_{\mathrm{r}_i}-r_{\mathrm{e}i}-\bar{r}_{\mathrm{d}_i}v_{\mathrm{d}_i})+\omega_i\Psi_i,\end{aligned}\tag{25}$$

其中$\Psi_i=x_{\mathrm{e}i}\bar{u}_{\mathrm{d}_i}\cos\psi_{\mathrm{e}i}+y_{\mathrm{e}i}\bar{u}_{\mathrm{d}_i}\sin\psi_{\mathrm{e}i}-\tilde{\psi}_{\mathrm{e}i}\bar{r}_{\mathrm{d}_i}$.

将式(23)代入式(25)得

$$\begin{aligned}\dot{V}_{1i}=&-k_{1i}x^2_{\mathrm{e}i}-k_{2i}y^2_{\mathrm{e}i}-k_{3i}\tilde{\psi}^2_{\mathrm{e}i}+\omega_i\Psi_i+\\&x_{\mathrm{e}i}u_{\mathrm{e}i}-\tilde{\psi}_{\mathrm{e}i}r_{\mathrm{e}i}+\Delta_i,\end{aligned}\tag{26}$$

式中$\Delta_i=\sin^2\alpha_{\psi_{\mathrm{e}i}}+\sin^2(\alpha_{\psi_{\mathrm{e}i}}-\tilde{\psi}_{\mathrm{e}i})$.

步骤 2 根据式(2), 对速度误差求导得

$$\dot{\ell}_{\mathrm{e}i}=\dot{\alpha}_{\ell_i}-\frac{f_{\ell_i}}{m_{\ell_i}}-\frac{d_{\mathrm{w}\ell_i}}{m_{\ell_i}}-\frac{\tau_{\ell_i}}{m_{\ell_i}}.\tag{27}$$

设计如下路径跟踪控制律:

$$\tau_{\ell_i}=k_{\ell_i}\ell_{\mathrm{e}i}+\dot{\alpha}_{\ell_i}-\hat{\lambda}_{\tau_{\ell i}}\Phi_{\ell_i}-\hat{d}_{\mathrm{w}\ell_i}.\tag{28}$$

基于MLP技术设计如下自适应律:

$$\dot{\hat{\lambda}}_{\tau_{\ell i}}=\Gamma_{\tau_{\ell_i}}(\Phi_{\ell_i}\ell_i-\sigma_{3\ell_i}(\hat{\lambda}_{\tau_{\ell_i}}-\hat{\lambda}_{\tau_{\ell_i}}(0))).\tag{29}$$

式(28)–(29)中$k_{\ell_i}, \Gamma_{\tau_{\ell_i}}, \sigma_{3\ell_i}$均为大于零的设计参数.

根据式(27)–(28)及杨氏不等式得

$$\begin{aligned}\ell_{\mathrm{e}i}\dot{\ell}_{\mathrm{e}i}=&-\frac{k_{\ell_i}}{m_{\ell_i}}\ell_{\mathrm{e}i}^2+\ell_{\mathrm{e}i}(1-\frac{1}{m_{\ell_i}})\dot{\alpha}_{\ell_i}+\\&\frac{\ell_{\mathrm{e}i}}{m_{\ell_i}}(\hat{\lambda}_{\tau_{\ell_i}}\varPhi_{\ell_i}-f_{\ell_i})-\frac{\ell_{\mathrm{e}i}}{m_{\ell_i}}(\tilde{d}_{\mathrm{w}\ell i})\leqslant\\&-(\frac{k_{\ell_i}}{m_{\ell_i}}-\frac{b_{1i}b_{\ell}^2}{m_{\ell_i}^2}-\frac{b_{2i}\tilde{d}_{\mathrm{w}\ell_i}^2}{m_{\ell_i}^2}-\\&\frac{b_{3\ell_i}(1+m_{\ell_i})^2\dot{\alpha}_{\ell_i}^2}{m_{\ell_i}^2})\ell_{\mathrm{e}i}^2-\frac{\ell_{\mathrm{e}i}}{m_{\ell_i}}\tilde{\lambda}_{\tau_{\ell_i}}\varPhi_{\ell_i}+\\&\frac{1}{4b_{1\ell_i}}+\frac{1}{4b_{2\ell_i}}+\frac{1}{4b_{3\ell_i}},\end{aligned}\tag{30}$$

其中: $\dot{\alpha}_{\ell_i}$可以通过微分滤波器$\frac{s}{(t_{\mathrm{c}}+1)}$逼近得到; t_{c}为时间常数, 从而避免复杂的求导计算过程; $b_{1\ell_i}$, $b_{2\ell_i}$为正常数.

