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Coordinated Target Tracking Strategy for Multiple Unmanned Underwater Vehicles With Time Delays

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ABSTRACT Focusing on coordination and consensus, this paper, addresses a control problem for a group of unmanned underwater vehicles (UUVs) by tracking a maneuvering target with varying velocity and time delays. To realize coordinated target tracking, consensus control of multiple UUVs requires neighboring UUV state information, detected target state information, and estimated target acceleration information. At least one UUV is assumed to be capable of obtaining information about the target, and the communication topology graph of the vehicle is assumed to be undirected connected. We consider the convergence analysis of this multi-UUV system for two conditions: information interaction between the target and an UUV with time delays and information interaction between the target and an UUV without time delays. Sufficient conditions for the uniform ultimate boundedness of the tracking errors and estimation errors are obtained by utilizing a Lyapnov-Krasovskii functional. Two simulations are presented to demonstrate the effectiveness of the proposed method.

INDEX TERMS Multiple unmanned underwater vehicles, target tracking, consensus control, time delay.

I. INTRODUCTION

The research interest in the coordination control of multiple unmanned underwater vehicles (UUVs) has increased due to advances in communication networks and challenging mission scenarios [1]–[5]. A multi-UUV system has potential in various applications, such as military surveillance, ocean exploration, rescue and research, due to an increasing task area, time reductions and improvements in the robustness and fault-tolerant ability of the entire system [6], [7]. One example of coordination control is coordinated target tracking control, in which a group of UUVs attain the desired relative position with respect to a moving target.

Coordinated target tracking control can be divided into two problems: estimation of the target state and consensus control of UUVs that follow the moving target. We focus on the consensus tracking control of a multi-UUV system when the target has time delays and only a subgroup of the UUV team can obtain the time-varying consensus reference state. Due to the severe communication constraints in the ocean, networked systems may possess a switching topology that is time-varying and communication time delays, which are factors that influence the stability of the networked systems [8]–[10]. Olfati-Saber and Murray [11] considered the consensus problem with directed fixed and switching topologies and considered that undirected networks provided conditions for consensus with communication time delays. Ren [12] proposed consensus tracking algorithms for multi-vehicle systems of directed fixed networks, in which only a portion of vehicles can obtain the reference state. Ren [13] extended the results of consensus tracking algorithms in [12] to the case with switching interaction topologies and bounded control effort. Tang *et al.* [14] considered the consensus problem of multiple agents in directed networks with time delays, in which the Lyapnov-Razumikhin function is a necessary and sufficient condition. Shen and Shi [15] proposed a distributed consensus tracking control method with an undirected graph for a fixed topology; however, the follower is assumed to be in strict-feedback form. Chen and Ho Daniel [16] proposed consensus control algorithms for multiple AUVs with communication faults for leaderless and leader-follower AUV systems; however, the issues of switching topology and time delays are not addressed.

The consensus tracking control is adopted in a cooperative target-capturing system based on a cyclic pursuit strategy [17]. However, all agents need complete target information, which is a limitation in an actual environment. Sharma *et al.* [18] proposed distributed consensus formation control to capture a maneuvering target with inaccurate target information. However, the topology is fixed and time delays are not considered, which is unrealistic. The target tracking problem is similar to the enclosing behavior of target-capturing. Wang and Gu [19] presented a coordinated target tracking control approach for multiple robots, in which the flocking algorithm based on the estimated target position is adopted. Cai and de Queiroz [20] proposed a distance-based control law for a multi-agent target tracking problem, in which the relative position and the target absolute velocity need to be broadcast to all followers. However, time delays or dynamic reference signals are not considered in this research.

Substantial research has been conducted about the observer to estimate the external disturbances, unknown vehicle dynamics and unmeasured velocity information. In [25], a sliding mode observer is developed to estimate the unmeasured states in a control system; this estimate can approximate the true value to any accuracy. An external disturbance estimation scheme is proposed to precisely estimate the disturbance in finite time [26]. In [27], a fuzzy system is employed to estimate the unknown kinetics based on the input and output data. Peng *et al* [28] proposed a neural observer to recover the unmeasured velocity and presented an echo state network-based observer to identify the unknown vessel dynamics and unmeasured velocity information; however, the algorithm is theoretical and is not applied to actual vehicles [29].

Inspired by the progress in the field, we proposed a consensus control strategy that enables multiple UUVs to track a maneuvering target with time delays; only a portion of the UUVs can obtain incomplete target information. Here, the acceleration of the maneuvering target is unknown, and some vehicles are unable to obtain the position and velocity of the target. We consider two cases: the target tracking protocol with time delays using neighboring state information and the target tracking protocol without time delays using neighboring state information. Based on the Lyapnov-Krasovskii functional theory, sufficient conditions for multiple UUVs with time delays are proposed to realize coordinated target tracking. The effectiveness of the proposed strategy is demonstrated by numerical simulations.

The remainder of the paper is organized as follows: In Section 2, the mathematical model of a UUV and the target and preliminaries are introduced. In Section 3, the design and analysis of the proposed coordination target tracking strategies are given. In Section 4, the simulation results are presented. Some concluding remarks and future research are shown in Section 5.

II. PROBLEM FORMULATION

The basic introduction of graph theory and the kinematic and dynamic models of the UUV that moves in the horizontal plane are given in this section; control objectives are also proposed.

A. GRAPH THEORY

Assume that the multi-UUV system has n vehicles, $\upsilon = \{1, 2, \cdots, n\}$ is the set of vertices of the communication graph, the vertex set represents the group of UUVs in the system, and UUV_i indicates the i-th UUV. The set of edges of the communication graph is represented as $\varepsilon = \{(j, i) : i, j \in \upsilon\} \subseteq \upsilon \times \upsilon$, and the edges represent the communication connection among the UUVs. The adjacency matrix is defined as $A = [a_{ij}] \in \mathbb{R}^{n\times n}$ by $a_{ij} = 1$ if $(j, i) \in \varepsilon$, which indicates that UUV_i can receive information from UUV_j, and $a_{ij} = 0$, otherwise, and $a_{ii} = 0$. The set of neighbors of UUV_i is denoted by $N_i = \{\upsilon_j : (\upsilon_j, \upsilon_i) \in \varepsilon\}$, which indicates that UUV_i can receive information from all vehicles in the set. The interaction topology of a network of UUVs is represented by the undirected graph $G = (\upsilon, \varepsilon, A)$. G is undirected if $a_{ij} = 1 \Leftrightarrow a_{ji} = 1$ for all $i = 1, 2, \ldots n$. An undirected graph is connected if an edge exists between any distinct pair of vertices.

