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ADAPTIVE NEURAL NETWORKS FORMATION CONTROL FOR UNMANNED SURFACE VEHICLES WITH NETWORK FAULTS

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Abstract. *In this paper, the problem of robust adaptive neural formation control for unmanned surface vehicles (USVs) is studied under undirected communication topology. The considered systems contain the unknown nonlinear functions and network faults, and neural networks are utilized to identify the unknown nonlinear functions. A new observer is designed for fault transformation signal observation in network. Then, an NNs adaptive observer consensus control scheme is developed. The presented formation control approach can not only ensure the multiple USVs with network faults are stable, but also the followers can track the leader.*
Keywords: Unmanned surface vehicle, Formation control, Network faults, Adaptive neural network

1. **Introduction.** Due to its wide application in the fields of ocean engineering such as sensor networks, cooperative search and rescue, and ocean survey, the formation control of multiple unmanned surface vehicles (USVs) has aroused great interest in [1,2]. Marine operations by using a group of unmanned surface vehicles contribute to improved effectiveness and efficiency over a single unmanned surface vehicle. The existing formation control schemes mainly include leader-follower method [3], graph-based mechanism [4], virtual structure [5], etc. However, nonlinear dynamics are unavoidable in the modeling of multiple unmanned surface vehicles. Some control approaches, such as sliding-mode control, input-to-state stability, robust control, and adaptive control, are developed to handle the formation control problem of nonlinear USVs. Especially, the approximation ability of fuzzy logic systems (FLSs) or neural networks (NNs) has become an effective tool for solving nonlinear functions problem. The authors in [6] investigated NN consensus maneuvering control methods for nonlinear strict feedback multivehicle systems. Note that the above NNs formation control methods are proposed for multiple USVs based on the accurate transmission signal of coupling agent. When the transmission signal is disturbed, more research should be carried out to offset the influence of the measurement error of disturbed coupling signal.

Furthermore, the agent cannot receive the original signal of the coupling agent to achieve consistent behavior. When the fault signal transmitter of the agent leads to network attenuation or there are various conversion media with long distance between agents, the coupling agent may receive the fault coupling signal, which seriously destroys the consensus. As far as we know, some fault networks have not been well studied in the multi-agent

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system. In recent years, some fault networks have been considered as the synchronization of complex networks and the consensus of multi-agent systems [7]. For nonlinear multi-agent systems, the authors of [8] proposed a consistency control method which is affected by network faults and actuator faults. Compared with the existing results, the features of the proposed adaptive NNs control method for formation maneuvering of USVs are as follows. First, this paper studies a novel NNs adaptive formation control method for multiple nonlinear USVs with network faults by using an adaptive observer. Then, by Lyapunov stability theory, it is proved that all signals of controlled system are bound and overcome the impact of network faults.

The reminder of this work is constructed as follows. Section 2 presents problem statement and preliminaries. The adaptive observer and NNs controller design is given in Section 3. Stability analysis is given in Section 4. Finally, the conclusion is given in Section 5.

2. **Problem Statement and Preliminaries.** Consider the mathematical model for the 3-DOF motion of USVs as

$$\begin{aligned} \dot{\eta}_i &= J(\eta_i)\nu_i \\ M_i\dot{\nu}_i &= -C(\nu_i)\nu_i - D(\nu_i)\nu_i + \tau_i \end{aligned} \tag{1}$$

where $\eta_i = [x_i, y_i, \psi_i]^{\mathrm{T}}$ is the vehicle output, (x_i, y_i) denotes the position of the ith vehicle; ψ_i is the yaw angle of the ith vehicle; and $\nu_i = [u_i, \upsilon_i, r_i]^{\mathrm{T}}$ are the corresponding velocities in surge, sway, and yaw of the ith vehicle. τ_i are the control inputs. The matrices $J(\eta_i)$, M_i, $C(\nu_i)$ and $D(\nu_i)$ are expressed by

$$J(\eta_i) = \begin{bmatrix} \cos\psi_i & -\sin\psi_i & 0 \\ \sin\psi_i & \cos\psi_i & 0 \\ 0 & 0 & 1 \end{bmatrix}, \ M_i = \begin{bmatrix} m_{11i} & 0 & 0 \\ 0 & m_{22i} & m_{23i} \\ 0 & m_{32i} & m_{33i} \end{bmatrix},$$

