

控制与决策

Control and Decision

基于改进人工势场法的欠驱动无人船编队协同避碰避障

李伟, 张永超, 宁君, 马昊冉, 刘陆, 彭周华

引用本文:

李伟, 张永超, 宁君, 等. 基于改进人工势场法的欠驱动无人船编队协同避碰避障[J]. *控制与决策*, 2025, 40(1): 252–260.

在线阅读 View online: <https://doi.org/10.13195/j.kzyjc.2024.0391>

您可能感兴趣的其他文章

Articles you may be interested in

[空间机器人双臂捕获卫星操作的事件采样输出反馈神经网络避撞柔顺控制](#)

Collision avoidance and compliance control based on event sampling output feedback neural network for space robot dual arm capture satellite operation

控制与决策. 2021, 36(9): 2113–2122 <https://doi.org/10.13195/j.kzyjc.2019.1754>

[大规模固定翼无人机集群编队控制方法](#)

Formation control of large-scale fixed-wing unmanned aerial vehicle swarms

控制与决策. 2021, 36(9): 2063–2073 <https://doi.org/10.13195/j.kzyjc.2020.0076>

[输出误差约束下四旋翼无人机预定性能反步控制](#)

Prescribed performance backstepping control for quadrotor UAV with output error constraint

控制与决策. 2021, 36(5): 1059–1068 <https://doi.org/10.13195/j.kzyjc.2019.1249>

[基于凸面体圆弧航路的无人机自主避障算法](#)

Autonomous obstacle avoidance algorithm designed for UAV based on convex circular trajectory

控制与决策. 2021, 36(3): 653–660 <https://doi.org/10.13195/j.kzyjc.2019.0768>

[基于领航-跟随的有人/无人机编队队形保持控制](#)

Formation keeping control for manned/unmanned aerial vehicle formation based on leader-follower strategy

控制与决策. 2021, 36(10): 2435–2441 <https://doi.org/10.13195/j.kzyjc.2020.0453>

基于改进人工势场法的欠驱动无人船编队协同避碰避障

李伟¹, 张永超¹, 宁君^{1†}, 马昊冉¹, 刘陆², 彭周华²

(1. 大连海事大学航海学院, 辽宁大连 116026; 2. 大连海事大学船舶电气工程学院, 辽宁大连 116026)

摘要: 提出一种基于改进人工势场法且带有输入量化的欠驱动无人船编队协同避碰避障策略. 借鉴导弹制导与控制机理, 分层设计无人船运动学制导律与动力学控制律. 首先, 基于辅助变量法在无人船运动学子系统中设计分布式制导律, 并引入改进人工势场法的斥力函数. 通过重构制导律实现运动学层面的协同避碰避障以及欠驱动无人船期望轨迹的跟踪; 其次, 通过使用径向基神经网络对无人船动力学子系统的外界干扰和系统未建模动态进行逼近, 采用均匀量化器对输入变量进行量化并对量化过程进行线性描述, 使得底层量化控制器无需预测关于量化参数的具体信息; 在稳定性分析中, 利用李雅普诺夫稳定性理论证明所设计 USV 编队跟踪控制系统的稳定性; 最后, 采用 Matlab 对理论策略进行仿真实验, 仿真结果验证了所提出策略的有效性.

关键词: 欠驱动无人船; 人工势场法; 分布式编队; 输入量化; RBF 神经网络; 避障

中图分类号: TP273 文献标志码: A

DOI: 10.13195/j.kzyjc.2024.0391

引用格式: 李伟, 张永超, 宁君, 等. 基于改进人工势场法的欠驱动无人船编队协同避碰避障[J]. 控制与决策, 2025, 40(1): 252-260.

Collision avoidance of under-actuated unmanned surface vehicles formation with improved artificial potential field method

LI Wei¹, ZHANG Yong-chao¹, NING Jun^{1†}, MA Hao-ran¹, LIU Lu², PENG Zhou-hua²

(1. College of Navigation, Dalian Maritime University, Dalian 116026, China; 2. College of Marine Electrical Engineering, Dalian Maritime University, Dalian 116026, China)

Abstract: The paper presents a strategy for cooperative collision avoidance and obstacle avoidance for underactuated unmanned ship formation based on an improved artificial potential field method and input quantization. The strategy involves designing kinematic guidance and dynamic control laws hierarchically, using a distributed guidance law and incorporating a repulsion function from the artificial potential field method to achieve cooperative collision and obstacle avoidance at the kinematics level. Additionally, a radial basis function neural network is utilized to approximate external disturbances and unmodeled dynamics, while an adaptive neural network quantization controller is designed to handle quantization of input variables. The stability of the USV formation tracking control system is proved using the Lyapunov stability theory. Finally, simulation results using Matlab validate the effectiveness of the proposed strategy.

Keywords: underdriven unmanned vessel; artificial potential field method; distributed formation; input quantization; RBF neural network; obstacle avoidance

0 引言

随着船舶自动化和智能化的不断发展, 智能航海领域的倍受关注, 无人水面船(USV)编队控制已成为行业内的研究热点^[1]. 与单无人船相比, 多 USV 系统能够为复杂的海洋工程任务提供更优越的解决方案, 通过彼此合作完成传统单 USV 无法完成的任务, 从而提高整体工作效率和鲁棒性^[2]. 此外, 多数 USV

具有欠驱动的特性, 由于在侧向上缺少实际的控制输入, 导致欠驱动无人船舶协同编队控制更为复杂^[3-5].

近年来, 量化问题在控制系统研究领域备受瞩目^[6-10]. 在航海实践中, 各传感器组件之间的信息需要经过量化与编码才能在信道中传输. 量化技术不仅可以降低通信速率, 还能够保证系统在给定带宽内正常运行. 因此, 在多 USV 编队控制中, 考虑输入量

收稿日期: 2024-04-09; 录用日期: 2024-08-22.

基金项目: 国家自然科学基金项目(51939001, 61976033); 中央高校基本科研业务费专项资金项目(3132024137); 大连海事大学航海学院 2023 年一流学科交叉研究项目(2023JXA09).

责任编辑: 闫敬.

[†]通讯作者. E-mail: junning@dlnu.edu.cn.

化具有重要的意义. 然而, 现有的研究^[6-10]均是基于量化误差有界的前提下开展控制器设计, 并未对量化过程进行描述及补偿.

此外, 现有的单无人船避碰避障研究成果较为丰富^[11-13], 而多无人船协同避障避碰的研究成果相对较少. 文献[14]提出了一种考虑输入量化的分布式欠驱动多无人船自适应模糊编队控制方法, 但并未考虑避碰及避障问题. 为解决此问题, 文献[15]提出了基于人工势能函数的多无人船协同控制器, 考虑了无人船与静态和动态障碍物以及编队中船舶之间的避碰. 然而, 在无人系统协同避碰避障方面的研究成果仍然相对有限. 文献[16]提出了一种基于领导跟随的分布式异构协同跟踪控制方法, 并采用了人工势能函数方法构建具有避碰机制的控制策略. 然而, 该研究注重于编队队形的避碰避障结果和编队控制系统的稳定性保证, 忽略了航海工程实践.

综上所述, 有3类问题值得进一步优化研究. 首先, 上述文献^[1-5]在船舶动力学子系统中直接加入风流干扰的做法与航海实践并不相符, 应在运动学子系统中关注海流的影响, 而在动力学子系统中考虑风浪的影响; 其次, 在面对复杂且受限的海洋通讯环境时, 多个无人水面船舶编队控制系统中存在的输入量化问题值得深入研究; 最后, 对于契合实际航海需求的多无人水面船舶编队的避碰和避障问题尚缺乏系统性的研究^[14-16].

基于以上分析, 本文提出一种基于改进人工势场法且带有输入量化的欠驱动无人船编队协同避障策略. 该策略在USV运动学子系统引入改进人工势场法的斥力函数, 重构制导律, 实现了欠驱动USV运动学层面期望轨迹的跟踪及协同避障. 通过使用径向基神经网络, 对无人船动力学子系统中的外界干扰和系统未建模动态进行逼近, 在稳定性分析中, 利用李雅普诺夫稳定性理论证明所设计USV编队跟踪控制系统的稳定性. 通过Matlab仿真实验验证了所提出策略的有效性.

