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Finite-time Containment Control for Autonomous Underwater Vehicles with Prescribed Performance

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***Abstract*—This paper proposes a finite-time prescribed performance containment control method for multiple autonomous underwater vehicles (AUVs) with uncertainty and disturbance. The control law is designed based on the conversion error derived from the prescribed performance control (PPC) framework. A new finite-time performance function, instead of exponential decay function, is used for error transformation, which enables the containment error converges in a finite time. The model uncertainty is approximated using the radial basis function neural networks (RBFNN), and the external disturbance is compensated with the unknow boundary being estimated using the adaptive approach. The simulation results confirm the validity of the proposed control protocol.**

Keywords—autonomous underwater vehicles, containment control, multi-agent systems, prescribed performance control.

I. Introduction

Cooperative formation for AUVs has been an active research topic in recent years due to its exceptional advantages in various applications, such as military defense, resource exploration, and environmental monitoring [1-4]. In certain scenarios, there is a desired outcome where the AUVs enter a region formed by more than one leader, which is called containment control and has garnered significant attention [5-7].

The complexity of cooperative control for autonomous underwater vehicles arises from various factors, such as inaccuracies in dynamic modeling and the presence of disturbances in underwater environment. A significant amount of work has been carried out in an attempt to address the aforementioned issues. [8] presented a sliding mode-based control law for AUVs subject to thruster failure, where the dynamics uncertainty is recovered using RBFNN and adaptive method, and the stability is evidenced via Lyapunov function. [9] introduced a control law which is designed based on a disturbance rejection algorithm, where the finite-time extended state observer is proposed to tackle the uncertainty including current disturbance and unknown model parameters.

Containment control has garnered much attention due to its distinctive cooperative formation characteristics, which has the potential to be utilized for safety assurance control. [10] proposed a containment control law for multi-agent system, which is designed based on the terminal sliding mode control technology, and the general switching and directed topology is further studied. A containment control law was proposed in [11], which focused on the quasi-containment and asymptotic containment problems, and the control law was derived based on neural network and backstepping framework. [12] studied the containment control problem, and a command filtered containment control law is derived via backstepping framework and output feedback, which ensures that the tracking error converges to a compact set while reducing the computing burden.

The aforementioned work tackled the challenge of containment control for multi-agent systems. However, it did not account for the constraints related to the dynamic and steady-state performance of the control law, which are crucial for accomplishing specific underwater tasks. The PPC method incorporates the error conversion, in which the performance function plays a crucial role in limiting the error convergence process [13]. [14] proposed an adaptive control law for underactuated AUVs in PPC framework, which enables the errors be effectively limited and the tracking performance be guaranteed.

In this paper, we present a novel finite-time prescribed performance containment control law for AUVs, considering model uncertainty and disturbance. The contributions can be outlined as follows:

The containment control law is designed within the PPC framework, which enables the containment tracking error be limited by performance function.

The finite-time performance function is utilized instead of the traditional exponential decay function in this paper, which leads to the containment tracking error converges in a finite time.

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The external disturbance is effectively compensated using a novel approach, where the unknow boundary is estimated using the adaptive approach.

II. Preliminaries

A. Model Dynamics

We examine a MAS consisting of n virtual leaders and m AUVs, whose dynamics are described as

$$\begin{aligned} \dot{\eta}_i &= R(\psi_i)\nu_i \\ M\dot{\nu}_i &= -C(\nu_i)\nu_i - D(\nu_i)\nu_i + \tau_{di} + \tau_i, \end{aligned} \tag{1}$$

where $i = 1,\ldots,m$, $\eta_i = [x_i, y_i, \psi_i]^T$ and $\nu_i = [u_i, \upsilon_i, r]^T$ denote the position and the velocity, respectively. $R(\psi_i)$ stands for the rotation matrix. The matrices M, $C(\nu_i)$, and $D(\nu_i)$ denote inertia, Coriolis, and damping, respectively. τ_i and τ_{di} stand for the control input and disturbance, respectively.

B. Control objective and assumptions

Control objective: Drive each follower AUV to enter a convex hull spanned by multiple virtual leaders in a finite time.