$$C(\nu_i) = \begin{bmatrix} 0 & 0 & c_{13i} \\ 0 & 0 & m_{11i}u_i \\ -c_{13i} & -m_{11i}u_i & 0 \end{bmatrix} \text{ and } D(\nu_i) = \begin{bmatrix} d_{11i} & 0 & 0 \\ 0 & d_{22i} & d_{23i} \\ 0 & d_{32i} & d_{33i} \end{bmatrix}$$

with $c_{13i} = -m_{22i}\upsilon_i - m_{23i}r_i$, $m_{11i} = m_i - X_{\dot{u}i}$, $m_{22i} = m_i - Y_{\dot{\upsilon}i}$, $m_{23i} = m_i x_{gi} - Y_{\dot{r}i}$ and $m_{33i} = I_{z_i} - N_{\dot{r}i}$ as unknown parameters. Here m_i is the mass of the ith vehicle. $X_{\dot{u}i}$, $Y_{\dot{\upsilon}i}$, $Y_{\dot{r}i}$ and $N_{\dot{r}i}$ are the added masses. I_{z_i} is the moment of inertia in yaw. x_{gi} is the vehicle center of gravity. d_{11i}, d_{22i}, d_{23i}, d_{32i} and d_{33i} are the modeling uncertainties.

It is assumed that the connection signal between agents may be attenuated due to transmitter failure and natural attenuation caused by communication medium and long distance. Then, the model of fault network is

$$y_i = \delta_i \eta_i \tag{2}$$

where y_i is the network faulty signal from agent i to the connected agent j; δ_i is an unknown constant, satisfying $\delta_i \in \left[\underline{\delta}_i, \overline{\delta}_i\right]$ where $\underline{\delta}_i$ and $\overline{\delta}_i$ are the known lower and upper bounds of δ_i and in practice, $0 < \underline{\delta}_i \le \overline{\delta}_i \le 1$.

Control Objective: For nonlinear multiple unmanned surface vehicles (1), an NN adaptive formation control method is proposed such that the system (1) is stable, and all followers can track the leaders subject to the network faults.

3. **Adaptive Observer and NNs Controller Design.** In the case of network failure, the agent may obtain abnormal signals from the connected agent, thus damaging the consistency of the agent. Based on the designed observer, the measured information can observe the fault coupling signal. Here, we design an adaptive observer based on neural network

$$\hat{\eta}_j = c_j\left(\hat{y}_j - y_j\right) \tag{3}$$

where $\hat{\eta}_j$ is the estimation of η_j, $\hat{y}_j = \hat{\delta}_j\hat{\eta}_j$, $y_j = \delta_j\eta_j$, $c_j = diag_{l=1}^{n}[c_{j,l}] > 0$.

Defining $\tilde{\eta}_j = \eta_j - \hat{\eta}_j(t)$, from (1) and (3), we have

$$\dot{\hat{\eta}}_i(t) = J(\eta_i)\nu_i + c_j(\hat{y}_j(t) - y_j(t)) \tag{4}$$

Define the following change of coordinates:

$$e_{i,1}(t) = \sum_{i=1}^{N} a_{i,j}(y_i - y_j) + a_{i,0}(y_i - y_d) \tag{5}$$

$$e_{i,2} = \nu_i - \alpha_i \tag{6}$$

where α_i is the virtual controller, $e_{i,1}$ and $e_{i,2}$ are the errors.

From (5), we have

$$\dot{e}_1(t) = (L + B)\sigma_1 \tag{7}$$

where $\sigma_1 = \overline{y} - y_d$, $\overline{y} = [y_1, \ldots, y_N]^{\mathrm{T}}, e_1 = [e_{1,1}, e_{2,1}, \ldots, e_{N,1}]^{\mathrm{T}}$, $\overline{y}_d = [\overline{y}_d, \ldots, \overline{y}_d]$.