构造如下形式Lyapunov函数:

$$V_{2i}=\sum_{\ell_i=u_i,r_i}(\frac{1}{2}\ell_{\mathrm{e}i}^2+\frac{1}{2m_{\ell_i}\Gamma_{\tau_{\ell_i}}}\tilde{\lambda}_{\tau_{\ell_i}}^2).\tag{31}$$

根据式(29)–(30), 沿着时间t对V_{2i}求导得

$$\begin{aligned}\dot{V}_{2i}=&\sum_{\ell_i=u_i,r_i}(-(\frac{k_{\ell_i}}{m_{\ell_i}}-\frac{b_{1i}b_{\ell_i}^2}{m_{\ell_i}^2}-\frac{b_{2i}\tilde{d}_{\mathrm{w}\ell_i}^2}{m_{\ell_i}^2}-\\&\frac{b_{3\ell_i}(1+m_{\ell_i})^2\dot{\alpha}_{\ell_i}^2}{m_{\ell_i}^2})\ell_{\mathrm{e}i}^2-\frac{\sigma_{3\ell_i}}{2m_{\ell_i}}\tilde{\lambda}_{\tau_{\ell_i}}^2\frac{\sigma_{3\ell_i}}{2m_{\ell_i}}\times\\&(\lambda_{\tau_{\ell_i}}-\hat{\lambda}_{\tau_{\ell_i}}(0))^2+\frac{1}{4}(\frac{1}{b_{1\ell_i}}+\frac{1}{b_{2\ell_i}}+\frac{1}{b_{3\ell_i}})).\end{aligned}\tag{32}$$

3.3　协同控制器设计

为实现多自主船的协同路径跟踪控制, 在满足单个自主船舶收敛于其对应预设参考位置的同时, 还需要各自主船舶的速度和路径参数变化率保持一致. 即设计一种协同控制律使得速度跟踪误差ω_i和路径参数协同误差$\theta_i-\theta_j$为任意小. 由第2.2节知, 各自主船对应G中的顶点, 多船系统内部的船间通信对应图G的边. 基于无向图的通信建模方式, 各自主船仅需其本身和相邻自主船舶的信息即可维持期望几何队形, 从而有效降低船间通信量, 故所设计的协同算法是分散式的.

对于多欠驱动自主船舶系统, 设计如下协同控制律:

$$\begin{cases}\dot{\omega}_i=-k_{4i}^{-1}(\sum\limits_{j\in N_i}a_{ij}(\theta_i-\theta_j)+\varDelta_i)-\gamma_i,\\\dot{\gamma}_i=-(k_{4i}+k_{5i})\gamma_i-\sum\limits_{j\in N_i}a_{ij}(\theta_i-\theta_j)-\varDelta_i,\end{cases}\tag{33}$$

其中: k_{4i}, k_{5i}均为大于零的设计参数, γ_i为辅助状态. 定义

$$\varOmega=[\omega_1\ \cdots\ \omega_n]^{\mathrm{T}}\in\mathbb{R}^n,\ \varTheta=[\theta_1\ \cdots\ \theta_n]^{\mathrm{T}}\in\mathbb{R}^n,$$
$$\varDelta=[\varDelta_1\ \cdots\ \varDelta_n]^{\mathrm{T}}\in\mathbb{R}^n,\ \varUpsilon=[\gamma_1\ \cdots\ \gamma_n]^{\mathrm{T}}\in\mathbb{R}^n,$$
$$\nu_{\mathrm{d}}=[v_{\mathrm{d}1}\ \cdots\ v_{\mathrm{d}n}]^{\mathrm{T}}\in\mathbb{R}^n,$$
$$K_4=\mathrm{diag}\{k_{4i}\}\in\mathbb{R}^{n\times n},\ K_5=\mathrm{diag}\{k_{5i}\}\in\mathbb{R}^{n\times n},$$

则式(33)可表示为

$$\begin{cases}\dot{\varTheta}=\nu_{\mathrm{d}}-K_4^{-1}(L\varTheta+\varDelta)-\varUpsilon,\\\dot{\varUpsilon}=-(K_4+K_5)\varUpsilon-L\varTheta-\varDelta.\end{cases}\tag{34}$$