Assumption 1: For all the follower AUVs, there exists at least one directed spanning tree that roots at the virtual leader.

Assumption 2: The disturbance τ_{di} is bounded and subject to an unknown bound.

Assumption 3: The virtual leaders' state and their first-order derivative are bounded.

III. Containment Control Law Design

A. Control Law Design

According to the containment control method, the tracking error for the i-th AUV can be defined as

$$e_i = R_i^T \left(\sum\nolimits_{j=1}^{m} a_{ij}\left(\eta_i - \eta_j\right) + \sum\nolimits_{k=m+1}^{m+n} a_{ik}\left(\eta_i - \eta_k\right) \right), \tag{2}$$

where $a_{ij} = 1$ if the i-th AUV has access to the state of the j-th AUV; otherwise, $a_{ij} = 0$. $a_{ik} = 1$ if the i-th AUV has access to the state of the k-th virtual leader.

$\dot{e}_i$ can be calculated as

$$\dot{e}_i = -r_i \mathrm{M}\, e_i + \xi_i \nu_i - \sum\nolimits_{j=1}^{m} a_{ij} R_i^T R_j \nu_j - \sum\nolimits_{k=m+1}^{m+n} a_{ik} R_i^T \dot{\eta}_k, \tag{3}$$

where $\mathrm{M} = \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$, $\xi_i = \sum\nolimits_{j=1}^{m+n} a_{ij}$.

Based on the PPC method, we define the error conversion

$$e_{ij} = p_{ij}(t) C_{ij}(z_{1,ij}), \; j = 1, 2, 3, \tag{4}$$

where $p_{ij}(t)$ denotes the performance function, $C_{ij}(z_{1,ij})$ is the conversion function defined by

$$G_{ij}(z_{1,ij}) = \frac{\exp\left(z_{1,ij}\right) - \exp\left(-z_{1,ij}\right)}{\exp\left(z_{1,ij}\right) + \exp\left(-z_{1,ij}\right)} \tag{5}$$

where $z_{1,ij}$ is the error used for control law design.

In this work, a finite-time performance function is used for error conversion, which is defined as

$$p_{ij}(t) = \begin{cases} \left(p_{ij}(0) - \dfrac{t}{T_p} \right) \exp\left(1 - \dfrac{T_p}{T_p - t} \right) + p_{ij}(\infty), 0 \le t < T_p, \\ p_{ij}(\infty), \qquad\qquad t \ge T_p, \end{cases} \tag{6}$$

where T_p stands for the preset time, $p_{ij}(0)$ and $p_{ij}(\infty)$ is the positive parameters.

Based on (5), the $z_{1,ij}$ can be derived as

$$z_{1,ij} = \frac{1}{2}\ln\left(1 + \frac{e_{ij}}{p_{ij}(t)}\right) - \frac{1}{2}\ln\left(1 - \frac{e_{ij}}{p_{ij}(t)}\right), \tag{7}$$

whose derivative is deduced as

$$\dot{z}_{1,ij} = b_{ij}\dot{e}_{ij} - d_{ij}e_{ij}, \tag{8}$$

where $b_{ij} = \dfrac{1}{2}\left(\dfrac{1}{p_{ij}(t) + e_{ij}} + \dfrac{1}{p_{ij}(t) - e_{ij}} \right)$, and $d_{ij} = \dfrac{1}{2}\left(\dfrac{\dot{p}_{ij}(t)}{p_{ij}(t)\left(p_{ij}(t) + e_{ij}\right)} + \dfrac{\dot{p}_{ij}(t)}{p_{ij}(t)\left(p_{ij}(t) - e_{ij}\right)} \right)$.

According to (3) and (8), $\dot{z}_{1,i}$ can be derived as

$$\dot{z}_{1,i} = \Gamma_i \left(-r_i \mathrm{M}\, e_i + \xi_i \nu_i - \sum\nolimits_{j=1}^{m} a_{ij} R_i^T R_j \nu_j - \sum\nolimits_{k=m+1}^{m+n} a_{ik} R_i^T \dot{\eta}_k \right) - \Xi_i e_i \tag{9}$$

where $\Gamma_i = \mathrm{diag}[b_{i1}, b_{i2}, b_{i3}]$ and $\Xi_i = \mathrm{diag}[d_{i1}, d_{i2}, d_{i3}]$.