1 问题描述

考虑一个由 N 艘 USV 组成的无人船编队系统, 将第 i 艘欠驱动 USV 的运动学和动力学模型^[17]分别表述为

$$\begin{cases} \dot{x}_i = u_i \cos \varphi_i - v_i \sin \varphi_i + u_{ci} \cos \varphi_{ci}, \\ \dot{y}_i = u_i \sin \varphi_i + v_i \cos \varphi_i + u_{ci} \sin \varphi_{ci}, \\ \dot{\varphi}_i = r_i. \end{cases} \quad (1)$$

其中: (x_i, y_i) 和 φ_i 为第 i 艘 USV 在大地坐标系下的位置坐标和艏摇角; u_i, v_i, r_i 分别为第 i 艘 USV 的前进

速度、横摇速度和艏摇速度; φ_{ci}, u_{ci} 分别为海流的流向和流速, 有

$$\begin{cases} m_{iu} \dot{u}_i = f_{iu}(u_i, v_i, r_i) + Q(\tau_{iu}) + \tau_{iuw}, \\ m_{iv} \dot{v}_i = f_{iv}(u_i, v_i, r_i) + \tau_{ivw}, \\ m_{ir} \dot{r}_i = f_{ir}(u_i, v_i, r_i) + Q(\tau_{ir}) + \tau_{irw}. \end{cases} \quad (2)$$

这里: m_{iu}, m_{iv}, m_{ir} 为第 i 艘 USV 的惯性质量; $f_{iu}(\cdot), f_{iv}(\cdot), f_{ir}(\cdot)$ 为非线性项, 由柯式力、向心力以及水动力阻尼组成; $\tau_{iuw}, \tau_{ivw}, \tau_{irw}$ 为外界的海洋环境干扰; $Q(\tau_{iu}), Q(\tau_{ir})$ 代表量化后的动力学控制输入, 可由均匀量化器表述; o_{iu}, o_{ir} 分别为量化器系数; 且有

$$Q(\tau_{iu}) = o_{iu} \cdot \text{round}\left(\frac{\tau_{iu}}{O_{iu}}\right),$$

$$Q(\tau_{ir}) = o_{ir} \cdot \text{round}\left(\frac{\tau_{ir}}{O_{ir}}\right).$$

本文的控制目标是在保证特定的编队队形的前提下, 满足避碰避障要求. 领导-跟随编队结构如图1所示.

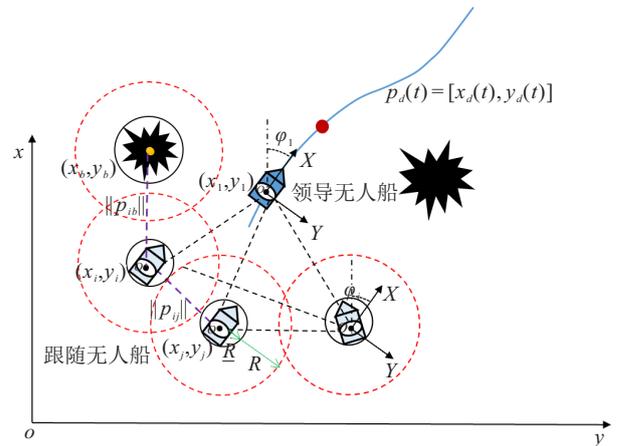


图1 领导-跟随编队结构

根据人工势场理论, 每个跟随-智能体均被假定具有相同的高势能场, 则无人船编队中各跟随无人船之间的避碰斥力场势函数表示为

$$\phi_{ij}^c(p_{ij}) = \left(\min \left\{ 0, \frac{\|p_{ij}\|^2 - \bar{R}^2}{\|p_{ij}\|^2 - \underline{R}^2} \right\} \right)^2. \quad (3)$$

其中: $i, j = 1, 2, \dots, n (i \neq j)$ 表示 n 艘 USV 中的第 i/j 艘 USV; $\|p_{ij}\| = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ 为编队中两艘 USV 之间的距离, $[x_i, y_i]^T$ 和 $[x_j, y_j]^T$ 为第 i 个 USV、第 j 个 USV 在大地坐标系中的位置; $\bar{R} > 0, \underline{R} > 0, \bar{R} > \underline{R}$ 表示避碰区域的上下界. 当势函数处于避碰区域上界外时, 斥力场势函数为 0, 在避碰区域下界斥力场势函数值为无穷大. 当编队系统中两 USV 间的距离满足 $\underline{R} < \|p_{ij}\| < \bar{R}$ 时, 避碰势函数大于零且势函数在附加的控制输入中是有效的. 对势函数(3)求取负梯度可得

$$\frac{\partial \phi_{ij}^c}{\partial p_i} = \begin{cases} \frac{4(\bar{R}^2 - \underline{R}^2)(\|p_{ij}\|^2 - \bar{R}^2)}{(\|p_{ij}\|^2 - \underline{R}^2)^3} p_{ij}, \\ \underline{R} < \|p_{ij}\| < \bar{R}; \\ 0, \|p_{ij}\| > \bar{R}. \end{cases} \quad (4)$$

设计避碰斥力所对应的速度为

$$v_{ij}^c = \frac{1}{m_i t} \frac{\partial \phi_{ij}^c}{\partial p_i}, \quad (5)$$

其中 m_i 为第 i 艘 USV 的质量. 同理, 由于在多 USV 编队航行过程中考虑有障碍物的存在, 各无人船与障碍物之间的避障势函数表示为

$$\phi_{ib}^o(p_{ib}) = \frac{1}{2} \eta_s R_{ts} \left(\frac{1}{\|p_{ib}\| - \underline{R}_o} - \frac{1}{\bar{R}_o} \right) d_g^2. \quad (6)$$

其中: $b = 1, 2, \dots, m$ 表示有 m 个障碍物, $\|p_{ib}\| = \sqrt{(x_i - x_b)^2 + (y_i - y_b)^2}$ 表示第 i 艘 USV 到第 b 个障碍物之间的欧氏距离, $[x_b, y_b]^T$ 为第 b 个障碍物在大地坐标系下的位置; $\bar{R}_o > 0$, $\underline{R}_o > 0$, $\bar{R}_o > \underline{R}_o$ 为避碰区域的上、下界; d_g 为各跟随 USV 与领导者的相对位置距离; R_{ts} 为障碍物膨化圆的半径; η_s 为障碍物斥力场系数. 该函数在检测区域上界外斥力场势函数为 0, 在检测区域下界斥力场势函数为无穷大. 如果两个 USV 之间的距离满足 $\underline{R}_o < \|p_{ib}\| < \bar{R}_o$, 则避碰势函数 $\phi_{ib}^o(p_{ib})$ 大于零且势函数在附加的控制输入中是有效的. 对势函数(6)求取负梯度可得

$$\frac{\partial \phi_{ib}^o}{\partial p_i} = \begin{cases} F_{io} + F_{i1}, \underline{R}_o < \|p_{ib}\| < \bar{R}_o; \\ 0, \|p_{ib}\| > \bar{R}_o. \end{cases} \quad (7)$$

其中: F_{io} 为跟随 USV 与障碍物之间的斥力, F_{i1} 为跟随 USV 与领导 USV 之间的斥力. F_{io} 、 F_{i1} 具体可表达为

$$\begin{cases} F_{io} = -\eta_s R_{ts} \left(\frac{1}{\|p_{ib}\| - \underline{R}_o} - \frac{1}{\bar{R}_o} \right) \left(\frac{d_g^2}{\|p_{ib}\|^2} \right), \\ F_{i1} = \eta_s R_{ts} d_g \left(\frac{1}{\|p_{ib}\| - \underline{R}_o} - \frac{1}{\bar{R}_o} \right). \end{cases} \quad (8)$$

式(8)考虑避障斥力所对应的速度为

$$v_{ib}^o = \frac{1}{m_i t} \frac{\partial \phi_{ib}^o}{\partial p_i}. \quad (9)$$

为了描述各个 USV 之间的联系过程, 采用图论进行表达. 将编队中所有 USV 个体表示为非空节点集合 $\nu = \{\nu_1, \nu_2, \nu_3, \dots, \nu_n\}$, 每个个体 i 对应一个节点 ν_i . 图中每一条边 $\varepsilon_{ij} = (\nu_i, \nu_j) \in \varepsilon$ 代表节点 i 对节点 j 的影响, 编队中各 USV 之间的关系对应图中的边集合 $\varepsilon \subseteq \{(\nu_i, \nu_j) : \nu_i, \nu_j \in \varepsilon\}$, 编队 USV 间有无信息交流由邻接矩阵 $A = [a_{ij}] \in \mathbb{R}^{N \times N}$ 描述. 元素 a_{ij} 表示对应边 ε_{ij} 的边权值. 其中: 对角元素 $a_{ij} = 0$, 非对角元素 $a_{ij} > 0$ 表示节点到存在信息流的通信, 否则

$a_{ij} = 0$.

假设 1 对于每艘跟随船, 至少存在一个虚拟领导者, 该虚拟领导者具有到该跟随船的定向通路, 且多 USV 之间的通信是无向的^[18].