定义Lyapunov函数

$$V=\sum_{i=1}^n(V_{\mathrm{d}_i}+V_{1i}+V_{2i})+\frac{1}{2}\varTheta^{\mathrm{T}}L\varTheta+\frac{1}{2}\varUpsilon^{\mathrm{T}}\varUpsilon.\tag{35}$$

对V求导并联立式(13)(32)–(33)得

$$\begin{aligned}\dot{V}\leqslant&\sum_{i=1}^n\sum_{\ell_i=u_i,r_i}(-(k_{\mathrm{d}\ell_i}-1)z_{\ell_i}^2-\frac{\sigma_{1\ell_i}}{2}\tilde{\lambda}_{\ell_i}^2-\frac{\sigma_{2\ell_i}}{2}\tilde{\xi}_{\ell_i}^2-\\&(k_{1i}-1)x_{\mathrm{e}i}^2-k_{2i}y_{\mathrm{e}i}^2-(k_{3i}-1)\psi_{\mathrm{e}i}^2-(\frac{k_{\ell_i}}{m_{\ell_i}}-\\&\frac{b_{1i}b_{\ell_i}^2}{m_{\ell_i}^2}-\frac{b_{2i}\tilde{d}_{\mathrm{w}\ell_i}^2}{m_{\ell_i}^2}-\frac{1}{4}-\frac{b_{3\ell_i}(1+m_{\ell_i})^2\dot{\alpha}_{\ell_i}^2}{m_{\ell_i}^2})\ell_{\mathrm{e}i}^2)-\\&\varOmega^{\mathrm{T}}K_4\varOmega-\varUpsilon^{\mathrm{T}}K_5\varUpsilon+\\&\sum_{i=1}^n\sum_{\ell_i=u_i,r_i}(\frac{\sigma_{1\ell_i}}{2}(\lambda_{\ell_i}-\hat{\lambda}_{\ell_i}(0))^2+\\&\frac{\sigma_{2\ell_i}}{2}(\xi_{\ell_i}-\hat{\xi}_{\ell_i}(0))^2+\frac{\sigma_{3\ell_i}}{2m_{\ell_i}}(\lambda_{\tau_{\ell_i}}-\hat{\lambda}_{\tau_{\ell_i}}(0))^2+\\&\frac{1}{4}(\frac{1}{b_{1\ell_i}}+\frac{1}{b_{2\ell_i}}+\frac{1}{b_{3\ell_i}})+b_{\ell_i}^2+\varDelta_i).\end{aligned}\tag{36}$$

定理 2　针对欠驱动自主船舶(1)–(2), 考虑自适应扰动观测器(7)–(8)、路径跟踪控制律(28)–(29)及分散式协同控制律(33), 存在

$$\begin{aligned}a_\tau=&\min\{(k_{\mathrm{d}\ell_i}-1),\frac{\sigma_{1\ell_1}}{2},\frac{\sigma_{2\ell_2}}{2},(k_{1i}-1),k_{2i},\\&(k_{3i}-1),\beta_{\tau_{\ell_i}}\}>0,\end{aligned}$$

使得闭环系统半全局一致最终有界.

证　根据式(36), 选取如下设计参数:

$$k_{\mathrm{d}\ell_i}>1,\ k_{3_i}>1,$$
$$k_{\ell_i}>\frac{b_{1i}b_{\ell_i}^2}{m_{\ell_i}^2}+\frac{b_{2i}\tilde{d}_{\mathrm{w}\ell_i}^2}{m_{\ell_i}}+\frac{1}{4}m_{\ell_i}+\frac{b_{3\ell_i}(1+m_{\ell_i})^2\dot{\alpha}_{\ell_i}^2}{m_{\ell_i}},$$

则$\dot{V}$可以转化为如下形式:

$$\dot{V}=-2a_\tau V+\sigma_\tau,\tag{37}$$

其中$a_\tau, \sigma_\tau>0$为常数且满足

$$\begin{aligned}a_\tau=&\min\{(k_{\mathrm{d}\ell_i}-1),\frac{\sigma_{1\ell_1}}{2},\frac{\sigma_{2\ell_2}}{2},(k_{1i}-1),\\&k_{2i},(k_{3i}-1),\beta_{\tau_{\ell_i}}\},\end{aligned}$$