The virtual control can be designed as

$$\begin{aligned} \alpha_i = \xi_i^{-1} \Big(& r_i \mathrm{M}\, e_i + \sum\nolimits_{j=1}^{m} a_{ij} R_i^T R_j \nu_j \\ & + \sum\nolimits_{k=m+1}^{m+n} a_{ik} R_i^T \dot{\eta}_k - \Gamma_i^{-1} K_{1i} z_{1,i} + \Gamma^{-1} \Xi_i e_i \Big). \end{aligned} \tag{10}$$

where $K_{1i} > 0$ is a diagonal matrix.

In this paper, the DSC concept is used to avoid direct calculation of $\dot{\alpha}_i$ and reduce the computing burden

$$\alpha_i = T_i \dot{\chi}_i + \chi_i, \tag{11}$$

where $T_i > 0$ is the time constant. Defining $\varsigma_i = \chi_i - \alpha_i$ and $z_{2,i} = \nu_i - \chi_i$, then we have

$$\nu_i = z_{2,i} + \chi_i = z_{2,i} + \varsigma_i + \alpha_i. \tag{12}$$

Combining (10) and (12), (9) can be expressed as

$$\dot{z}_{1,i} = -K_{1i} z_{1,i} + \Gamma_i \xi_i z_{2,i} + \Gamma_i \xi_i \varsigma_i. \tag{13}$$

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$\dot{z}_{2,i}$ can be calculated as

$$\begin{aligned}\dot{z}_{2,i} &= \dot{\nu}_i - \dot{\chi}_i \\ &= H_i + \tau_{Di} + M_i^{-1}\tau_i + \varsigma_i / T_i\end{aligned} \tag{14}$$

where $\tau_{Di} = M^{-1}\tau_{di}$ denotes the disturbance and satisfies $|\tau_{Di}| \le \bar{\tau}_{di}$, $H_i(\vartheta_i) = M^{-1}\left(-C(\nu_i)\nu_i - D(\nu_i)\nu_i\right) = [h_{i1}, h_{i2}, h_{i3}]^T$ stands for the uncertainties, which is approximated using the RBFNN in this paper.

$$h_{ij}(\vartheta_i) = W_{ij}^{*T}\Theta_j(\vartheta) + \varepsilon_{ij}, \tag{15}$$

where $\vartheta_i = [\eta_i^T, \nu_i^T]^T$.

The control law is designed as

$$\tau_i = M\left(-K_{2i}z_{2,i} - \Gamma\xi_i z_{1,i} - \hat{W}_i^T\Theta(\vartheta_i) - \hat{\bar{\tau}}_{Di}\tanh\left(\frac{\hat{\bar{\tau}}_{Di}z_{2,i}}{s}\right) - \frac{\varsigma_i}{T_i}\right) \tag{16}$$

where $K_{2i} > 0$ is a diagonal matrix, $s > 0$ is a parameter, $\hat{W}_i^T$ is the estimate of W_i^{*T}, $W_i^{*T} = \text{blockdiag}[W_{i1}^{*T}, W_{i2}^{*T}, W_{i3}^{*T}] \in \mathbb{R}^{3\times 3q}$, $\Theta(\vartheta_i) = [\Theta_1^T(\vartheta_i), \Theta_2^T(\vartheta_i), \Theta_3^T(\vartheta_i)]^T \in \mathbb{R}^{3q}$, $\hat{\bar{\tau}}_{Di} = \text{diag}[\hat{\bar{\tau}}_{d,i1}, \hat{\bar{\tau}}_{d,i2}, \hat{\bar{\tau}}_{d,i3}]$, and $\hat{\bar{\tau}}_{d,ij}$ stands for the estimate of $\bar{\tau}_{d,ij}$ whose update law is designed as

$$\dot{\hat{\bar{\tau}}}_{d,ij} = \sigma_{ij}\left(\delta_{d,ij}\bar{\tau}_{d,ij} + |z_{2,ij}|\right), \tag{17}$$

where $\sigma_{ij} > 0$, $\delta_{d,ij} > 0$.