Construct the following Lyapunov function as

$$V_0 = \sum_{i=1}^{N} \left[e_1^{\mathrm{T}}(L + B)e_1 + \tilde{\eta}_i^{\mathrm{T}}\tilde{\eta}_i\right] \tag{8}$$

From (7) and (8), the time derivate of V_0

$$\begin{aligned}\dot{V}_0 &= \sum_{i=1}^{N} \left[e_{i,1}^{\mathrm{T}} (\dot{y}_i - \dot{y}_d) + [J(\eta_i)\nu_i + c_i(\hat{y}_i(t) - y_i(t))]^{\mathrm{T}} (\eta_i - \hat{\eta}_i)\right] \\ &\leq \sum_{i=1}^{N} \left[e_{i,1}^{\mathrm{T}} [\delta_i(J(\eta_i)\nu_i) - \dot{y}_d] + \left[J(\eta_i)\nu_i + c_i\left(\hat{\delta}_i\hat{\eta}_i - \delta_j\eta_i\right)\right]^{\mathrm{T}} |\eta_i - \hat{\eta}_i|\right]\end{aligned} \tag{9}$$

Here, we can deduce that, in the case of $|\tilde{\eta}_i| \geq \zeta_i$, where $\zeta_i > 0$ is a constant, when choosing c_i large enough, we have

$$\begin{aligned}&c_i\left(\hat{\delta}_i\hat{\eta}_i - \delta_i\eta_i\right)^{\mathrm{T}} |\eta_i - \hat{\eta}_i| \\ &= c_i\delta_i(\hat{\eta}_i - \eta_i)^2 - c_i\tilde{\delta}_i\hat{\eta}_i(\hat{\eta}_i - \eta_i) \geq \|y_i - \hat{y}_j\|^2 + c_i\tilde{\delta}_i\hat{\eta}_i(\hat{\eta}_i - \eta_i)\end{aligned} \tag{10}$$

From (9) and (10), we have

$$\dot{V}_0 \leq \sum_{i=1}^{N} \left[e_1^{\mathrm{T}}\left[\left(\tilde{\delta}_j + \hat{\delta}_j\right)(J(\eta_i)(\alpha_i + e_{i,2}) - \dot{y}_d)\right] + c_i\tilde{\delta}_i\hat{\eta}_i(\hat{\eta}_i - \eta_i) - \|y_i - \hat{y}_j\|^2\right] \tag{11}$$

Design the virtual controller as

$$\alpha_i = \frac{1}{\hat{\delta}_i J}(-c_{i,1}e_1 + \dot{y}_d) \tag{12}$$

From (11) and (12), we have

$$\begin{aligned}\dot{V}_0 \leq \sum_{i=1}^{N} &\left[e_1^{\mathrm{T}}\left[J(\eta_i)\left(\tilde{\delta}_i + \hat{\delta}_i\right)e_{i,2} + e_1^{\mathrm{T}}J(\eta_i)\tilde{\delta}_i\alpha_i - c_{i,1}e_1^{\mathrm{T}}e_1\right]\right. \\ &\left. + c_i\hat{\eta}_i(\hat{\eta}_i - \eta_i)\tilde{\delta}_i - \|y_i - \hat{y}_j\|^2\right]\end{aligned} \tag{13}$$

From (1) and (6), we have

$$\dot{e}_{i,2} = M_i^{-1}(-C(\nu_i)\nu_i - D(\nu_i)\nu_i + \tau_i) - \dot{\alpha}_i \tag{14}$$

Due to the fact that the unmanned surface vehicle $f_{i,2}(\nu_i) = -M_i^{-1}C(\nu_i)\nu_i - M_i^{-1}D(\nu_i)\nu_i$ is unknown, an NN is adopted to identify $f_{i,2}(\nu_i)$, such that

$$f_{i,2}(\nu_i) - w_i^{*\mathrm{T}}\zeta_i(\nu_i) = \hbar_i \tag{15}$$

where $|\hbar_i| \leq \hbar_i^*$, $\hbar_i^* > 0$ is an unknown constant.

From (14) and (15), we have

$$\dot{e}_{i,2} = \left(w_i^{*\mathrm{T}}\zeta_i(\nu_i) + M_i^{-1}\tau_i + \hbar_i\right) - \dot{\alpha}_i \tag{16}$$

Construct the Lyapunov functions as

$$V_1 = V_0 + \sum_{i=1}^{N}\left[e_{2,i}^{\mathrm{T}}M_i e_{2,i} + \frac{1}{2}\sum_{k=1}^{N}\tilde{w}_{ki}^{\mathrm{T}}\Upsilon_{ki}^{-1}\tilde{w}_{ki} + \tilde{\delta}_i^{\mathrm{T}}\tilde{\delta}_i\right] \tag{17}$$