其中:

$$\beta_{\tau_{\ell_i}}=(\frac{k_{\ell_i}}{m_{\ell_i}}-\frac{b_{1i}b_{\ell_i}^2}{m_{\ell_i}^2}-\frac{b_{2i}\tilde{d}_{\mathrm{w}\ell_i}^2}{m_{\ell_i}^2}-\frac{1}{4}-$$

$$\frac{b_{3\ell_i}(1+m_{\ell_i})^2\dot{\alpha}_{\ell_i}^2}{m_{\ell_i}^2}),$$

$$\tau=\sum_{i=1}^{n}\sum_{\ell_i=u_i,r_i}\{\frac{\sigma_{1\ell_i}}{2}(\lambda_{\ell_i}-\hat{\lambda}_{\ell_i}(0))^2+\frac{\sigma_{2\ell_i}}{2}(\xi_{\ell_i}-\hat{\xi}_{\ell_i}(0))^2+\frac{\sigma_{3\ell_i}}{2m_{\ell_i}}(\lambda_{\tau_{\ell_i}}-\hat{\lambda}_{\tau_{\ell_i}}(0))^2+\frac{1}{4}(\frac{1}{b_{1\ell_i}}+\frac{1}{b_{2\ell_i}}+\frac{1}{b_{3\ell_i}})+b_{\ell_i}^2+\Delta_i\}.$$

对式(37)两边进行积分

$$V\leqslant\frac{\sigma_\tau}{2a_\tau}+(V(0)-\frac{\sigma_\tau}{2a_\tau})\mathrm{e}^{-2a_\tau t}. \tag{38}$$

显然$\lim\limits_{t\to\infty}V(t)=\dfrac{\sigma_\tau}{2a_\tau}$, 故闭环系统内的状态$x_{\mathrm{e}i},y_{\mathrm{e}i},\tilde{\psi}_{\mathrm{e}i},u_{\mathrm{e}i},r_{\mathrm{e}i},\tilde{\lambda}_{\tau_{\ell_i}},\omega_i,\gamma_i$可以达到半全局一致最终有界稳定. 由此定理2得证. 证毕.

4 仿真实验

为验证本文所提出算法的有效性, 考虑由5艘欠驱动自主船组成的编队, 图论中的节点对应于自主船, 图论中的边对应于船间的通信关系, 其通信拓扑结构为

$$L=\begin{bmatrix}2&-1&0&0&-1\\-1&2&-1&0&0\\0&-1&2&-1&0\\0&0&-1&2&-1\\-1&0&0&-1&2\end{bmatrix}.$$

以欠驱动船模Cybership II为仿真对象, 其具体模型参数可参考文献[23]. 采用常值干扰叠加正余弦时变干扰的形式模拟海洋环境扰动产生的力和力矩:

$$\begin{cases}d_{\mathrm{wu}_i}=\dfrac{18}{11}(1+0.55\sin(0.3t)+0.15\cos(0.4t)),\\ d_{\mathrm{wv}_i}=\dfrac{26}{17.76}(1+0.68\sin(0.4t)+0.2\cos(0.1t)),\\ d_{\mathrm{wr}_i}=\dfrac{950}{636}(1+0.63\sin(0.3t)+0.1\cos(0.5t)),\end{cases}$$

船舶的初始速度为$u_i(0)=v_i(0)=0$ m/s, $r_i(0)=0$ rad/s, $i=1,2,\cdots,5$. 初始位置及航向为

$$\begin{bmatrix}x_i(0)\\y_i(0)\\\psi_i(0)\end{bmatrix}=\begin{bmatrix}0&2&4&-6&-7\\8&0&-2&2&5\\30^\circ&45^\circ&120^\circ&135^\circ&15^\circ\end{bmatrix}.$$

扰动观测器的设计参数选取为

$$k_{\mathrm{du}_i}=1,\ k_{\mathrm{dv}_i}=6,\ k_{\mathrm{dr}_i}=2,\ \varGamma_{1\mathrm{u}_i}=\varGamma_{2\mathrm{u}_i}=1,$$
$$\varGamma_{1\mathrm{v}_i}=\varGamma_{2\mathrm{v}_i}=0.1,\ \varGamma_{1\mathrm{r}_i}=\varGamma_{2\mathrm{r}_i}=0.01,\ i=1,\cdots,5.$$