The update law of $\hat{W}_i^T$ is designed as

$$\dot{\hat{W}}_{ij} = \Pi_{ij}\left(-\Theta_j z_{2,ij} + \delta_{W,ij}\hat{W}_{ij}\right) - \beta_{ij}\sum_{k=1}^{m} a_{ik}\left(\hat{W}_{ij} - \hat{W}_{kj}\right) \tag{18}$$

where Π_{ij} is the positive definite gain matrix, $\delta_{W,ij} > 0$, and $\beta_{ij} > 0$.

B. Stability Analysis

Theorem 1: Consider the AUVs with dynamic described by (1), the control law (16), the update law (17) and (18), the tracking error (2) will converge to a compact set in a finite time.

Proof: Consider the Lyapunov function

$$V_i = \frac{1}{2}z_{1,i}^T z_{1,i} + \frac{1}{2}z_{2,i}^T z_{2,i} + \frac{1}{2}\sum_{j=1}^{3}\tilde{W}_{ij}^T\Pi_{ij}^{-1}\tilde{W}_{ij} + \frac{1}{2}\sigma_{ij}^{-1}\sum_{j=1}^{3}\tilde{\bar{\tau}}_{d,ij}^2 + \frac{1}{2}\varsigma_i^T\varsigma_i \tag{19}$$

where $\tilde{W}_{ij} = W_{ij}^* - \hat{W}_{ij}$ and $\tilde{\bar{\tau}}_{d,ij} = \bar{\tau}_{d,ij} - \hat{\bar{\tau}}_{d,ij}$.

According to (13), (14), (16), (17), and (18), the derivative of V_i can be calculated as

$$\begin{aligned}\dot{V}_i &= -z_{1,i}^T K_{1i}z_{1,i} - z_{2,i}^T K_{2i}z_{2,i} + z_{1,i}^T\Gamma_i\xi_i\varsigma_i + \varsigma_i^T\dot{\varsigma}_i + z_{2,i}^T\varepsilon_i \\ &\quad - \sum_{j=1}^{3}\left(\delta_{W,ij}\tilde{W}_{ij}^T\hat{W}_{ij} + \delta_{d,ij}\tilde{\bar{\tau}}_{d,ij}\hat{\bar{\tau}}_{d,ij}\right) - \sum_{j=1}^{3}\mathbf{\Pi}_j^{-1}\boldsymbol{\beta}_j\tilde{\mathbf{W}}_j^T\left(L_1 \otimes I\right)\tilde{\mathbf{W}}_j \\ &\quad + \sum_{j=1}^{3}\left(z_{2,ij}\tau_{d,ij} - |z_{2,ij}|\bar{\tau}_{d,ij} + |z_{2,ij}|\hat{\bar{\tau}}_{d,ij} - z_{2,ij}\hat{\bar{\tau}}_{d,ij}\tanh\left(\frac{z_{2,ij}\hat{\bar{\tau}}_{d,ij}}{s}\right)\right)\end{aligned} \tag{20}$$

where $\mathbf{\Pi}_j^{-1} = \text{diag}[\Pi_{1j}^{-1}, \ldots, \Pi_{mj}^{-1}] > 0$, $\boldsymbol{\beta}_j = \text{diag}[\beta_{1j}, \ldots, \beta_{mj}] > 0$, $\tilde{\mathbf{W}}_j = [\tilde{W}_{1j}^T, \ldots, \tilde{W}_{mj}^T]^T$, and $L_1 > 0$ according to *Assumption 1*. Based on the property $0 \le |m| - m\tanh(m/s) \le \iota s$, where $\iota = 0.2785$, we can conclude that

$$\begin{aligned}&z_{2,ij}\tau_{d,ij} - |z_{2,ij}|\bar{\tau}_{d,ij} + |z_{2,ij}|\hat{\bar{\tau}}_{d,ij} - z_{2,ij}\hat{\bar{\tau}}_{d,ij}\tanh\left(z_{2,ij}\hat{\bar{\tau}}_{d,ij}/s\right) \\ &\le \left|z_{2,ij}\hat{\bar{\tau}}_{d,ij}\right| - z_{2,ij}\hat{\bar{\tau}}_{d,ij}\tanh\left(z_{2,ij}\hat{\bar{\tau}}_{d,ij}/s\right) \le \iota s\end{aligned} \tag{21}$$