The in-degree matrix is defined as the diagonal matrix $D = diag\left(d_1^{in}, d_2^{in}, \ldots d_n^{in},\right)$, where

$$d_i^{in} = \sum_{j\in\upsilon} a_{ij}$$

represents the number of vehicles whose information can be received by UUV_i; the out-degree

$$d_i^{out} = \sum_{j\in\upsilon} a_{ji}$$

represents the number of vehicles that can obtain information from UUV_i; and $d_i^{in} = d_i^{out}$ for the undirected graph. The Laplacian matrix is defined as $L = \left[l_{ij}\right] = D - A$, where

$$l_{ii} = \sum_{j=1, j\neq i}^{n} a_{ij}$$

and $l_{ii} = -a_{ij}$ when $i \neq j$.

In this paper, the communication topology graph of the group of UUVs is undirected connected, the Laplacian matrix L is symmetric and positive semi-definite and the eigenvalue $\lambda(L) = 0$ is unique. Define the matrix $B = diag\{b_i\}$, if UUV_i can obtain state information about the target $b_i = 1$; otherwise, $b_i = 0$. At least one UUV can obtain information about the target, which indicates that B is not a zero matrix. Based on the characteristics of matrix L and B, we determine that the eigenvalue of the matrix $H = L + B$ that is related to the system topology is positive.

Thus, the system has the following assumptions:

Assumption 1: The communication topology graph of the group of UUVs is undirected connected.

Assumption 2: At least one UUV can obtain information about the target.

B. THE UUV MODEL AND THE TARGET

The kinematic and dynamic equations of a UUV are described in two coordinate frames, namely, the earth-fixed frame {E} and the body-fixed frame {B} (refer to Fig. 1).

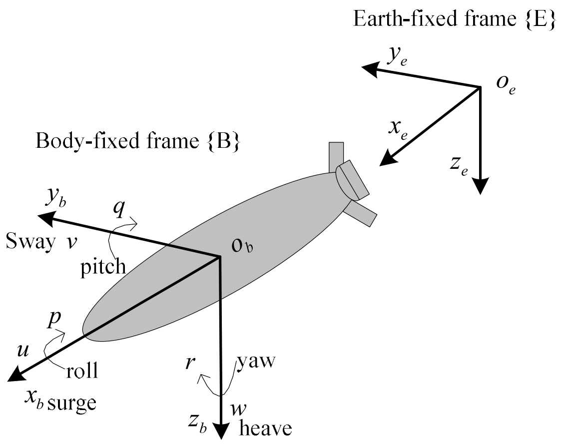

FIGURE 1. UUV model in six DOF.

In the body-fixed frame, the motion equations of a UUV with standard notation can be described as [21]

$$\begin{aligned}\dot{\boldsymbol{\eta}} &= \boldsymbol{R}(\boldsymbol{\psi})\boldsymbol{v}\\ \boldsymbol{M}\dot{\boldsymbol{v}} &= \boldsymbol{\tau} - \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} - \boldsymbol{D}(\boldsymbol{v})\boldsymbol{v} - \boldsymbol{g}(\boldsymbol{\eta})\end{aligned} \tag{1}$$

where $\boldsymbol{\eta} = [x, y, \psi]^T \in \mathbb{R}^3$ denotes the position and the heading angle of the UUV in the earth-fixed frame, and $\boldsymbol{v} = [u, v, r]^T \in \mathbb{R}^3$ is the corresponding velocity of the UUV in the body-fixed frame, where u is the velocity in the surge, $\boldsymbol{v}$ is the velocity in the sway, and r is the angular rate in the yaw. $\boldsymbol{R}(\boldsymbol{\psi})$ is the transformation matrix from the body-fixed frame to the earth-fixed frame. $\boldsymbol{M}$, $\boldsymbol{C}(\boldsymbol{v})$ and $\boldsymbol{D}(\boldsymbol{v})$ are the inertia matrix, the centripetal and Coriolis matrix and the hydrodynamic damping matrix, respectively. $\boldsymbol{g}(\boldsymbol{\eta})$ denotes the vector of buoyancy and gravitational forces and moments; and $\boldsymbol{\tau} = [\tau_u, \tau_v, \tau_r]^T \in \mathbb{R}^3$ denotes the corresponding control input signal. $\boldsymbol{R}(\boldsymbol{\psi})$ is the transformation matrix.

Without loss of generality, we consider a group of n UUVs consensus control in the horizontal plane. Then, we assume $\boldsymbol{g}(\boldsymbol{\eta}) = 0$ and $\boldsymbol{\tau} = [\tau_u, \tau_v, \tau_r]^T \in \mathbb{R}^3$. Other parameters are given as

$$\boldsymbol{M} = \begin{bmatrix} m_{11} & 0 & 0\\ 0 & m_{22} & 0\\ 0 & 0 & m_{33}\end{bmatrix}, \boldsymbol{C}(\boldsymbol{v}) = \begin{bmatrix} 0 & 0 & -m_{22}v\\ 0 & 0 & m_{11}u\\ m_{22}v & -m_{11}u & 0\end{bmatrix}$$

$$\boldsymbol{D}(\boldsymbol{v}) = \begin{bmatrix} d_{11} & 0 & 0\\ 0 & d_{22} & 0\\ 0 & 0 & d_{33}\end{bmatrix}, \boldsymbol{R}(\boldsymbol{\psi}) = \begin{bmatrix} \cos\psi & -\sin\psi & 0\\ \sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{bmatrix}$$

where

$$m_{11} = m - X_{\dot{u}}, m_{22} = m - Y_{\dot{v}}, m_{33} = I_z - N_{\dot{r}},$$
$$d_{11} = X_u + X_{u|u|}|u|, d_{22} = Y_v + Y_{v|v|}|v|, d_{33} = N_r + N_{r|r|}|r|.$$

The selection of the coordinated controller is difficult due to the nonlinear and strong coupling of the vehicle. To solve this problem, feedback linearization is adopted to obtain a standard double integrator dynamic model as [22]

$$\dot{\boldsymbol{p}}_i = \boldsymbol{v}_i, \quad \dot{\boldsymbol{v}}_i = \boldsymbol{u}_i \tag{2}$$

where $\boldsymbol{p}_i \in \mathbb{R}^3$, $\boldsymbol{v}_i \in \mathbb{R}^3$, $\boldsymbol{u}_i \in \mathbb{R}^3$, and $i = 1, 2, \ldots n$.