From (17), the time derivate of V_1 is

$$\begin{aligned}\dot{V}_1 &= \dot{V}_0 + \sum_{i=1}^{N}\left[e_{2,i}^{\mathrm{T}}M_i\dot{e}_{2,i} + \sum_{k=1}^{N}\tilde{w}_{ki}^{\mathrm{T}}\Upsilon_{ki}^{-1}\dot{\tilde{w}}_{ki} + \tilde{\delta}_i^{\mathrm{T}}\dot{\tilde{\delta}}_i\right]\\
&\le \sum_{i=1}^{N}\left[e_1^{\mathrm{T}}\left[\left(\tilde{\delta}_i + \hat{\delta}_i\right)J(\eta_i)e_{i,2}\right] - \|y_i - \hat{y}_j\|^2 + \tilde{\delta}_i^{\mathrm{T}}\dot{\hat{\delta}}_i + c_i\tilde{\delta}_i\hat{\eta}_i(\hat{\eta}_i - \eta_i)\right]\\
&\quad + \sum_{k=1}^{N}\tilde{w}_{ki}^{\mathrm{T}}\Upsilon_{ki}^{-1}\dot{\tilde{w}}_{ki} + \sum_{i=1}^{N}\left[e_{2,i}^{\mathrm{T}}M_i\left(\hbar_i + w_i^{*\mathrm{T}}\zeta_i(\nu_i) - \dot{\alpha}_i + M_i^{-1}\tau_i\right) + \tilde{\delta}_i^{\mathrm{T}}\dot{\tilde{\delta}}_i - c_{i,1}e_1^{\mathrm{T}}e_1\right]\end{aligned} \tag{18}$$

By using Young's inequality, one obtains

$$e_{2,i}^{\mathrm{T}}\hbar_i \le \frac{1}{2}e_{2,i}^{\mathrm{T}}e_{2,i} + \frac{1}{2}\hbar_i^{*2} \tag{19}$$

Substituting (19) into (18), we have

$$\begin{aligned}\dot{V}_1 &= \dot{V}_0 + \sum_{i=1}^{N}\left[e_{2,i}^{\mathrm{T}}M_i\dot{e}_{2,i} + \sum_{k=1}^{N}\tilde{w}_{ki}^{\mathrm{T}}\Upsilon_{ki}^{-1}\dot{\tilde{w}}_{ki} + \tilde{\delta}_i^{\mathrm{T}}\dot{\tilde{\delta}}_i\right]\\
&\le \sum_{i=1}^{N}\left[-\|y_i - \hat{y}_j\|^2 + \tilde{\delta}_i^{\mathrm{T}}\left(e_1^{\mathrm{T}}J(\eta_i)\nu_i - \dot{\hat{\delta}}_i + e_1^{\mathrm{T}}J(\eta_i)\alpha_i\right)\right]\\
&\quad + \sum_{i=1}^{N}\Bigg[e_{2,i}^{\mathrm{T}}M_i\left(\hat{w}_i^{\mathrm{T}}\zeta_i(\nu_i) + \frac{1}{2}e_{2,i} + \hat{\delta}_iJ(\eta_i) + M_i^{-1}\tau_i - \dot{\alpha}_i\right)\\
&\quad - c_{i,1}e_1^{\mathrm{T}}e_1 + \frac{1}{2}\hbar_i^{*2} + \sum_{k=1}^{N}\tilde{w}_{ki}^{\mathrm{T}}\Upsilon_{ki}^{-1}\left(e_{2,i}^{\mathrm{T}}\Upsilon_{ki}M_i\zeta_i(\nu_i) - \dot{\hat{w}}_{ki}\right)\Bigg]\end{aligned} \tag{20}$$

Design the actual controller and adaptive laws of parameters $\hat{\delta}_i$ and $\hat{w}_{ki}$ as

$$\tau_i = -c_{i,2}e_{2,i} - \hat{w}_i^{\mathrm{T}}\zeta_i + \dot{\alpha}_i - \hat{\delta}_iJ(\eta_i) - \frac{1}{2}e_{2,i} \tag{21}$$

$$\dot{\hat{w}}_{ki} = e_{2,i}^{\mathrm{T}}\Upsilon_{ki}M_i\zeta_i - l_{ki}\hat{w}_{ki} \tag{22}$$

$$\dot{\hat{\delta}}_i = e_1^{\mathrm{T}}J(\eta_i)\nu_i + e_1^{\mathrm{T}}J(\eta_i)\alpha_i - \bar{l}_i\hat{\delta}_i \tag{23}$$