本文的控制目标是在满足避碰避障的前提下完成 USV 编队轨迹跟踪任务, 即:

1) 轨迹跟踪任务. 考虑一个连续可导的参数化路径 $p_d(t) = [x_d(t), y_d(t)]^T \in \mathbb{R}^2$, 使编队 USV 跟踪参数化路径, 使 $\lim_{t \rightarrow \infty} |x_{le}| \rightarrow 0$, $\lim_{t \rightarrow \infty} |y_{le}| \rightarrow 0$, 每个跟随 USV 跟随领导 USV, 形成所需的队形, 以确保 $\lim_{t \rightarrow \infty} \|p_i(t) - p_0(t) - p_{id}(t)\| \leq e_{i1}$.

2) 避碰避障任务. 避免各无人船间以及 USV 与障碍物之间的碰撞, 以确保 $\|p_i(t) - p_j(t)\| \geq \underline{R}$, $\|p_i(t) - p_b(t)\| \geq \underline{R}_o$.

2 控制器设计

2.1 运动学制导律设计

将分布式多无人船编队误差定义为

$$z_i = R_i^T(\varphi_i) \left[\sum_{j=1}^N a_{ij} (p_i - p_j - p_{ijd}) + a_{i0} (p_i - p_0 - p_{id}) \right]. \quad (10)$$

其中 $p_{ijd} = p_{id} - p_{jd} \in \mathbb{R}^2$ 为编队中第 i 艘 USV 与第 j 艘 USV 之间相对位置偏差, 若第 i 艘 USV 能够获取第 j 艘 USV 的状态信息, 则 $a_{ij} = 1$, 否则 $a_{ij} = 0$. 旋转矩阵可表示为

$$R_i(\varphi_i) = \begin{bmatrix} \cos \varphi_i & -\sin \varphi_i \\ \sin \varphi_i & \cos \varphi_i \end{bmatrix}. \quad (11)$$

对式(10)求导可得

$$\begin{aligned} \dot{z}_i = & -r_i S z_i + d_i [u_i, v_i]^T - \sum_{j=1}^N a_{ij} R_i^T(\varphi_i) \dot{p}_j + \\ & \sum_{j=1}^N a_{ij} R_i^T(\varphi_i) R_{ci}(\varphi_{ci}) - a_{i0} R_i^T(\varphi_i) \dot{p}_0(t) - \\ & \sum_{j=0}^N a_{ij} R_i^T(\varphi_i) \dot{p}_{ijd}. \end{aligned} \quad (12)$$

其中

$$d_i = \sum_{j=1}^N a_{ij}, \quad S = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix},$$

$$R_{ci}(\varphi_{ci}) = [u_{ci} \cos \varphi_{ci}, u_{ci} \sin \varphi_{ci}]^T.$$

由于 USV 模型具有典型的欠驱动特性, 为解决该问题, 考虑误差转移方程

$$\dot{\bar{z}}_i = z_i + [\delta_0, 0]^T \in \mathbb{R}^2, \quad (13)$$

其中 $\delta_0 \in R$ 为大于零的常数. 将式(12)代入求导后

的式(13)可得

$$\dot{z}_i = \chi_i [u_i, r_i]^T - a_{i0} R_i^T(\varphi_i) \dot{p}_0(t) + \sigma_i. \quad (14)$$

其中

$$\begin{aligned} \chi_i &= \text{diag}\{d_i, \delta_0\}, \\ \sigma_i &= -r_i S \bar{z}_i - \sum_{j=1}^N a_{ij} R_i^T(\varphi_i) \dot{p}_j - \sum_{j=0}^N a_{ij} R_i^T(\varphi_i) \dot{p}_{ijd} + \\ & [0, d_i v_i]^T + \sum_{j=1}^N a_{ij} R_i^T(\varphi_i) R_{ci}(\varphi_{ci}). \end{aligned}$$

定义 $q = [q_{ix}, q_{iy}]^T = \bar{z}_i + R_i^T(\varphi_i) z_{if}$, 其中

$$z_{if} = \frac{1}{m_i t} \left(\frac{\partial \phi_{ij}^c}{\partial p_i} + \frac{\partial \phi_{ib}^o}{\partial p_i} \right). \quad (15)$$

因此, 基于分布式运动学制导律可设计为

$$\begin{aligned} \begin{bmatrix} u_{id} \\ r_{id} \end{bmatrix} &= \\ \chi_i^{-1} & \left(-\frac{K_i q_i}{\Pi_i} + \sum_{j=0}^N a_{ij} R_i^T(\varphi_i) \dot{p}_j + \right. \\ & \left. \sum_{j=0}^N a_{ij} R_i^T(\varphi_i) \dot{p}_{ijd} - \sum_{j=1}^N a_{ij} R_i^T(\varphi_i) R_{ci}(\varphi_{ci}) - \right. \\ & \left. \frac{q_i}{\|q_i\|} z_i^T \begin{bmatrix} 0 \\ d_i v_i \end{bmatrix} - \frac{q_i}{\|q_i\|} z_{if}^T R_i(\varphi_i) \begin{bmatrix} 0 \\ v_i \end{bmatrix} \right). \end{aligned} \quad (16)$$

其中: $K_i = \text{diag}\{k_{i1}, k_{i2}\} \in \mathbb{R}^{2 \times 2}$ 是一个正常数, $\Pi_i = \sqrt{\|q_i\|^2 + \varepsilon_i^2}$, ε_i 是一个正常数. 运动学误差动态方程可表示为

$$\dot{z}_i = -\frac{K_i q_i}{\Pi_i} + \varpi, \quad (17)$$

其中

$$\begin{aligned} \varpi &= -r_i S \bar{z}_i - \frac{q_i}{\|q_i\|} z_i^T \begin{bmatrix} 0 \\ d_i v_i \end{bmatrix} + [0, d_i v_i]^T - \\ & \frac{q_i}{\|q_i\|} z_{if}^T R_i(\varphi_i) \begin{bmatrix} 0 \\ v_i \end{bmatrix}. \end{aligned}$$

2.2 动力学控制律设计

针对由 N 艘无人船组成的编队系统, 采用 RBF 神经网络对 USV 动力学子系统模型中的未知项进行估计. 同时, 使用一种线性解析模型描述输入量化过程. 根据式(2)可得

$$\begin{cases} \dot{u}_i = F_{iu} + m_{iu}^{-1} Q(\tau_{iu}) + d_{iu}, \\ \dot{r}_i = F_{ir} + m_{ir}^{-1} Q(\tau_{ir}) + d_{ir}. \end{cases} \quad (18)$$

其中

$$\begin{aligned} F_{iu} &= m_{iu}^{-1} f_{iu}(u_i, v_i, r_i), \quad F_{ir} = m_{ir}^{-1} f_{ir}(u_i, v_i, r_i), \\ d_{iu} &= m_u^{-1} \tau_{uw}, \quad d_{ir} = m_r^{-1} \tau_{rw}. \end{aligned}$$

令

$$Q(\tau_{iu}) = q_{1iu}(t) \tau_{iu} + q_{2iu}(t),$$

$$Q(\tau_{ir}) = q_{1ir}(t) \tau_{ir} + q_{2ir}(t).$$

取

$$\begin{aligned} q_{1iu}(t) &= \begin{cases} \frac{Q(\tau_{iu}(t))}{\tau_{iu}(t)}, & |\tau_{iu}(t)| \geq \xi_i; \\ 1, & |\tau_{iu}(t)| < \xi_i. \end{cases} \\ q_{1ir}(t) &= \begin{cases} \frac{Q(\tau_{ir}(t))}{\tau_{ir}(t)}, & |\tau_{ir}(t)| \geq \xi_i; \\ 1, & |\tau_{ir}(t)| < \xi_i. \end{cases} \\ q_{2iu}(t) &= \begin{cases} 0, & |\tau_{iu}(t)| \geq \xi_i; \\ Q(\tau_{iu}(t)) - \tau_{iu}(t), & |\tau_{iu}(t)| < \xi_i. \end{cases} \\ q_{2ir}(t) &= \begin{cases} 0, & |\tau_{ir}(t)| \geq \xi_i; \\ Q(\tau_{ir}(t)) - \tau_{ir}(t), & |\tau_{ir}(t)| < \xi_i. \end{cases} \end{aligned} \quad (19)$$

其中 $q_{1iu}(t)$ 和 $q_{1ir}(t)$ 为未知参数. 由于量化过程符号不变, $q_{1iu}(t) > 0, q_{1ir}(t) > 0$. 当 $|\tau_{iu}(t)| < \xi_i, |\tau_{ir}(t)| < \xi_i$ 时, $Q(\tau_{iu}(t)), Q(\tau_{ir}(t))$ 有界, 则 $q_{2iu}(t), q_{2ir}(t)$ 是有界的. 取 $|q_{2iu}(t)| \leq \bar{q}_{2j}, |q_{2ir}(t)| \leq \bar{q}_{2j}$. 动力学控制子系统的控制目标为

$$\begin{cases} \lim_{t \rightarrow \infty} |e_{iu}| = |u_i - u_{id}| \leq \delta_1, \\ \lim_{t \rightarrow \infty} |e_{ir}| = |r_i - r_{id}| \leq \delta_2, \end{cases} \quad (20)$$