The target model is the same as the dynamic model of the UUV as follows:

$$\dot{\boldsymbol{p}}_0 = \boldsymbol{v}_0, \dot{\boldsymbol{v}}_0 = \boldsymbol{a}_0 \tag{3}$$

where $\boldsymbol{a}_0 \in \mathbb{R}^3$ denotes the acceleration information of the target, which is unknown; however, the position and velocity are detectable. For simplicity of presentation, we assume that the states of the system are one-dimensional variables, which indicates $p(t)$, $v(t)$, $u(t)$, $a(t) \in \mathbb{R}$. However, all research results remain effective and are extended to 3D using the Kronecker product. Assume that $a_0(t)$ can be linearized by

$$a_0(t) = \phi_a^T(t)w_a \tag{4}$$

where $w_a \in \mathbb{R}^2$, $\phi_a^T(t)$ is a nonlinear basis function.

C. CONTROL OBJECTIVES

The goal of this paper is to study the coordinated target tracking problem for a multi-UUV system using neighboring state information with time delays. The control problems can be formally stated by the following objectives:

$$\lim_{t\to\infty} \left\|\boldsymbol{p}_i(t) - \boldsymbol{p}_0(t)\right\| = c, \quad i \in (1, 2, \ldots n) \tag{5}$$

$$\lim_{t\to\infty} \left\|\boldsymbol{v}_i(t) - \boldsymbol{v}_0(t)\right\| = 0, \quad i \in (1, 2, \ldots n) \tag{6}$$

where $\boldsymbol{p}_0(t)$ and $\boldsymbol{v}_0(t)$ denote the position of the target and the velocity of the target, respectively, $c \geq 0$ is a constant and $\|\cdot\|$ is a Euclidean norm. In this paper, we assumed that the desired relative position between the vehicles and the target is zero. Because the desired relative position is constant, it does not affect the universality of the result.

III. PROPOSED CONTROL STRATEGY

In this section, we present a coordination control strategy to achieve a solution to control the objectives formulated in the previous section. Due to the severe communication constraints in the ocean, each UUV encounters difficulty obtaining information about the target. We assume that at least one UUV can obtain state information about the target and assume a detect time delay of τ for the vehicle that can detect the target. In the following section, coordinated target tracking control strategies are presented for the conditions of $\tau = 0$ and $\tau \neq 0$.

A. COORDINATED TARGET TRACKING CONTROL OF MULTI-UUV WITHOUT TIME DELAYS

In this subsection, the time delay is zero; we propose the following target tracking control laws:

$$u_i(t) = \phi_a^T(t)\hat{w}_i(t) - K_p\xi_i(t) - K_v\zeta_i(t) \tag{7}$$

where $\hat{w}_i(t)$ is the estimate of w_a at time t, and $K_p, K_v > 0$ is the control gain to be discussed in the following section. $\xi_i(t)$, $\zeta_i(t)$ are the position tracking error and the velocity tracking error, respectively, which are defined as

$$\begin{aligned}\xi_i(t) &= \sum_{j\in N_i} a_{ij}(p_i(t) - p_j(t)) + b_i(p_i(t) - p_0(t))\\ \zeta_i(t) &= \sum_{j\in N_i} a_{ij}(v_i(t) - v_j(t)) + b_i(v_i(t) - v_0(t))\end{aligned} \tag{8}$$

where N_i denotes the neighbors of UUV_i, a_{ij} and b_i are elements of the adjacency matrix A and the matrix B, which are defined in section II. From the definition, we can obtain

$$\begin{aligned}\dot{\xi}_i(t) &= \zeta_i(t)\\ \dot{\zeta}_i(t) &= \sum_{j\in N_i} a_{ij}(u_i(t)-u_j(t)) + b_i(u_i(t)-a_0(t))\end{aligned} \tag{9}$$

Thus, the tracking errors of the multi-UUV system is obtained in vector form as

$$\begin{aligned}\boldsymbol{\xi}(t) &= [\xi_1(t), \xi_2(t), \cdots \xi_n(t)]^T\\ \boldsymbol{\zeta}(t) &= [\zeta_1(t), \zeta_2(t), \cdots \zeta_n(t)]^T\end{aligned}$$

From (7) and (10), we can obtain

$$\boldsymbol{u}(t) = \Phi^T(t)\hat{W}(t) - K_p\boldsymbol{\xi}(t) - K_v\boldsymbol{\zeta}(t) \tag{10}$$

where

$$\begin{aligned}\boldsymbol{u}(t) &= [u_1(t), u_2(t), \cdots u_n(t)]^T,\\ \hat{W}(t) &= [\hat{w}_1^T(t), \hat{w}_2^T(t), \cdots \hat{w}_n^T(t)]^T,\\ \Phi^T(t) &= I_n \otimes \phi_a^T(t),\end{aligned}$$

According to the definition $H = L + B$, we have

$$\begin{aligned}\dot{\boldsymbol{\xi}}(t) &= \boldsymbol{\zeta}(t)\\ \dot{\boldsymbol{\zeta}}(t) &= H(\boldsymbol{u}(t) - \mathbf{1}_N a_0(t))\end{aligned} \tag{11}$$

Define the system tracking error as follows:

$$\boldsymbol{\varepsilon}(t) = \begin{bmatrix}\boldsymbol{\xi}^T(t) & \boldsymbol{\zeta}^T(t)\end{bmatrix}^T$$

Taking its time derivative along (10) and (11), let $\tilde{w}_i(t) = \hat{w}_i(t) - w_a$, which yields

$$\begin{aligned}\dot{\boldsymbol{\varepsilon}}(t) &= \begin{bmatrix}0 & I_n\\ -K_pH & -K_vH\end{bmatrix}\boldsymbol{\varepsilon}(t) + \begin{bmatrix}0\\ H\Phi^T(t)\tilde{W}(t)\end{bmatrix}\\ &= E\boldsymbol{\varepsilon}(t) + \Delta(t)\end{aligned} \tag{12}$$

The parameter update rate is chosen as follows

$$\begin{aligned}\dot{\hat{w}}_i(t) &= -k_1\phi_a(t)(\sum_{j\in N_i} a_{ij}(\zeta_i(t)-\zeta_j(t)) + b_i\zeta_i(t))\\ &\quad - k_2\phi_a(t)(\sum_{j\in N_i} a_{ij}(\xi_i(t)-\xi_j(t)) + b_i\xi_i(t))\end{aligned} \tag{13}$$

Here, we present Theorem 1.