$\dot{\varsigma}_i$ can be calculated as

$$\begin{aligned}\dot{\varsigma}_i &= \dot{\chi}_i - \dot{\alpha}_i \\ &= T_i^{-1}(\alpha_i - \chi_i) - \dot{\alpha}_i\end{aligned} \tag{22}$$

According to [15], there exist a bounded function $\wp$ satisfying

$$\dot{\varsigma}_i + \varsigma_i / T_i = \wp \otimes I_3, \tag{23}$$

which leads to

$$\begin{aligned}\varsigma_i^T\dot{\varsigma}_i &= -\varsigma_i^T\varsigma_i / T_i + \varsigma_i^T(\wp \otimes I_2) \\ &\le (1/2 - 1/T_i)\varsigma_i^T\varsigma_i + 1/2\,\bar{\wp}^2,\end{aligned} \tag{24}$$

where $\bar{\wp}$ is the bound of $\wp$.

According to the above discussion and the Young's inequality, we have

$$\dot{V}_i \le -\mu_i V_i + \mathrm{C}_i \tag{25}$$

where $\mu_i = \min\{\lambda_{\min}(2K_{1i} - \|\Gamma_i\|^2), \lambda_{\min}(2K_{2i} - 1), \delta_{W,ij}\lambda_{\min}(\Pi_{ij}), \delta_{d,ij} \times\lambda_{\min}(\sigma_{ij}), \lambda_{\min}(2/T - 1 - \xi_i)\}$, $\mathrm{C}_i = \left(\|\bar{\varepsilon}_i\|^2 / 2 + \sum_{j=1}^{3}\left(\mu_{W,ij}\|W_{ij}^*\|^2 / 2 + \mu_{d,ij}\|\tau_{d,ij}^*\|^2 / 2\right) + \bar{\wp}^2/2 + 3\iota s\right)$.

Based on (25), we conclude that

$$V_i \le V_i(0)e^{-\mu_i t} + \mathrm{D}_i, \tag{26}$$

where $\mathrm{D}_i = \mathrm{C}_i / \mu_i$ can be a compact set by choosing proper parameters, which leads to

$$\begin{aligned}&\|z_{1,i}\| \le \sqrt{2\mathrm{D}_i},\ \|z_{2,i}\| \le \sqrt{2\mathrm{D}_i},\ \|\varsigma_i\| \le \sqrt{2\mathrm{D}_i}, \\ &\|\tilde{W}_{ij}\| \le \sqrt{2\mathrm{D}_i / \lambda_{\min}\left(\Pi_{ij}^{-1}\right)},\ \left|\tilde{\bar{\tau}}_{d,ij}\right| \le \sqrt{2\mathrm{D}_i\delta_{ij}}.\end{aligned} \tag{27}$$