From (20)-(23), we have

$$\dot{V}_1 \le \sum_{i=1}^{N}\left[-\|y_i - \hat{y}_j\|^2 + \bar{l}_i\tilde{\delta}_i^{\mathrm{T}}\hat{\delta}_i - c_{i,2}e_{2,i}^{\mathrm{T}}e_{2,i} + \sum_{k=1}^{N}l_{k,i}\tilde{w}_{ki}^{\mathrm{T}}\hat{w}_{ki} - c_{i,1}e_1^{\mathrm{T}}e_1 + \frac{1}{2}\hbar_i^{*2}\right] \tag{24}$$

4. **Stability Analysis.**

Theorem 4.1. *For a group of unmanned surface vehicle systems (1), the controller (21), virtual controller (12), and adaptive laws (13), (22) and (23), can ensure that all variables of system (1) are stable, and all followers can converge to the leader.*

Proof: Construct the following functions as

$$V_1 = V_0 + \sum_{i=1}^{N}\left[e_{2,i}^{\mathrm{T}} M_i e_{2,i} + \frac{1}{2}\sum_{k=1}^{N}\tilde{w}_{ki}^{\mathrm{T}}\Upsilon_{ki}^{-1}\tilde{w}_{ki} + \tilde{\delta}_i^{\mathrm{T}}\tilde{\delta}_i\right] \tag{25}$$

From (24), the time derivative of V_1 is

$$\dot{V}_1 \leq \sum_{i=1}^{N}\left[-\|y_i - \hat{y}_j\|^2 + \bar{l}_i\tilde{\delta}_i^{\mathrm{T}}\hat{\delta}_i + e_{2,i}^{\mathrm{T}} e_{2,i} + \sum_{k=1}^{N} l_{k,i}\tilde{w}_{ki}^{\mathrm{T}}\hat{w}_{ki} + \frac{1}{2}\hbar_i^{*2}\right] \tag{26}$$

By using Young's inequality, we have

$$l_{k,i}\tilde{w}_{ki}^{\mathrm{T}}\hat{w}_{ki} \leq -\frac{1}{2}l_{k,i}\tilde{w}_{ki}^{\mathrm{T}}\tilde{w}_{ki} + \frac{1}{2}l_{k,i}w_{ki}^{*\mathrm{T}}w_{ki}^{*} \tag{27}$$

$$\bar{l}_i\tilde{\delta}_i^{\mathrm{T}}\hat{\delta}_i \leq -\frac{1}{2}\bar{l}_i\tilde{\delta}_i^{\mathrm{T}}\tilde{\delta}_i + \frac{1}{2}\bar{l}_i\delta_i^{\mathrm{T}}\delta_i \tag{28}$$

Substituting (27) and (28) into (26), we have

$$\begin{aligned}\dot{V}_1 \leq & \sum_{i=1}^{N}\Bigg[-\|y_i - \hat{y}_j\|^2 - c_{i,2}e_{2,i}^{\mathrm{T}}e_{2,i} - c_{i,1}e_1^{\mathrm{T}}e_1 - \frac{1}{2}\bar{l}_i\tilde{\delta}_i^{\mathrm{T}}\tilde{\delta}_i \\ & + \frac{1}{2}\bar{l}_i\delta_i^{\mathrm{T}}\delta_i + \sum_{k=1}^{N}\left(-\frac{1}{2}l_{k,i}\tilde{w}_{ki}^{\mathrm{T}}\tilde{w}_{ki} + \frac{1}{2}l_{k,i}w_{ki}^{*\mathrm{T}}w_{ki}^{*}\right) + \frac{1}{2}\hbar_i^{*2}\Bigg] \\ \leq & -CV_1 + D\end{aligned} \tag{29}$$

where $C = \min\left\{c_{i,1}, c_{i,2}, l_{k,i}, \bar{l}_i\right\}$, and $D = \frac{1}{2}l_{k,i}w_{ki}^{*\mathrm{T}}w_{ki}^{*} + \frac{1}{2}\bar{l}_i\delta_i^{\mathrm{T}}\delta_i + \frac{1}{2}\hbar_i^{*2}$.

5. **Conclusions.** An adaptive NNs formation control method is proposed for a class of nonlinear USV with network faults. Different from the existing formation control methods, this method deals with the nonlinear nature of network faults by designing an adaptive observer. Based on the ability of backstepping and neural network, the formation controller is obtained. Using Lyapunov stability theory, it is proved that the controlled system is stable. In the case of network failure, all followers can track the leader. In future work, the proposed control method is expected to be extended to multiships with actuator fault in [9].

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