其中 δ_1 与 δ_2 为较小的正数. 取滑模函数为

$$\begin{cases} s_{iu} = b_{iu} \int_0^t e_{iu} dt + e_{iu}(t), \\ s_{ir} = b_{ir} \int_0^t e_{ir} dt + e_{ir}(t), \end{cases} \quad (21)$$

其中 b_{iu} 和 b_{ir} 均为大于零的常数. 则对式(21)求导得

$$\begin{aligned} \dot{s}_{iu} &= b_{iu} e_{iu} + \dot{e}_{iu} = \\ & b_{iu} e_{iu} + F_{iu} + m_{iu}^{-1} Q(\tau_{iu}) + d_{iu} - \dot{u}_{id} = \\ & b_{iu} e_{iu} + F_{iu} + m_{iu}^{-1} q_{1iu} \tau_{iu} + m_{iu}^{-1} q_{2iu} + d_{iu} - \dot{u}_{id}, \end{aligned} \quad (22)$$

$$\begin{aligned} \dot{s}_{ir} &= b_{ir} e_{ir} + \dot{e}_{ir} = \\ & b_{ir} e_{ir} + F_{ir} + m_{ir}^{-1} Q(\tau_{ir}) + d_{ir} - \dot{r}_{id} = \\ & b_{ir} e_{ir} + F_{ir} + m_{ir}^{-1} q_{1ir} \tau_{ir} + m_{ir}^{-1} q_{2ir} + d_{ir} - \dot{r}_{id}. \end{aligned} \quad (23)$$

因此有

$$\begin{aligned} s_{iu} \dot{s}_{iu} &= \\ & s_{iu} m_{iu}^{-1} q_{1iu} \tau_{iu} + s_{iu} m_{iu}^{-1} q_{2iu} + s_{iu} d_{iu} + \\ & s_{iu} F_{iu} + s_{iu} (b_{iu} e_{iu} - \dot{u}_{id}) \leq \\ & s_{iu} \left[-l_{iu} s_{iu} - \eta_{iu} \text{sgn} s_{iu} + \eta_{iu} \text{sgn} s_{iu} + \right. \\ & \left. l_{iu} s_{iu} + \frac{1}{2} m_{iu}^{-1} s_{iu} + \bar{d}_{iu} + F_{iu} + b_{iu} e_{iu} - \right. \end{aligned}$$

$$\dot{u}_{id}] + s_{iu}m_{iu}^{-1}q_{1iu}\tau_{iu} + \frac{1}{2}m_{iu}^{-1}\bar{q}_{2iu}^2. \quad (24)$$

假设2 外界未知干扰项有界且满足 $d_{iu} < \bar{d}_{iu}$, 其中 \bar{d}_{iu} 为正常数.

由于 F_{iu} 为未知项, 根据万能逼近定理^[19], 对于任意小的常数 ε_N 存在神经网络系统 $W_{iu}^{*\text{T}}h_{iu}$, 使得 $F_{iu} = W_{iu}^{*\text{T}}h_{iu} + \varepsilon_{iu}$. 其中: $W_{iu}^{*\text{T}}$ 为 RBF 的理想权重; h_{iu} 为神经网络基向量; ε_{iu} 为神经网络逼近误差, 满足 $|\varepsilon_{iu}| \leq \varepsilon_N$. 令 \hat{F}_{iu} 为 F_{iu} 的估计值, 且 $\hat{F}_{iu} = \hat{W}_{iu}^{\text{T}}h_{iu}$, 其中 \hat{W}_{iu}^{T} 为理想权重 $W_{iu}^{*\text{T}}$ 的估计值. 有

$$W_{iu}^{*\text{T}} = \arg \min_{W_{iu} \in \Omega} [\sup_{x \in R^2} |\hat{F}_{iu} - F_{iu}|]. \quad (25)$$

定义

$$\begin{aligned} \kappa_{iu} &= l_{iu}s_{iu} + \eta_{iu}\text{sgn}s_{iu} + \frac{1}{2}m_{iu}^{-1}s_{iu} + \\ &\bar{d}_{iu} + F_{iu} + b_{iu}e_{iu} - \dot{u}_{id}, \end{aligned} \quad (26)$$

其中 l_{iu}, η_{iu} 为大于零的常数, 且 $\eta_{iu} \geq \varepsilon_N + \eta_d + d_{iu}$, $\eta_d > 0$. 进而有

$$\begin{aligned} s_{iu}\dot{s}_{iu} &\leq \\ &-l_{iu}s_{iu}^2 - \eta_{iu}|s_{iu}| + s_{iu}\kappa_{iu} + \\ s_{iu}\tilde{F}_{iu} &+ s_{iu}m_{iu}^{-1}q_{1iu}\tau_{iu} + \frac{1}{2}m_{iu}^{-1}\bar{q}_{2iu}^2 \leq \\ &-l_{iu}s_{iu}^2 - \eta_d|s_{iu}| + s_{iu}\kappa_{iu} + \\ s_{iu}\tilde{W}_{iu}^{\text{T}}h_{iu} &+ s_{iu}m_{iu}^{-1}q_{1iu}\tau_{iu} + \frac{1}{2}m_{iu}^{-1}\bar{q}_{2iu}^2. \end{aligned} \quad (27)$$

其中: $\tilde{W}_{iu} = W_{iu} - \hat{W}_{iu}$, $\tilde{F}_{iu} = F_{iu} - \hat{F}_{iu}$. 类似地, 可得

$$\begin{aligned} s_{ir}\dot{s}_{ir} &\leq \\ &-l_{ir}s_{ir}^2 - \eta_d|s_{ir}| + s_{ir}\kappa_{ir} + \\ s_{ir}\tilde{W}_{ir}^{\text{T}}h_{ir} &+ s_{ir}m_{ir}^{-1}q_{1ir}\tau_{ir} + \frac{1}{2}m_{ir}^{-1}\bar{q}_{2ir}^2. \end{aligned} \quad (28)$$

其中: $\tilde{W}_{ir} = W_{ir} - \hat{W}_{ir}$, \hat{W}_{ir} 为 W_{ir} 的估计值; l_{ir}, η_{ir} 为大于零的常数, 且 $\eta_{ir} \geq \varepsilon_N + \eta_d + d_{ir}$, $\eta_d > 0$.

注1 通过对下界进行估计的方法, 实现对时变且未知的参数 $q_{1iu}(t)$ 和 $q_{1ir}(t)$ 的自适应估计.

将控制律与自适应律设计为

$$\begin{cases} \tau_{iu} = -m_{iu} \frac{s_{iu}\hat{\alpha}_{iu}^2\kappa_{iu}^2}{|s_{iu}\hat{\alpha}_{iu}\kappa_{iu}| + \rho_{iu}}, \\ \tau_{ir} = -m_{ir} \frac{s_{ir}\hat{\alpha}_{ir}^2\kappa_{ir}^2}{|s_{ir}\hat{\alpha}_{ir}\kappa_{ir}| + \rho_{ir}}. \end{cases} \quad (29)$$

$$\begin{cases} \dot{\hat{\alpha}}_{iu} = \gamma_2 s_{iu}\kappa_{iu} - \gamma_2 s_{iu}\hat{\alpha}_{iu}, \\ \dot{\hat{\alpha}}_{ir} = \gamma_4 s_{ir}\kappa_{ir} - \gamma_4 s_{ir}\hat{\alpha}_{ir}. \end{cases} \quad (30)$$

$$\begin{cases} \dot{\hat{W}}_{iu} = \gamma_1 s_{iu}h_{iu}, \\ \dot{\hat{W}}_{ir} = \gamma_3 s_{ir}h_{ir}. \end{cases} \quad (31)$$

其中 $\gamma_1, \gamma_2, \gamma_3, \gamma_4, \rho_{iu}, \rho_{ir}, s_{iu}, s_{ir}$ 为正常值.