Theorem 1: Consider the target tracking system of n UUVs (1) and the target (3). We apply the target tracking law (7) and the parameter update rate (13) to the system. If the system satisfies [assumption 1 and assumption 2] and K_p, K_v, k_1, k_2, $k_3 > 0$, then

$$PE < 0,$$

where

$$P = \begin{bmatrix}k_3 & k_2\\ k_2 & k_1\end{bmatrix} \otimes I_n > 0.$$

Then, $\lim_{t\to\infty} \boldsymbol{\varepsilon}(t) = 0$, $\lim_{t\to\infty} \tilde{W}(t) = 0$.

Proof: We define a Lyapunov function candidate as follows:

$$V(t) = \boldsymbol{\varepsilon}^T(t)P\boldsymbol{\varepsilon}(t) + \tilde{W}^T(t)\tilde{W}(t) \tag{14}$$

Taking the derivatives of this formula yields

$$\begin{aligned}\dot{V}(t) &= 2\boldsymbol{\varepsilon}^T(t)P\dot{\boldsymbol{\varepsilon}}(t) + 2\tilde{W}^T(t)\dot{\tilde{W}}(t)\\ &= 2\boldsymbol{\varepsilon}^T(t)P(E\boldsymbol{\varepsilon}(t) + \Delta(t)) + 2\tilde{W}^T(t)\dot{\tilde{W}}(t)\\ &= 2\boldsymbol{\varepsilon}^T(t)PE\boldsymbol{\varepsilon}(t) + 2\boldsymbol{\varepsilon}^T(t)P\Delta(t) + 2\tilde{W}^T(t)\dot{\tilde{W}}(t)\\ &= 2\boldsymbol{\varepsilon}^T(t)PE\boldsymbol{\varepsilon}(t) + 2k_2\boldsymbol{\xi}^T(t)H\Phi^T(t)\tilde{W}(t)\\ &\quad + 2k_1\boldsymbol{\zeta}^T(t)H\Phi^T(t)\tilde{W}(t) + 2\tilde{W}^T(t)\dot{\tilde{W}}(t)\end{aligned} \tag{15}$$

Form (13) and the definition $\tilde{w}_i(t) = \hat{w}_i(t) - w_a$ can be combined to easily obtain

$$\dot{\tilde{W}}(t) = \dot{\hat{W}}(t) = -k_1\Phi(t)H\boldsymbol{\zeta}(t) - k_2\Phi(t)H\boldsymbol{\xi}(t) \tag{16}$$

Submitting (16) into (15) produces

$$\dot{V}(t) = 2\boldsymbol{\varepsilon}^T(t)PE\boldsymbol{\varepsilon}(t) \tag{17}$$

According to conditions in Theorem 1, the positive constant λ satisfies

$$\dot{V}(t) \leq -\lambda\,\|\boldsymbol{\varepsilon}(t)\|^2 < 0 \tag{18}$$

From (18), the tracking error system of the multi-UUV is asymptotically stable, which indicates that

$$\lim_{t\to\infty} \boldsymbol{\xi}(t) = 0; \quad \lim_{t\to\infty} \boldsymbol{\zeta}(t) = 0 \tag{19}$$

We can obtain

$$\lim_{t\to\infty} \dot{\boldsymbol{\xi}}_z(t) = 0; \quad \lim_{t\to\infty} \dot{\boldsymbol{\zeta}}_z(t) = 0 \tag{20}$$

Since

$$\dot{\boldsymbol{\zeta}}(t) = -K_pH\boldsymbol{\xi}(t) - K_vH\boldsymbol{\zeta}(t) + H\Phi^T(t)\tilde{W}(t) \tag{21}$$

while $\lim_{t\to\infty} H\Phi^T(t)\tilde{W}(t) = 0$, a sufficient amount of time t exists for a sufficiently small constant σ, which satisfies

$$\int_t^{t+\delta} \tilde{W}^T(t)\Phi(t)HH\Phi^T(t)\tilde{W}(t)dt < \sigma \tag{22}$$

where $\delta > 0$.

Since the eigenvalues of matrix HH are positive values, σ' exists, which satisfies

$$\int_t^{t+\delta} \tilde{W}^T(t)\Phi(t)\Phi^T(t)\tilde{W}(t)dt < \sigma' \tag{23}$$

According to (16), the constant vector $\tilde{W}_0$ is expressed as

$$\lim_{t\to\infty} \tilde{W}(t) = \tilde{W}_0 \tag{24}$$

From (23) and (24),

$$\begin{aligned}&\lim_{t\to\infty}\int_t^{t+\delta} \tilde{W}^T(t)\Phi(t)\Phi^T(t)\tilde{W}(t)dt\\ &\qquad = \tilde{W}_0^T \lim_{t\to\infty}\int_t^{t+\delta} \Phi(t)\Phi^T(t)dt\tilde{W}_0\end{aligned} \tag{25}$$

The nonlinear basis function $\phi(t)$ should satisfy the persistent excitation condition

$$\lim_{t\to\infty}\int_t^{t+\delta} \Phi(t)\Phi^T(t)dt > \rho I \tag{26}$$

From (25) and (26), we obtain

$$\tilde{W}_0^T\tilde{W}_0 \leq \frac{\sigma'}{\rho} \tag{27}$$

where ρ is a sufficiently small constant, and

$$\lim_{t\to\infty} \tilde{W}^T(t)\tilde{W}(t) = 0 \tag{28}$$

The proof is completed.

B. COORDINATED TARGET TRACKING CONTROL OF MULTI-UUV WITH TIME DELAYS

This section presents a target tracking controller of the multi-UUV, in which the multi-UUV system detects the target with time delays.