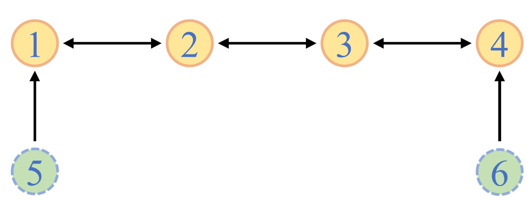

Fig. 1. The communication topology

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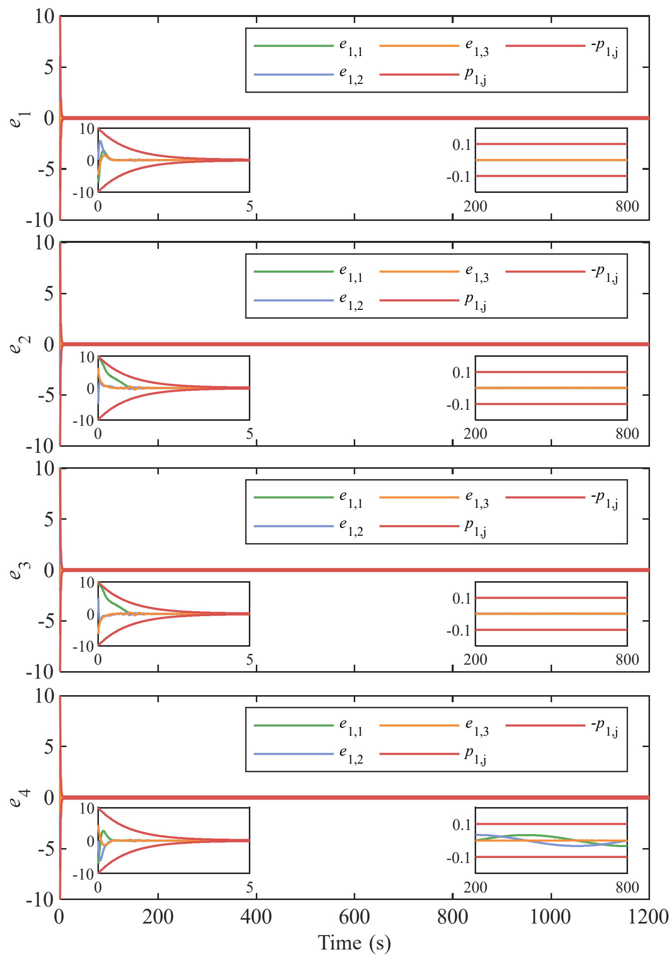

Fig. 2. The containment tracking error

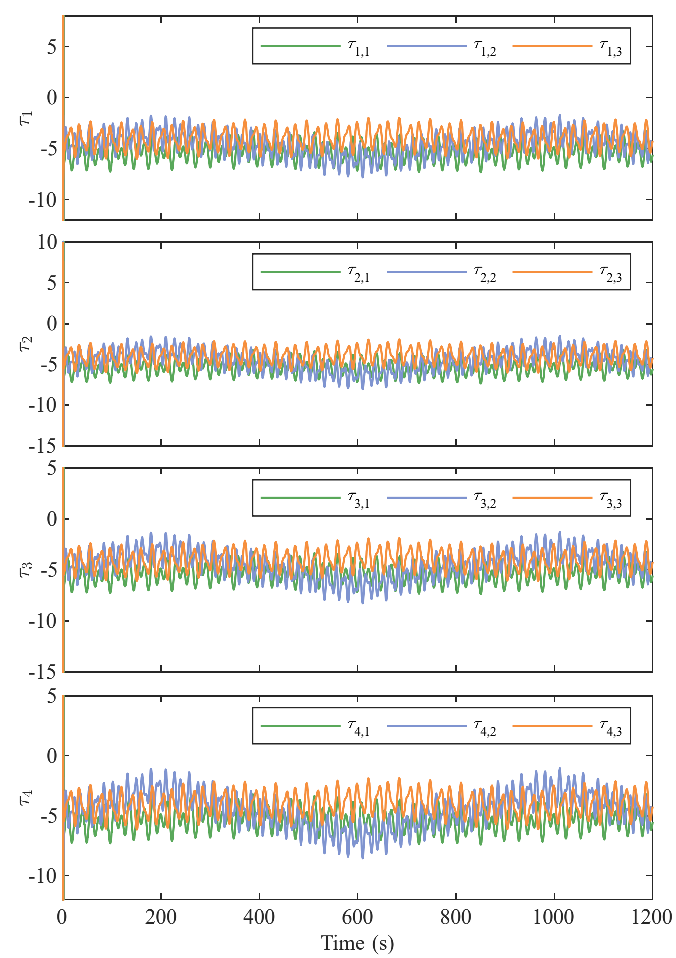

Fig. 3. The control input

According to (27), we conclude that $z_{1,i}$ is ultimately uniformly bounded. Combining (4), (5), and (6), we conclude that the containment tracking error e_i will converge to a compact set in a finite time.■