基于 $\bar{z}_i, s_{iu}, s_{ir}, \tilde{\alpha}_{iu}, \tilde{\alpha}_{ir}, \tilde{W}_{iu}, \tilde{W}_{ir}$ 所构成的误差动态系统可描述为

$$\begin{cases} \dot{\bar{z}}_i = -\frac{K_i q_i}{\Pi_i} + \varpi, \\ \dot{s}_{iu} = b_{iu}e_{iu} + F_{iu} + m_{iu}^{-1}q_{1iu}\tau_{iu} + \\ \quad m_{iu}^{-1}q_{2iu} + d_{iu} - \dot{u}_{id}, \\ \dot{s}_{ir} = b_{ir}e_{ir} + F_{ir} + m_{ir}^{-1}q_{1ir}\tau_{ir} + \\ \quad m_{ir}^{-1}q_{2ir} + d_{ir} - \dot{r}_{id}, \\ \dot{\hat{\alpha}}_{iu} = \dot{\alpha}_{iu} - \dot{\alpha}_{iu} = \gamma_2 s_{iu}\kappa_{iu} - \gamma_2 s_{iu}\hat{\alpha}_{iu}, \\ \dot{\hat{\alpha}}_{ir} = \dot{\alpha}_{ir} - \dot{\alpha}_{ir} = \gamma_4 s_{ir}\kappa_{ir} - \gamma_4 s_{ir}\hat{\alpha}_{ir}, \\ \dot{\tilde{W}}_{iu} = \dot{W}_{iu}^* - \dot{\hat{W}}_{iu} = -\gamma_1 s_{iu}h_{iu}, \\ \dot{\tilde{W}}_{ir} = \dot{W}_{ir}^* - \dot{\hat{W}}_{ir} = -\gamma_3 s_{ir}h_{ir}. \end{cases} \quad (32)$$

3 稳定性分析

定理1 考虑带有输入量化的 USV 自适应编队跟踪控制系统, 当假设1成立时, 级联系统是输入到状态稳定的, 跟踪误差能够收敛于一个较小的残差集合内, 并且所设计的跟踪控制系统内的所有信号最终一致有界.

证明 考虑如下的 Lyapunov 函数:

$$\begin{aligned} V_2 &= \frac{1}{2} \sum_{i=1}^N \left(s_{iu}^2 + \frac{1}{\gamma_2 \alpha_{iu}} \tilde{\alpha}_{iu}^2 + \frac{1}{\gamma_1} \tilde{W}_{iu}^{\text{T}} \tilde{W}_{iu} + \right. \\ &\quad s_{ir}^2 + \frac{1}{\gamma_4 \alpha_{ir}} \tilde{\alpha}_{ir}^2 + \frac{1}{\gamma_3} \tilde{W}_{ir}^{\text{T}} \tilde{W}_{ir} + \bar{z}_i^{\text{T}} \bar{z}_i + \\ &\quad \left. d_i \sum_{j \in N_i^c} \phi_{ij}^c + d_i \sum_{b \in N_i^c} \phi_{ib}^o \right). \end{aligned} \quad (33)$$

其中 $\tilde{\alpha}_{iu} = \hat{\alpha}_{iu} - \alpha_{iu}$, $\tilde{\alpha}_{ir} = \hat{\alpha}_{ir} - \alpha_{ir}$, $\alpha_{iu} > 0, \alpha_{ir} > 0$. 对式(33)沿(14)方向求导, 并将式(27)和(28)代入可得

$$\begin{aligned} \dot{V}_2 &\leq \\ &\sum_{i=1}^N \left\{ -l_{iu}s_{iu}^2 - \eta_d|s_{iu}| + s_{iu}\kappa_{iu} + s_{iu}m_{iu}^{-1}q_{1iu}\tau_{iu} + \right. \\ &\quad \left. \frac{1}{2}m_{iu}^{-1}\bar{q}_{2iu}^2 + \frac{1}{\gamma_2\alpha_{iu}}\tilde{\alpha}_{iu}\dot{\hat{\alpha}}_{iu} + \right. \\ &\quad \tilde{W}_{iu}^{\text{T}} \left[s_{iu}h_{iu} - \frac{1}{\gamma_1}\dot{\tilde{W}}_{iu} \right] l_{ir}s_{ir}^2 - \eta_d|s_{ir}| + s_{ir}\kappa_{ir} + \\ &\quad s_{ir}m_{ir}^{-1}q_{1ir}\tau_{ir} + \frac{1}{2}m_{ir}^{-1}\bar{q}_{2ir}^2 + \frac{1}{\gamma_4\alpha_{ir}}\tilde{\alpha}_{ir}\dot{\hat{\alpha}}_{ir} + \\ &\quad \tilde{W}_{ir}^{\text{T}} \left[s_{ir}h_{ir} - \frac{1}{\gamma_3}\dot{\tilde{W}}_{ir} \right] + \bar{z}_i^{\text{T}} \chi_i \begin{bmatrix} u_i \\ r_i \end{bmatrix} - \\ &\quad \sum_{j=0}^N a_{ij}\bar{z}_i^{\text{T}} R_i^{\text{T}}(\varphi_i) \dot{p}_j - \sum_{j=0}^N a_{ij}\bar{z}_i^{\text{T}} R_i^{\text{T}}(\varphi_i) \dot{p}_{jd} + \\ &\quad \left. \sum_{j=1}^N a_{ij}\bar{z}_i^{\text{T}} R_i^{\text{T}}(\varphi_i) R_{ci}(\varphi_{ci}) + d_i z_{if}^{\text{T}} R_i^{\text{T}}(\varphi_i) \begin{bmatrix} u_i \\ v_i \end{bmatrix} \right\}. \end{aligned} \quad (34)$$

将式(29)~(31)代入(34)可得

$$\begin{aligned} \dot{V}_2 \leq & \sum_{i=1}^N \left\{ -l_{iu}s_{iu}^2 - \eta_d|s_{iu}| + s_{iu}\kappa_{iu} + \frac{1}{2}m_{iu}^{-1}\bar{q}_{2iu}^2 - \right. \\ & q_{1iu} \frac{s_{iu}^2 \hat{\alpha}_{iu}^2 \kappa_{iu}^2}{|s_{iu} \hat{\alpha}_{iu} \kappa_{iu}| + \rho_{iu}} + \frac{1}{\gamma_2 \alpha_{iu}} \tilde{\alpha}_{iu} (\gamma_2 s_{iu} \kappa_{iu} - \\ & \gamma_2 s_{iu} \hat{\alpha}_{iu}) - l_{ir}s_{ir}^2 - \eta_d|s_{ir}| + s_{ir}\kappa_{ir} + \\ & \frac{1}{2}m_{ir}^{-1}\bar{q}_{2ir}^2 + q_{1ir} \frac{s_{ir}^2 \hat{\alpha}_{ir}^2 \kappa_{ir}^2}{|s_{ir} \hat{\alpha}_{ir} \kappa_{ir}| + \rho_{ir}} + \\ & \left. \frac{1}{\gamma_4 \alpha_{ir}} \tilde{\alpha}_{ir} (\gamma_2 s_{ir} \kappa_{ir} - \gamma_2 s_{ir} \hat{\alpha}_{ir}) + \bar{z}_i^T \chi_i \begin{bmatrix} u_i \\ r_i \end{bmatrix} - \right. \\ & \sum_{j=0}^N a_{ij} \bar{z}_i^T R_i^T(\varphi_i) \dot{p}_j - \sum_{j=0}^N a_{ij} \bar{z}_i^T R_i^T(\varphi_i) \dot{p}_{j,d} + \\ & \left. \sum_{j=1}^N a_{ij} \bar{z}_i^T R_i^T(\varphi_i) R_{ci}(\varphi_{ci}) + d_i z_{if}^T R_i^T(\varphi_i) \begin{bmatrix} u_i \\ v_i \end{bmatrix} \right\}. \end{aligned} \quad (35)$$

注意到 $|a| - \frac{a^2}{\bar{\rho} + |a|} = \frac{\bar{\rho}a}{\bar{\rho} + |a|} < \bar{\rho}$, 可得

$$\begin{cases} -\frac{s_{iu}^2 \hat{\alpha}_{iu}^2 \kappa_{iu}^2}{|s_{iu} \hat{\alpha}_{iu} \kappa_{iu}| + \rho_{iu}} \leq \rho_{iu} - s_{iu} \hat{\alpha}_{iu} \kappa_{iu}, \\ -\frac{s_{ir}^2 \hat{\alpha}_{ir}^2 \kappa_{ir}^2}{|s_{ir} \hat{\alpha}_{ir} \kappa_{ir}| + \rho_{ir}} \leq \rho_{ir} - s_{ir} \hat{\alpha}_{ir} \kappa_{ir}. \end{cases} \quad (36)$$