Similar to Theorem 1, the target tracking control laws are chosen as

$$\begin{aligned} u_i(t) = {} & \phi_a^T(t)\hat{w}_i(t) - K_p(\sum_{j\in N_i} a_{ij}(p_i(t)-p_j(t)) \\ & + b_i(p_i(t-\tau)-p_0(t-\tau))) \\ & - K_v(\sum_{j\in N_i} a_{ij}(v_i(t)-v_j(t)) \\ & + b_i(v_i(t-\tau)-v_0(t-\tau))) \end{aligned} \tag{29}$$

Define the position error and velocity error as follows:

$$\begin{aligned} e_{pi}(t) &= p_i(t) - p_0(t) \\ e_{vi}(t) &= v_i(t) - v_0(t) \end{aligned} \tag{30}$$

The vector form can be written as

$$E_p(t) = [e_{p1}, e_{p2}, \cdots e_{pn}], \quad E_v(t) = [e_{v1}, e_{v2}, \cdots e_{vn}]$$

From (29) and the system states (2), we have

$$\begin{aligned} \dot{E}_p(t) &= E_v(t) \\ \dot{E}_v(t) &= -K_pLE_p(t) - K_pBE_p(t-\tau) \\ &\quad - K_vLE_v(t) - K_vBE_v(t-\tau) + \Phi^T(t)\tilde{W}(t) \end{aligned} \tag{31}$$

The system tracking error is defined as

$$E(t) = [E_p^T(t), E_v^T(t)]^T \tag{32}$$

Taking derivatives of (32) along (29) and (31), the dynamic equation of the system is obtained as

$$\begin{aligned} \dot{E}(t) = {} & (M \otimes I_n - (NK)\otimes L)E(t) \\ & - ((NK)\otimes B)E(t-\tau) \\ & + (N\otimes I_n)\Phi^T(t)\tilde{W}(t) \end{aligned} \tag{33}$$

where

$$K = [K_p \;\; K_v], M = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad N = \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

The desired parameter update rate is expressed as

$$\begin{aligned} \dot{\hat{w}}_i^d(t) = {} & \tau r\phi_a(t)K_p(p_i(t-\tau)-p_0(t-\tau)) \\ & + \tau r\phi_a(t)K_v(v_i(t-\tau)-v_0(t-\tau)) \\ & + \tau r\phi_a(t)K_p\sum_{j\in N_i}(p_i(t)-p_j(t)) \\ & + \tau r\phi_a(t)K_v\sum_{j\in N_i}(v_i(t)-v_j(t)) \\ & - \phi_a(t)p_{12}(\sum_{j\in N_i}(p_i(t)-p_j(t)) + (p_i(t)-p_0(t))) \\ & - \phi_a(t)p_{22}(\sum_{j\in N_i}(v_i(t)-v_j(t)) + (v_i(t)-v_0(t))) \\ & - \rho_1\hat{w}_i(t) - \rho_2\sum_{j\in N_i}(\hat{w}_i(t)-\hat{w}_j(t)) \end{aligned} \tag{34}$$

where ρ_1, ρ_2, r are the parameters, and

$$P' = \begin{bmatrix} p_{11} & p_{12} \\ p_{12} & p_{22} \end{bmatrix}$$

is defined as a positive definite matrix.

The target state $p_0(t)$ and $v_0(t)$ are undetected by any UUV due to time delays, and the desired parameter update rate cannot be obtained. To solve the tracking problem for this condition, (35) is established, and assumption 3 is presented.

$$\begin{aligned} p_0(t) &= p_0(t-\tau) + \tau\Delta_p(t) \\ v_0(t) &= v_0(t-\tau) + \tau\Delta_v(t) \end{aligned} \tag{35}$$

Assumption 3: The velocity and acceleration of the target is bounded, which satisfy $\left|\Delta_p(t)\right| < \Delta_{p0}$, $|\Delta_v(t)| < \Delta_{v0}$.

From (35), (34) can be rewritten as

$$\begin{aligned} \dot{\hat{w}}_i^d(t) = {} & \tau r\phi_a(t)K_p(p_i(t-\tau)-p_0(t-\tau)) \\ & + \tau r\phi_a(t)K_v(v_i(t-\tau)-v_0(t-\tau)) \\ & + \tau r\phi_a(t)K_p\sum_{j\in N_i}(p_i(t)-p_j(t)) \\ & + \tau r\phi_a(t)K_v\sum_{j\in N_i}(v_i(t)-v_j(t)) \\ & - \phi_a(t)p_{12}(\sum_{j\in N_i}(p_i(t)-p_j(t))) \\ & - \phi_a(t)p_{22}(\sum_{j\in N_i}(v_i(t)-v_j(t))) \\ & - \phi_a(t)p_{12}(p_i(t)-p_0(t-\tau)) \\ & - \phi_a(t)p_{22}(v_i(t)-v_0(t-\tau)) \\ & + \phi_a(t)\tau(p_{12}\Delta_p(t)+p_{22}\Delta_v(t)) \\ & - \rho_1\hat{w}_i(t) - \rho_2\sum_{j\in N_i}(\hat{w}_i(t)-\hat{w}_j(t)) \end{aligned} \tag{36}$$

Then, the parameter update rate is

$$\dot{\hat{w}}_i(t) = \dot{\hat{w}}_i^d(t) - \phi_a(t)\tau(p_{12}\Delta_p(t)+p_{22}\Delta_v(t)) \tag{37}$$

Define

$$\begin{aligned} E^\tau(t) = {} & [p_1(t)-p_0(t-\tau), \cdots p_n(t)-p_0(t-\tau), \\ & v_1(t)-v_0(t-\tau), \cdots v_n(t)-v_0(t-\tau)]^T \end{aligned}$$

the parameter update rate can be written as

$$\begin{aligned} \dot{\hat{W}}(t) = {} & \tau r\Phi(t)(K\otimes L)(E(t)+E(t-\tau)) \\ & - \Phi(t)((N^TP')\otimes L)E(t) \\ & - \Phi(t)((N^TP')\otimes I)E^\tau(t) \end{aligned}$$

$$- \rho_1 \hat{W}(t) - \rho_2 (L \otimes I_2) \tilde{W}(t) \tag{38}$$

Theorem 2: Consider the target tracking system of n UUVs (1) and the target (3). We apply the target tracking law (29) and the parameter update rate (38) to the system with the time delays τ. If the system satisfies [assumption 1-3] and the parameters K_p, K_v, ρ_1, ρ_2, r, and the matrices P', Q, K satisfy the conditions C1-C3:

C1) $(P' \otimes H)(M \otimes I_n - (NK) \otimes H) + (M \otimes I_n - (NK) \otimes H)^T (P' \otimes H) + Q + \tau r \left((M^T M) \otimes I_n + (K^T K) \otimes (LL) + I \right) + \frac{\tau}{r} \left((P' N K K^T N^T P') \otimes (H B B^T H) \right) < 0$

C2) $\tau r \left((K^T K) \otimes (BB) + (K^T K K^T K) \otimes (BLLB) \right) - Q < 0$

C3) $- \rho_1 I - 2\rho_2 (L \otimes I_2) + \tau r \Phi(t) \Phi^T(t) + \tau \Phi(t) \left((N^T P' P' N) \otimes I \right) \Phi^T(t) < 0$

Then, the state error and the estimation bias of the target tracking system are bounded.