路径跟踪控制器的设计参数选取为

$$k_{11}=15,\ k_{12}=12,\ k_{13}=6.3,\ k_{14}=4.2,$$
$$k_{15}=4.8,\ k_{21}=5.6,\ k_{22}=3.2,\ k_{23}=7.2,$$
$$k_{24}=6.2,\ k_{25}=7.4,\ k_{31}=0.32,\ k_{32}=0.3,$$
$$k_{33}=0.7,\ k_{34}=0.8,\ k_{35}=0.22,$$
$$\varGamma_{\tau_{\mathrm{u}_i}}=1.8,\ \varGamma_{\tau_{\mathrm{r}_i}}=6.8,\ i=1,\cdots,5.$$

协同控制器的设计参数选取为

$$K_4=\mathrm{diag}\{1,1.2,1.2,1.3,1.6\},$$
$$K_5=\mathrm{diag}\{1,0.6,0.8,0.3,0.2\}.$$

采用RBFNNs对各自主船模型中的非线性项进行逼近, 选取RBFNNs的节点个数为25, 宽度为$h_j=3$, 中心μ_j分布在论域$[-10,10]\times[-10,10]\times[-2.5,2.5]$.

注 1 在设计参数的选取过程中, 系统对部分主要设计参数$k_{\mathrm{d}\ell_i},k_{1i},k_{2i},k_{3i},k_{4i},k_{5i}$调节的响应较为明显, 参数选取过大或过小都将导致系统发散. 其它参数$k_{\ell_i},\varGamma_{1\ell_i},\varGamma_{2\ell_i},\varGamma_{\tau_{\ell_i}}$等对系统收敛性影响较小, 通过对此类参数的调节可以进一步增加系统的跟踪精度.

图3–5描述了5艘自主船舶的控制结果. 由图3可知, 在本文所提出算法的作用下, 多自主船舶可以精确跟踪参考路径, 并保持正五边形的队形航行. 图4表明自主船舶的路径参数误差及速度误差逐渐趋于一致. 图5描述了各自主船的控制输入变化规律.

考虑单自主船舶为研究对象, 图6–7分别描述了本文所提出的算法和文献[15]中算法作用下的对比结果.

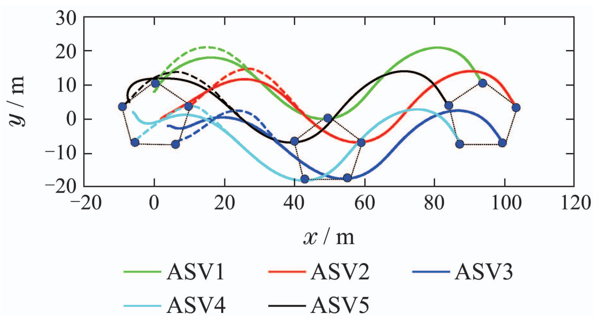
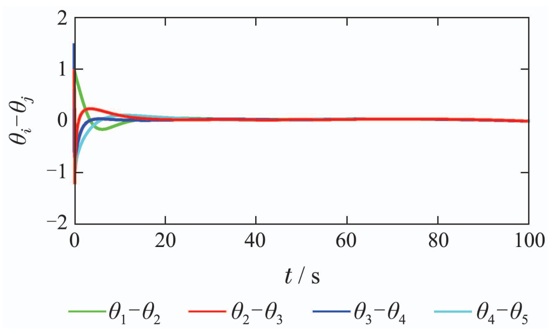