IV. SIMULATION EXPERIMENT

The simulation experiments are executed based on a MAS consisting of 2 virtual leaders and 4 AUVs. The dynamics model of the AUVs are same as that used in [16]. The initial state of 4 AUVs are assigned as $\eta_1(0)=[85,42,-\pi/2]^T$, $\eta_2(0)=[90,37,\pi/2]^T$, $\eta_3(0)=[90,23,-\pi/2]^T$, $\eta_4(0)=[85,18,\pi/2]^T$, and $v_i(0)=[0,0,0]^T$, $i=1,\ldots,4$. The moving path of the virtual leaders are described as $\eta_5(t)=[80-40\sin(2\pi t/1600),80-40\cos(2\pi t/1600),2\pi t/1600]^T$, and $\eta_6(t)=[80-60\sin(2\pi t/1600),80-60\cos(2\pi t/1600),2\pi t/1600]^T$. The external disturbances are designated as $\tau_d=[3+0.8\sin(0.5t+\pi/3)+1.5\cos(0.2t),2+1.3\cos(0.3t+\pi/6)+0.3\sin(0.7t),\ 0.5+0.6\cos(t+\pi/6)+0.25\sin(1.5t)]^T$. The communication topology is shown in Fig. 1.

The parameters in (16) are designed as $K_{1i}=\mathrm{diag}[0.3,0.3,1]$, $K_{2i}=\mathrm{diag}[3,3,10]$, $T_i=0.01$, and $s=0.01$. The parameters in PPC are specified as $T_p=10$, $p_{ij}(0)=10,\ p_{ij}(\infty)=0.05,\ j=1,2$, and $p_{i3}(0)=3,\ p_{i3}(\infty)=0.02$. The parameters in update law are designed as $\sigma_{ij}=2$, $\Pi_{ij}=\mathrm{diag}\{1\}$, $\delta_{d,ij}=0.01$, $\delta_{W,ij}=0.01$, and $\beta_{ij}=0.5$. The RBFNN using 300 nodes spaced on $[-5,5]\times[-5,5]\times[-2,2]$, and the width is set to be 1.

The results are illustrated in Figs. 2-4. Figs. 2 reveals the containment error converge in a finite-time using the proposed PPC. The control input is shown in Fig. 3, which is bounded and practical. The feasibility are visually demonstrated through the illustration of the containment tracking path in Fig. 4.

V. CONCLUSION

This paper focused on the containment control problem for AUVs. The finite-time containment control task is achieved by combining the containment control and PPC, where a new type of finite-time performance function is proposed to enable the error to converge in a finite time. The dynamic uncertainty is recovered using the RBFNN, and the disturbance is compensated using adaptive method. In future work, it makes sense to work on collision avoidance in multi-AUV systems.

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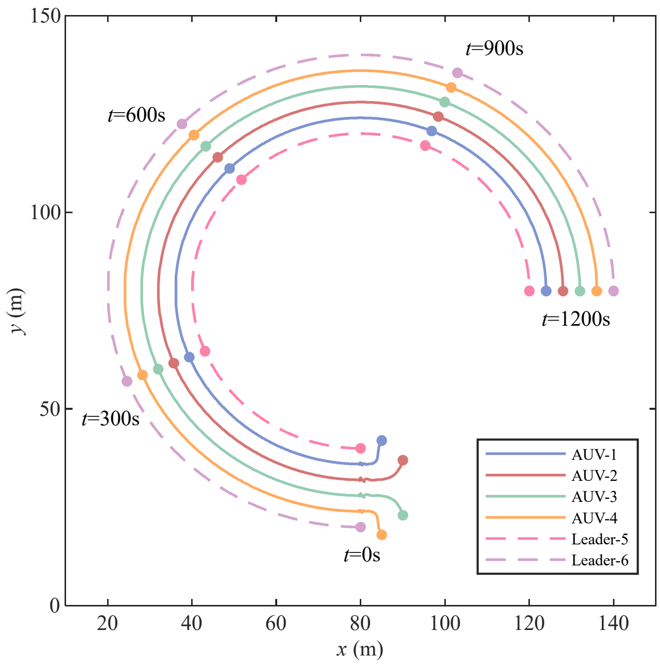

Fig. 4. The containment tracking path

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