Proof: We define a Lyapunov-Krasovskii functional as

$$V(t) = E^T(t)(P' \otimes H)E(t) + \int_{t-\tau}^{t} E^T(t) Q E(t) ds + \int_{-\tau}^{0} \int_{t+\theta}^{t} \dot{E}^T(s) R \dot{E}(s) ds d\theta + \tilde{W}^T(t) \tilde{W}(t) \tag{39}$$

where Q, R are positive definite matrices. From (33) the and properties of the Kronecker product, the derivatives of (39) are obtained as

$$\begin{aligned} \dot{V}(t) = {} & 2E^T(t)(P' \otimes H) \{ M \otimes I_n - ((NK) \otimes L) E(t) \\ & \qquad - ((NK) \otimes B) E(t-\tau) \} \\ & + 2E^T(t)(P' \otimes H)(N \otimes I_n) \Phi^T(t) \tilde{W}(t) \\ & + E^T(t) Q E(t) - E^T(t-\tau) Q E(t-\tau) \\ & - \int_{t-\tau}^{t} \dot{E}^T(s) R \dot{E}(s) ds \\ & + \tau \dot{E}^T(t) R \dot{E}(t) + 2\tilde{W}^T(t) \dot{\tilde{W}}(t) \end{aligned} \tag{40}$$

While $E(t) = E(t-\tau) + \int_{t-\tau}^{t} \dot{E}(s) ds$, (40) is rewritten as

$$\begin{aligned} \dot{V}(t) = {} & -E^T(t) \left\{ (P' \otimes H)((NK) \otimes B) \right. \\ & \qquad \left. + ((NK) \otimes B)^T (P' \otimes H) \right\} E(t) \\ & + 2\tilde{W}^T(t) \dot{\tilde{W}}(t) \\ & + E^T(t) \left\{ (P' \otimes H)(M \otimes I_n - (NK) \otimes L) \right. \\ & \qquad \left. + (M \otimes I_n - (NK) \otimes L)^T (P' \otimes H) \right\} E(t) \\ & + E^T(t) Q E(t) - E^T(t-\tau) Q E(t-\tau) \\ & - \int_{t-\tau}^{t} \dot{E}^T(s) R \dot{E}(s) ds + \tau \dot{E}^T(t) R \dot{E}(t) \\ & + 2E^T(t)(P' \otimes H)((NK) \otimes B) \int_{t-\tau}^{t} \dot{E}(s) ds \\ & + 2E^T(t)(P' \otimes H)(N \otimes I_n) \Phi^T(t) \tilde{W}(t) \end{aligned} \tag{41}$$

If (41) satisfies

$$\begin{aligned} & 2E^T(t)(P' \otimes H)((NK) \otimes B) \int_{t-\tau}^{t} \dot{E}(s) ds \\ & \quad \leq \int_{t-\tau}^{t} \dot{E}^T(s) R \dot{E}(s) ds \\ & \qquad + \tau [E^T(t)(P' \otimes H)((NK) \otimes B)] R^{-1} \\ & \qquad \cdot [E^T(t)(P' \otimes H)((NK) \otimes B)]^T \end{aligned} \tag{42}$$

From (41) and (42), we obtain

$$\begin{aligned} \dot{V}(t) = {} & \tau [E^T(t)(P' \otimes H)((NK) \otimes B)] R^{-1} \\ & \cdot [E^T(t)(P' \otimes H)((NK) \otimes B)]^T \\ & + 2\tilde{W}^T(t) \dot{\tilde{W}}(t) \\ E^T(t) & \left\{ (P' \otimes H)(M \otimes I_n - (NK) \otimes H) \right. \\ & \left. + (M \otimes I_n - (NK) \otimes H)^T (P' \otimes H) \right\} E(t) \\ & + E^T(t) Q E(t) - E^T(t-\tau) Q E(t-\tau) \\ & + 2E^T(t)(P' \otimes H)(N \otimes I_n) \Phi^T(t) \tilde{W}(t) \\ & + \tau \dot{E}^T(t) R \dot{E}(t) \end{aligned} \tag{43}$$

R is chosen as $R = rI$, and $M^T N = 0$, then

$$\begin{aligned} \tau \dot{E}^T(t) R \dot{E}(t) = {} & \tau r E^T(t)(M^T M) \otimes I_n \\ & + \tau r E^T(t)(K^T K) \otimes (LL) E(t) \\ & + \tau r E^T(t-\tau)((K^T K) \otimes (BB)) E(t-\tau) \\ & - 2\tau r \tilde{W}^T(t) \Phi(t)(K \otimes L) E(t) \\ & - 2\tau r \tilde{W}^T(t) \Phi(t)(K \otimes B) E(t-\tau) \\ & + 2\tau r E^T(t)((K^T K) \otimes (LB)) E(t-\tau) \\ & + \tau r \tilde{W}^T(t) \Phi(t) \Phi^T(t) \tilde{W}(t) \end{aligned} \tag{44}$$

and

$$\begin{aligned} & 2\tau r E^T(t)((K^T K) \otimes (LB)) E(t-\tau) \\ & \quad \leq \tau r E^T(t) E(t) + \tau r E^T(t-\tau) \\ & \quad \times \left((K^T K K^T K) \otimes (BLLB) \right) E(t-\tau) \end{aligned} \tag{45}$$