考虑到 $q_{1iu} > 0, q_{1ir} > 0, -\eta_{iu}|s_{iu}| + \varepsilon_{iu}s_{iu} \leq 0, -\eta_{ir}|s_{ir}| + \varepsilon_{ir}s_{ir} \leq 0$, 可得

$$\begin{cases} -q_{1iu} \frac{s_{iu}^2 \hat{\alpha}_{iu}^2 \kappa_{iu}^2}{|s_{iu} \hat{\alpha}_{iu} \kappa_{iu}| + \rho_{iu}} \leq \frac{1}{\alpha_{iu}} (\rho_{iu} - s_{iu} \hat{\alpha}_{iu} \kappa_{iu}), \\ -q_{1ir} \frac{s_{ir}^2 \hat{\alpha}_{ir}^2 \kappa_{ir}^2}{|s_{ir} \hat{\alpha}_{ir} \kappa_{ir}| + \rho_{ir}} \leq \frac{1}{\alpha_{ir}} (\rho_{ir} - s_{ir} \hat{\alpha}_{ir} \kappa_{ir}). \end{cases} \quad (37)$$

基于式(37), 不等式(35)可写为

$$\begin{aligned} \dot{V}_2 \leq & \sum_{i=1}^N \left\{ -l_{iu}s_{iu}^2 - \eta_d|s_{iu}| + \frac{1}{2}m_{iu}^{-1}\bar{q}_{2iu}^2 + \frac{1}{\alpha_{iu}}\rho_{iu} - \right. \\ & \frac{1}{\alpha_{iu}} \tilde{\alpha}_{iu} s_{iu} \hat{\alpha}_{iu} - l_{ir}s_{ir}^2 - \eta_d|s_{ir}| + \frac{1}{2}m_{ir}^{-1}\bar{q}_{2ir}^2 + \\ & \frac{1}{\alpha_{ir}}\rho_{ir} - \frac{1}{\alpha_{ir}} \tilde{\alpha}_{ir} s_{ir} \hat{\alpha}_{ir} + \bar{z}_i^T \chi_i \begin{bmatrix} u_i \\ r_i \end{bmatrix} - \\ & \sum_{j=0}^N a_{ij} \bar{z}_i^T R_i^T(\varphi_i) \dot{p}_j - \sum_{j=0}^N a_{ij} \bar{z}_i^T R_i^T(\varphi_i) \dot{p}_{j,d} + \\ & \left. \sum_{j=1}^N a_{ij} \bar{z}_i^T R_i^T(\varphi_i) R_{ci}(\varphi_{ci}) + d_i z_{if}^T R_i^T(\varphi_i) \begin{bmatrix} u_i \\ v_i \end{bmatrix} \right\}. \end{aligned} \quad (38)$$

由于

$$\begin{cases} -\frac{1}{\alpha_{iu}} \tilde{\alpha}_{iu} s_{iu} \hat{\alpha}_{iu} \leq -\frac{s_{iu}}{2\alpha_{iu}} \tilde{\alpha}_{iu}^2 + \frac{s_{iu}}{2} \alpha_{iu}, \\ -\frac{1}{\alpha_{ir}} \tilde{\alpha}_{ir} s_{ir} \hat{\alpha}_{ir} \leq -\frac{s_{ir}}{2\alpha_{ir}} \tilde{\alpha}_{ir}^2 + \frac{s_{ir}}{2} \alpha_{ir}. \end{cases} \quad (39)$$

将式(39)和(16)代入(38), 可得

$$\begin{aligned} \dot{V}_2 \leq & \sum_{i=1}^N \left\{ -l_{iu}s_{iu}^2 - \eta_d|s_{iu}| - \frac{1}{2\alpha_{iu}} s_{iu} \tilde{\alpha}_{iu}^2 + D_{iu} - l_{ir}s_{ir}^2 - \right. \\ & \eta_d|s_{ir}| - \frac{1}{2\alpha_{ir}} s_{ir} \tilde{\alpha}_{ir}^2 + D_{ir} - q_i^T K_i' q_i + z_{if}^T \bar{v}_i \left. \right\} \leq \\ & \sum_{i=1}^N \left\{ -l_{iu}s_{iu}^2 - \frac{1}{2\alpha_{iu}} s_{iu} \tilde{\alpha}_{iu}^2 + D_{iu} - l_{ir}s_{ir}^2 + D_{ir} - \right. \\ & \left. \frac{1}{2\alpha_{ir}} s_{ir} \tilde{\alpha}_{ir}^2 - \lambda_{\min}(K_i') \|q_i\|^2 + \frac{1}{2} \|z_{if}\|^2 + \frac{1}{2} \|\bar{v}_i\|^2 \right\}. \end{aligned} \quad (40)$$

其中

$$\begin{aligned} K_i' &= K_i / \Pi_i, \\ D_{iu} &= m_{iu}^{-1} \bar{q}_{2iu}^2 / 2 + \rho_{iu} / \alpha_{iu} + s_{iu} \alpha_{iu} / 2, \\ D_{ir} &= m_{ir}^{-1} \bar{q}_{2ir}^2 / 2 + \rho_{ir} / \alpha_{ir} + s_{ir} \alpha_{ir} / 2, \\ \bar{v}_i &= \sum_{j=0}^N a_{ij} \dot{p}_{j,d} + \sum_{j=0}^N a_{ij} \dot{p}_j - \delta_0 R_i(\varphi_i) \begin{bmatrix} 0 \\ r_i \end{bmatrix}. \end{aligned}$$

将稳定性分析分为两步. 首先, 分析避碰区域外闭环系统的稳定性; 其次给出避碰区域内的稳定性分析. 定义

$$\begin{aligned} \bar{z} &= [\bar{z}_1^T, \dots, \bar{z}_N^T]^T, \quad s_u = [s_{1u}, \dots, s_{Nu}]^T, \\ s_r &= [s_{1r}, \dots, s_{Nr}]^T, \quad \tilde{\alpha}_u = [\tilde{\alpha}_{1u}, \dots, \tilde{\alpha}_{Nu}]^T, \\ \tilde{\alpha}_r &= [\tilde{\alpha}_{1r}, \dots, \tilde{\alpha}_{Nr}]^T, \quad q = [q_1, \dots, q_N]^T, \\ E_2 &= [s_u, s_r, \tilde{\alpha}_u, \tilde{\alpha}_r, \bar{z}], \end{aligned}$$

$$\bar{h}_2 = \min_{i=1,2,\dots,N} (l_{iu}, l_{ir}, s_{iu}/2\alpha_{iu}, s_{ir}/2\alpha_{ir}, \lambda_{\min}).$$

step 1: 在避撞区域 $\|p_{ij}\| > \bar{R}$ 之外, $\partial\phi_{ij}/\partial p_i = 0$, 因此 $q_i = \bar{z}_i$ 且式(40)可以改写为

$$\begin{aligned} \dot{V}_2 \leq & -(1 - \bar{\theta}_2) \bar{h}_2 \|E_2\|^2 - \bar{\theta}_2 \bar{h}_2 \|E_2\|^2 + \sum_{i=1}^N (D_{iu} + D_{ir}). \end{aligned} \quad (41)$$

注意到

$$\|E_2\| \geq \sum_{i=1}^N \left(\sqrt{\frac{D_{ir} + D_{iu}}{\bar{\theta}_2 \bar{h}_2}} \right), \quad (42)$$

使得

$$\dot{V}_2 \leq -(1 - \bar{\theta}_2) \bar{h}_2 \|E_2\|^2, \quad (43)$$

其中 $0 < \bar{\theta}_2 < 1$. 分布式编队控制闭环系统的误差是

一致最终有界的,且

$$\|E_2(t)\| \leq \sqrt{\frac{\lambda_{\max}(P_c)}{\lambda_{\min}(P_c)}} \left\{ \max \left(\|E_2(t_0)\| e^{-\rho_2(t-t_0)}, \sum_{i=1}^N \left(\sqrt{\frac{2D_{ir} + 2D_{iu} + \|\bar{v}_i\|^2 + \|z_{if}\|^2}{2\bar{\theta}_2 \bar{h}_2}} \right) \right) \right\}, \quad \forall t \geq t_0. \quad (44)$$

其中

$$\rho_2 = 2\bar{h}_2(1 - \bar{\theta}_2)/\lambda_{\max}(P_c),$$

$$P_c = \text{diag}\{1, 1/2\gamma_2\alpha_{1u}, \dots, 1/2\gamma_2\alpha_{Nu}, 1/2\gamma_4\alpha_{1r}, \dots, 1/2\gamma_4\alpha_{Nr}, 1/2\gamma_1, 1/2\gamma_3\}.$$

step 2: 在避碰区域内,式(40)可表示为

$$\dot{V}_2 \leq -(1 - \bar{\theta}_2)\bar{h}_2\|E_2\|^2 - \bar{\theta}_2\bar{h}_2\|E_2\|^2 + \sum_{i=1}^N \left(D_{iu} + D_{ir} + \frac{1}{2}\|\bar{v}_i\|^2 + \frac{1}{2}\|z_{if}\|^2 \right). \quad (45)$$