图 3 自主船舶路径队形图

Fig. 3 Paths of autonomous vessels with pentagon formation



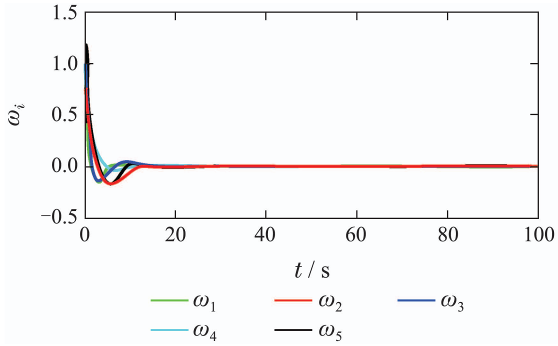


图 4 协同误差

Fig. 4 Cooperative errors

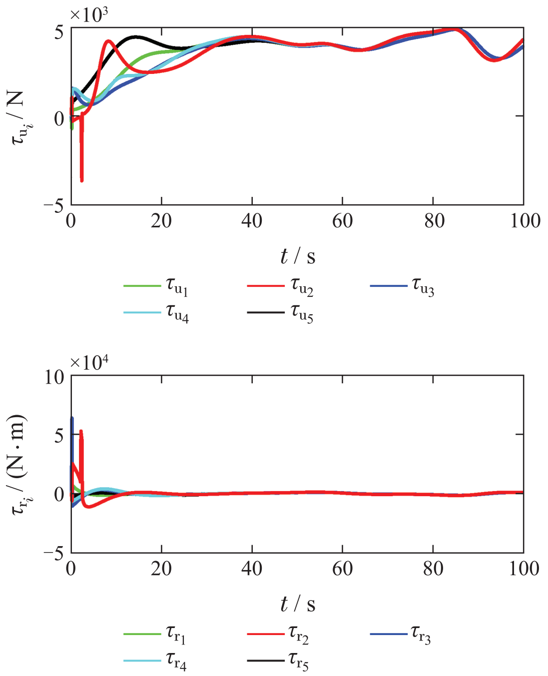
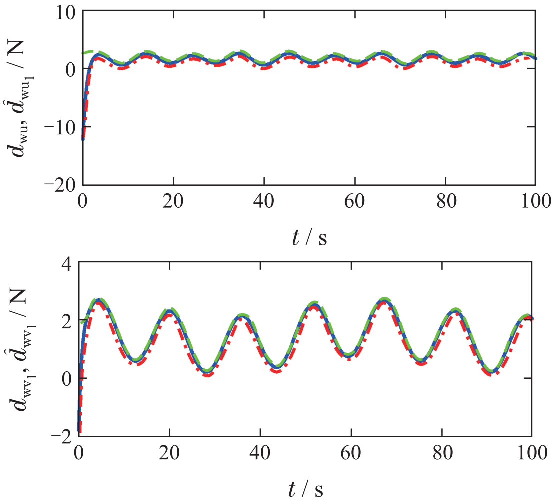


图 5 控制输入

Fig. 5 Control inputs

从图6–7可以看出, 对比文献[15]中的基于观测器的鲁棒控制(observer based robust control, OBRC)算法, 本文所提出的算法可以获得更高的扰动观测精度.



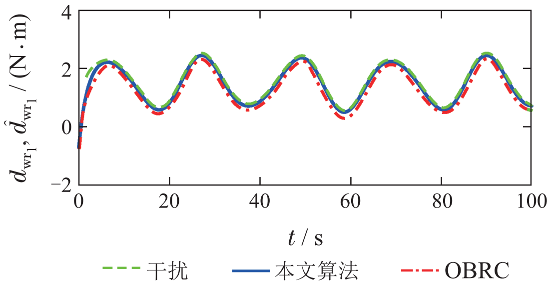


图 6 环境扰动及其观测值

Fig. 6 Environmental disturbance and its estimations

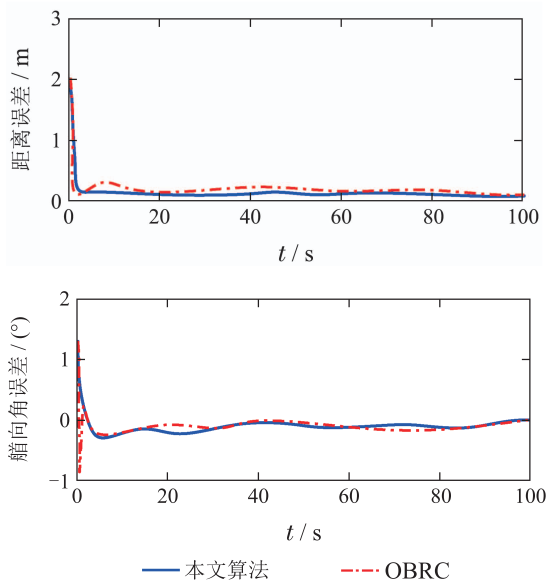


图 7 误差信号

Fig. 7 Error signals

5 结论

本文采用RBFNNs, MLP技术和无向图理论, 对未知海洋环境扰动下的多欠驱动自主船舶的协同路径跟踪问题进行研究. 解决了路径跟踪控制器结构复杂及船舶模型参数不确定问题, 所构造的自适应扰动观测器不需要环境扰动上界的精确信息. 进一步, 考虑了船间通信约束问题, 通过设计分散式协同控制律有效提高了通信效率, 实现了多自主船对预设参考路径的精确跟踪. 通过Lyapunov稳定性理论, 证明了闭环系统的半全局一致最终有界性. 最后通过数值仿真实验, 验证了所提出算法的有效性.

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