From (43), (44) and (45), the derivatives of (39) are obtained as

$$\begin{aligned} \dot{V}(t) = {} & E^T(t) Q E(t) - E^T(t-\tau) Q E(t-\tau) \\ & + \tau r E^T(t-\tau) \left((K^T K) \otimes (BB) \right) E(t-\tau) \\ & + E^T(t)(P' \otimes H)(M \otimes I_n - (NK) \otimes H) E(t) \\ & + E^T(t)(M \otimes I_n - (NK) \otimes H)^T (P' \otimes H) E(t) \\ & + \frac{\tau}{r} E^T(t) \left((P' N K K^T N^T P') \otimes (H B B^T H) \right) E(t) \\ & - 2\tau r \tilde{W}^T(t) \Phi(t)(K \otimes L) E(t) \\ & - 2\tau r \tilde{W}^T(t) \Phi(t)(K \otimes B) E(t-\tau) + 2\tilde{W}^T(t) \dot{\tilde{W}}(t) \\ & + \tau r \tilde{W}^T(t) \Phi(t) \Phi^T(t) \tilde{W}(t) \\ & + \tau r E^T(t) \left\{ (M^T M) \otimes I_n + (K^T K) \otimes (LL) + I \right\} E(t) \\ & + \tau r E^T(t-\tau) \left((K^T K K^T K) \otimes (BLLB) \right) E(t-\tau) \\ & + 2E^T(t)(P' \otimes H)(N \otimes I_n) \Phi^T(t) \tilde{W}(t) \end{aligned} \tag{46}$$

For simplicity of analyzing the properties of (46), assume that $\dot{V}(t) = \dot{V}_1(t) + \dot{V}_2(t) + \dot{V}_3(t)$ while

$$\begin{aligned}\dot{V}_1(t) = \tau E^T(t)\left\{r\left((M^T M)\otimes I_n + (K^T K)\otimes(LL)+I\right)\right\}E(t)\\ + E^T(t)QE(t)\\ + E^T(t)(P'\otimes H)(M\otimes I_n - (NK)\otimes H)E(t)\\ + E^T(t)(M\otimes I_n - (NK)\otimes H)^T(P'\otimes H)E(t)\\ + \tau E^T(t)\left\{\frac{1}{r}\left((P'NKK^TN^TP')\otimes(HBB^TH)\right)\right\}E(t)\end{aligned}$$

$$\begin{aligned}\dot{V}_2(t) = \tau r E^T(t-\tau)\left((K^T K)\otimes(BB)\right)E(t-\tau)\\ - E^T(t-\tau)QE(t-\tau)\\ + \tau r E^T(t-\tau)\left((K^TKK^TK)\otimes(BLLB)\right)E(t-\tau)\end{aligned}$$

$$\begin{aligned}\dot{V}_3(t) = 2\tilde{W}^T(t)\dot{\tilde{W}}(t)\\ + 2E^T(t)\left((P'N)\otimes H\right)\Phi^T(t)\tilde{W}(t)\\ + \tau r\tilde{W}^T(t)\Phi(t)\Phi^T(t)\tilde{W}(t)\\ - 2\tau r\tilde{W}^T(t)\Phi(t)(K\otimes L)E(t)\\ - 2\tau r\tilde{W}^T(t)\Phi(t)(K\otimes B)E(t-\tau)\end{aligned}$$

While the tracking system satisfies conditions C1 and C2, $\beta_1 > 0, \beta_2 > 0$,

$$\dot{V}_1(t) < -\beta_1 E^T(t)E(t) \tag{47}$$

$$\dot{V}_2(t) < -\beta_2 E^T(t-\tau)E(t-\tau) \tag{48}$$

From (37),

$$\begin{aligned}\dot{V}_3(t) = 2\tilde{W}^T(t)(-\rho_1\hat{W}(t) - \rho_2(L\otimes I_2)\tilde{W}(t))\\ + \tau r\tilde{W}^T(t)\Phi(t)\Phi^T(t)\tilde{W}(t)\\ - 2\tau\tilde{W}^T(t)\Phi(t)\left((N^TP')\otimes I\right)\mathbf{\Delta}(t)\end{aligned} \tag{49}$$

where $\mathbf{\Delta}(t) = [\mathbf{1}_{1\times N}\Delta_p(t) \quad \mathbf{1}_{1\times N}\Delta_v(t)]^T$.

While $-2\rho_1\tilde{W}^T(t)\hat{W}(t) \le -\rho_1\tilde{W}^T(t)\tilde{W}(t) + \rho_1 W^T W$, integrating assumption 3, we have

$$\begin{aligned}\dot{V}_3(t) \le -\rho_1\tilde{W}^T(t)\tilde{W}(t) - 2\rho_2\tilde{W}^T(t)(L\otimes I_2)\tilde{W}(t)\\ + \tau r\tilde{W}^T(t)\Phi(t)\Phi^T(t)\tilde{W}(t)\\ + \tau\tilde{W}^T(t)\Phi(t)\left((N^TP'P'N)\otimes I\right)\Phi^T(t)\tilde{W}(t)\\ + \rho_1 W^T W + \tau N(\Delta_{p0}^2 + \Delta_{v0}^2)\end{aligned} \tag{50}$$

By choosing appropriate values of ρ_1, ρ_2, (50) will satisfy

$$\dot{V}_3(t) \le -\beta_3\tilde{W}^T(t)\tilde{W}(t) + c_w \tag{51}$$

where $c_w = \rho_1 W^T W + \tau N(\Delta_{p0}^2 + \Delta_{v0}^2)$.

From (47), (48), and (51), we can obtain

$$\begin{aligned}\dot{V}(t) \le -\beta_1 E^T(t)E(t) - \beta_2 E^T(t-\tau)E(t-\tau)\\ - \beta_3\tilde{W}^T(t)\tilde{W}(t) + c_w\end{aligned} \tag{52}$$

From (33) and (38), we obtain (53), as shown at the bottom of the next page.

From lemma 1 and lemma 2, we know that the state error and estimate bias of the target tracking system are uniformly ultimately bounded. This process completes the proof.