注意到

$$\|E_2\| \geq \sum_{i=1}^N \left(\sqrt{\frac{2D_{ir} + 2D_{iu} + \|\bar{v}_i\|^2 + \|z_{if}\|^2}{2\bar{\theta}_2 \bar{h}_2}} \right), \quad (46)$$

使得

$$\dot{V}_2 \leq -(1 - \bar{\theta}_2)\bar{h}_2\|E_2\|^2, \quad (47)$$

其中 $0 < \bar{\theta}_2 < 1$. 分布式编队控制闭环系统的误差是一致最终有界的,且

$$\|E_2(t)\| \leq \sqrt{\frac{\lambda_{\max}(P_c)}{\lambda_{\min}(P_c)}} \left\{ \max \left(\|E_2(t_0)\| e^{-\rho_2(t-t_0)}, \sum_{i=1}^N \left(\sqrt{\frac{2D_{ir} + 2D_{iu} + \|\bar{v}_i\|^2 + \|z_{if}\|^2}{2\bar{\theta}_2 \bar{h}_2}} \right) \right) \right\}, \quad \forall t \geq t_0. \quad (48)$$

定理得证. \square

4 仿真实例

考虑由1艘领导USV和4艘USV组成的欠驱动编队系统,其中领导者沿着期望轨迹 $p_d(t) = [t, 1.12t - 2.61]$ 航行,5艘无人船的参数选取如下:

$$m_{iu} = \{12.9, 25.8, 38.7, 51.6, 64.5\} \text{ kg},$$

$$m_{ir} = \{1.38, 2.76, 4.14, 5.52, 6.90\} \text{ kg} \cdot \text{m}^2,$$

$$f_{iu}(\cdot) = -5.87u^3 - 1.33|u|u - 0.72u + m_{iv}vr + 1.0948r^2,$$

$$f_{ir}(\cdot) = -0.75|r|r - 1.90r + 0.08|v|r +$$

$$(m_{iu} - m_{iv})uv - 1.0948ur.$$

外界的未知环境干扰为 $\tau_{iuw} = \sin t, \tau_{iuv} = \cos t, \tau_{irw} = \sin t + \cos t$. USVs的初始位置状态设为 $p_1 = [2, 3]^T, p_2 = [-1, 3]^T, p_3 = [2, 0]^T, p_4 = [-4, 3]^T, p_5 = [4, -3]^T$;所需的编队队形设置为 $p_{1d} = [0, 0]^T, p_{2d} = [-3.5 + \cos((t+30)/32), 0]^T, p_{3d} = [0, -3.5 + \cos((t+30)/32)]^T, p_{4d} = [-7 + \cos((t+30)/16), 0]^T, p_{5d} = [0, -7 + \cos((t+30)/16)]^T$. 控制器参数 $K_i = \text{diag}\{0.1, 0.1\}, \delta_0 = 0.1, \varepsilon_i = 0.01, \eta_{iu} = \eta_{ir} = 2, \gamma_3 = \gamma_4 = 3$. 均匀量化器的量化参数取 $o_{iu} = 0.1, o_{ir} = 0.1$. 势函数的选取参数为 $\underline{R} = 5, \bar{R} = 8, \underline{R}_o = 2, \bar{R}_o = 4.5, R_{ts} = 5, \eta_s = 100000$. 仿真结果如图2~图6所示. 由图2可知,4艘跟随USV能够保持一定的队形跟踪领导者,红色领导者无人船沿特定参数化轨迹航行,且编队中无人船与障碍物间无碰撞危险. 图3和图4为无人船编队中各无人船的跟踪误差对比曲线,当存在碰撞风险时,避碰及避障的优先级高于编队队形保持. 在无碰撞危险区域内,编队误差收敛到平衡点附近的较小邻域内. 图5和图6为控制输入力矩与转舵力矩对比曲线. 通过分析仿真结果分析可得,所设计的带有反向斥力速度的运动学制导

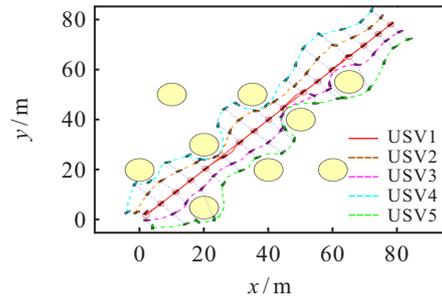


图2 无人船编队跟踪控制路径

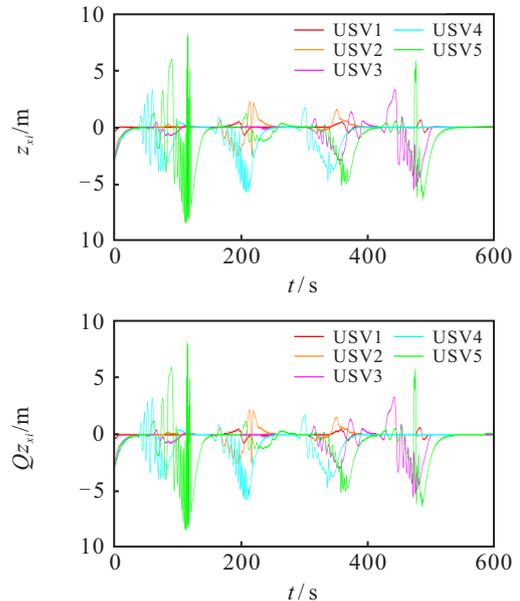


图3 无人船编队横向跟踪误差对比曲线

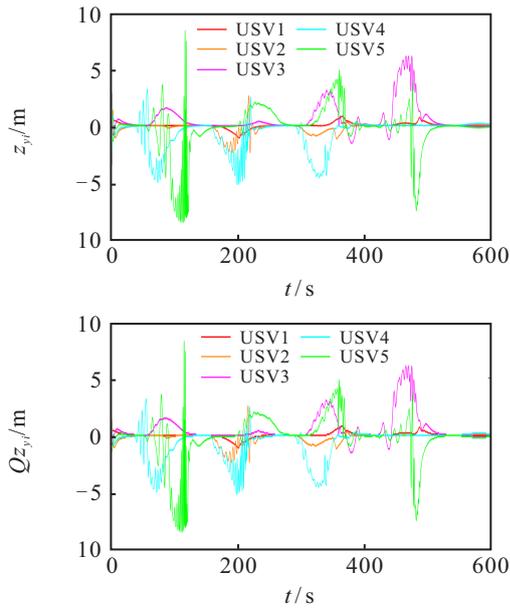


图4 无人船编队纵向跟踪误差对比曲线

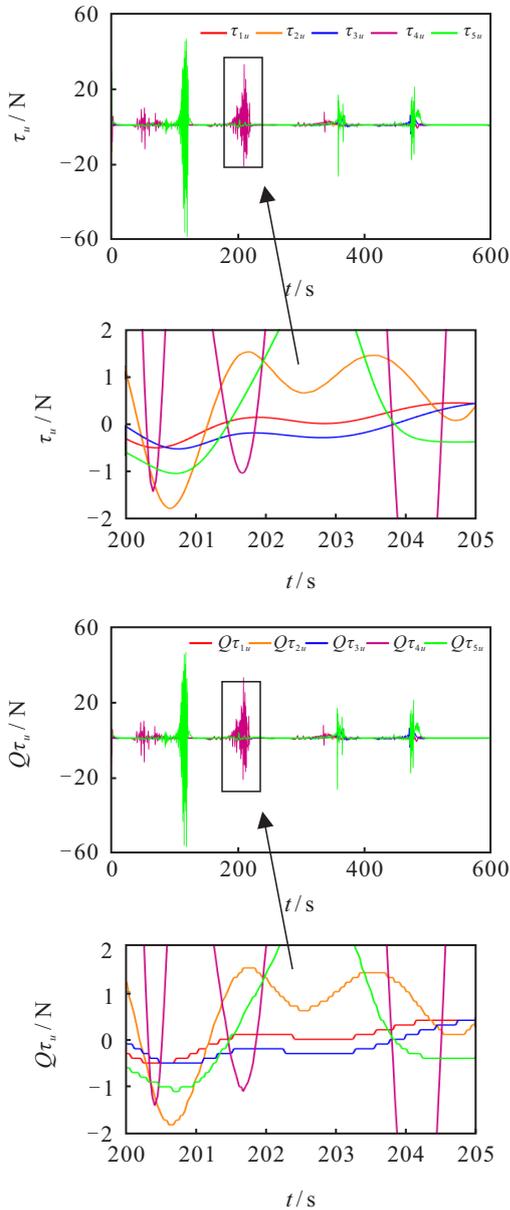


图5 控制输入推进力对比曲线

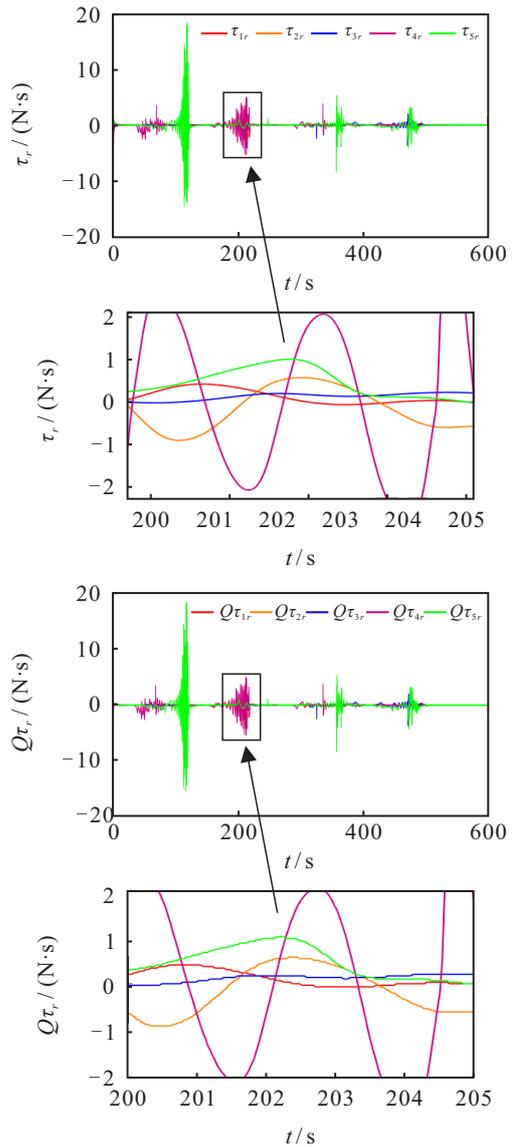


图6 控制输入转舵力矩对比曲线

律可以使USV编队控制系统在保持队形的同时实现避碰避障,所构造的动力学控制律能够快速跟踪运动学子系统给出的制导律,实现欠驱动无人船编队的跟踪控制.

5 结论

本文探究了基于改进人工势场法的无人船编队协同避碰避障策略.基于图论法与领导-跟随法相结合的编队结构框架,在运动学子系统引入改进人工势场法的斥力函数,重构无人船编队运动学制导律,从而解决编队系统中各船舶之间、船舶与障碍物间避碰避障问题.在动力学子系统通过采用RBF神经网络实现了对无人船动力学干扰及系统未建模动态的估计,所设计的滑模自适应控制律能够实现对运动学制导律的有效跟踪.仿真实验验证了所提出的基于改进人工势场法且带有输入量化的船舶编队协同避碰避障策略的有效性.

参考文献(References)

- [1] 余明裕, 李仲昆, 王泊桦. 基于固定时间扰动观测器的水面无人艇精确编队控制[J]. 控制与决策, 2023, 38(2): 379-387.
(Yu M Y, Li Z K, Wang B H. Fixed-time disturbance observer-based accurate formation control of unmanned surface vehicles[J]. Control and Decision, 2023, 38(2): 379-387.)
- [2] 隋丽蓉, 高曙, 何伟. 基于多智能体深度强化学习的船舶协同避碰策略[J]. 控制与决策, 2023, 38(5): 1395-1402.
(Sui L R, Gao S, He W. Ship cooperative collision avoidance strategy based on multi-agent deep reinforcement learning[J]. Control and Decision, 2023, 38(5): 1395-1402.)
- [3] Zhang J X, Chai T Y. Singularity-free continuous adaptive control of uncertain underactuated surface vessels with prescribed performance[J]. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 2022, 52(9): 5646-5655.
- [4] 马俊达, 谭冲, 刘可. 欠驱动无人船非奇异固定时间鲁棒包容控制[J]. 控制与决策, 2023, 38(5): 1286-1294.
(Ma J D, Tan C, Liu K. Non-exotic fixed time robust tolerant control [J]. Control and Decision, 2023, 38(5): 1286-1294.)
- [5] Park B S, Yoo S J. Connectivity-maintaining and collision-avoiding performance function approach for robust leader-follower formation control of multiple uncertain underactuated surface vessels[J]. Automatica, 2021, 127: 109501.
- [6] Wang C L, Wen C Y, Lin Y, et al. Decentralized adaptive tracking control for a class of interconnected nonlinear systems with input quantization[J]. Automatica, 2017, 81: 359-368.
- [7] Choi Y H, Yoo S J. Distributed quantized feedback design strategy for adaptive consensus tracking of uncertain strict-feedback nonlinear multiagent systems with state quantizers[J]. IEEE Transactions on Cybernetics, 2022, 52(7): 7069-7083.
- [8] Zhou J, Wen C Y, Yang G H. Adaptive backstepping stabilization of nonlinear uncertain systems with quantized input signal[J]. IEEE Transactions on Automatic Control, 2014, 59(2): 460-464.
- [9] Wu J, Sun W, Su S F, et al. Adaptive asymptotic tracking control for input-quantized nonlinear systems with multiple unknown control directions[J]. IEEE Transactions on Cybernetics, 2023, 53(8): 5216-5225.
- [10] Hao L Y, Zhang H, Guo G, et al. Quantized sliding mode control of unmanned marine vehicles: Various thruster faults tolerated with a unified model[J]. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 2019: 51(3): 2012-2026.
- [11] Han S, Wang L, Wang Y T. A COLREGs-compliant guidance strategy for an underactuated unmanned surface vehicle combining potential field with grid map[J]. Ocean Engineering, 2022, 255: 111355.
- [12] Lyridis D V. An improved ant colony optimization algorithm for unmanned surface vehicle local path planning with multi-modality constraints[J]. Ocean Engineering, 2021, 241: 109890.
- [13] Woo J, Kim N. Collision avoidance for an unmanned surface vehicle using deep reinforcement learning[J]. Ocean Engineering, 2020, 199: 107001.
- [14] 宁君, 彭周华, 李铁山, 等. 带有输入量化的分布式多无人船舶自适应模糊编队控制[J]. 控制与决策, 2024, 39(8): 2588-2596.
(Ning J, Peng Z H, Li T S, et al. Distributed adaptive fuzzy formation control for multiple unmanned ships with input quantization[J]. Control and Decision, 2024, 39(8): 2588-2596.)
- [15] Peng Z, Wang D, Li T, et al. Output-feedback cooperative formation maneuvering of autonomous surface vehicles with connectivity preservation and collision avoidance[J]. IEEE Transactions on Cybernetics, 2020, 50(6): 2527-2535.
- [16] Xue K, Wu T Y. Distributed consensus of USVs under heterogeneous UAV-USV multi-agent systems cooperative control scheme[J]. Journal of Marine Science and Engineering, 2021, 9(11): 1314.
- [17] 郝立颖, 韩金城, 郭戈, 等. 带有推进器故障的船舶动力定位系统的鲁棒滑模容错控制[J]. 控制与决策, 2020, 35(6): 1291-1296.
(Hao L Y, Han J C, Guo G, et al. Robust sliding mode fault-tolerant control for dynamic positioning system of ships with thruster faults[J]. Control and Decision, 2020, 35(6): 1291-1296.)
- [18] Peng Z H, Wang J, Wang D. Distributed containment maneuvering of multiple marine vessels via neurodynamics-based output feedback[J]. IEEE Transactions on Industrial Electronics, 2017, 64(5): 3831-3839.
- [19] 沈智鹏, 曹晓明. 输入受限四旋翼飞行器的模糊自适应动态面轨迹跟踪控制[J]. 控制与决策, 2019, 34(7): 1401-1408.
(Shen Z P, Cao X M. Fuzzy adaptive dynamic surface trajectory tracking control for quadrotor UAV with input constraints[J]. Control and Decision, 2019, 34(7): 1401-1408.)

作者简介

李伟(1968—), 男, 教授, 博士, 硕士生导师, 主要研究方向为船舶智能控制、船舶自动避碰, E-mail: li_wei@dlnu.edu.cn;

张永超(2001—), 男, 硕士生, 主要研究方向为船舶编队控制, E-mail: ZYChao0324@126.com;

宁君(1988—), 男, 副教授, 博士, 主要研究方向为船舶编队控制、船舶自动避碰, E-mail: juning@dlnu.edu.cn;

马昊冉(1998—), 女, 硕士生, 主要研究方向为船舶路径规划与跟踪控制, E-mail: mhaora@163.com;

刘陆(1990—), 女, 副教授, 博士, 主要研究方向为智能船舶制导与控制, E-mail: lulu@dlnu.edu.cn;

彭周华(1982—), 男, 教授, 博士, 主要研究方向为无人船集群控制, E-mail: zhpeng@dlnu.edu.cn.