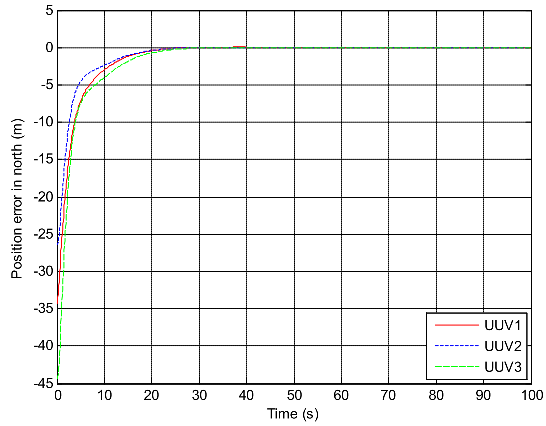

FIGURE 2. **Position errors in north without time delays.**

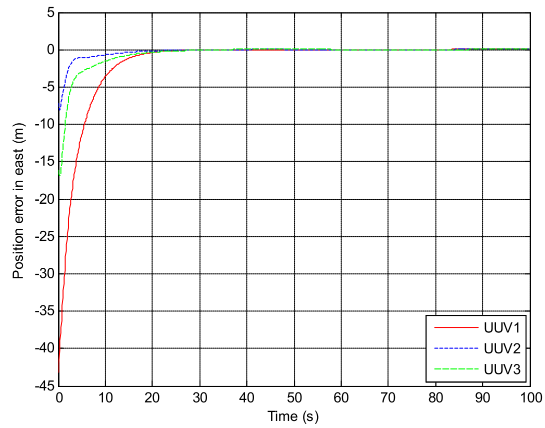

FIGURE 3. **Position errors in east without time delays.**

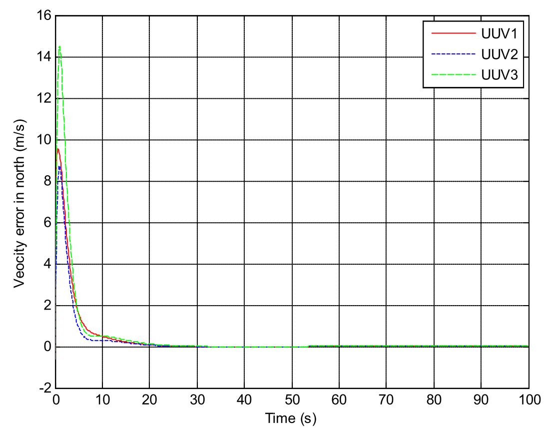

FIGURE 4. **Velocity errors in north without time delays.**

IV. NUMERICAL SIMULATION

In this section, simulation examples are included to illustrate the efficiency and effectiveness of the proposed control scheme. Simulations are performed on the model of the UUV, with an implementation in MATLAB. Consider the system with three members, which indicates that $n = 3$. The initial positions of the target in the X and Y axes are randomly

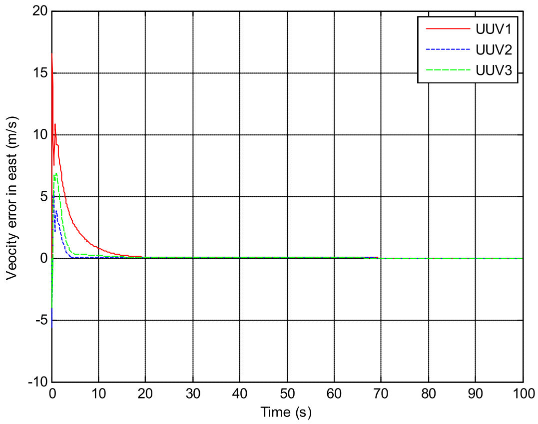

FIGURE 5. Velocity errors in east without time delays.

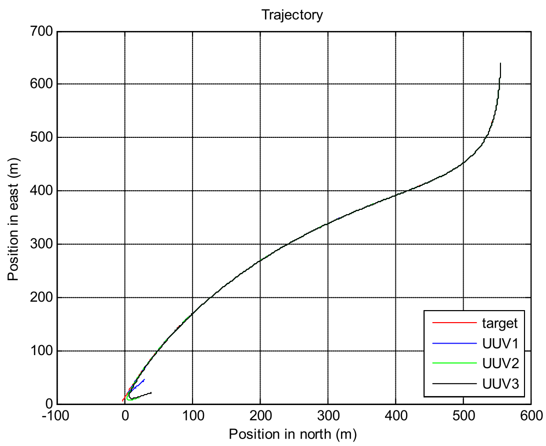

FIGURE 6. Trajectories of the target and UUVs without time delays.

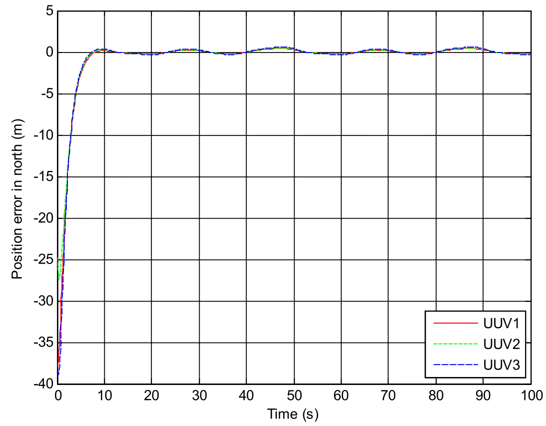

FIGURE 7. Position errors in north with time delays.

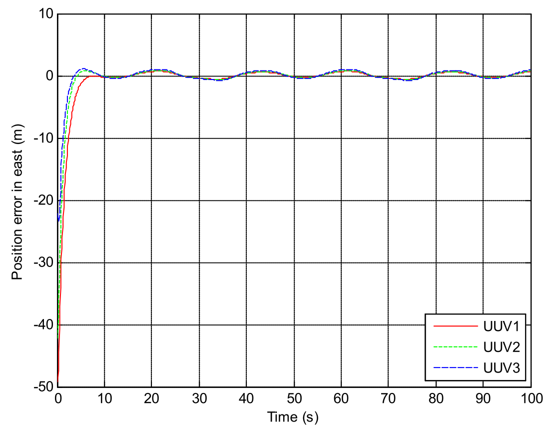

FIGURE 8. Position errors in east with time delays.

selected in $[-10, 10]m$, and the initial velocity u is randomly selected in $[0, 0.5]m/s$; the remaining states are zero. The communication topology is expressed as follows:

$$L = \begin{bmatrix} 2 & -1 & 0 \\ -1 & 2 & -1 \\ -1 & 0 & 1 \end{bmatrix}; \quad B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Example 1: In this case, the time delays are assumed to be zero, and the input of the target is adopted as follows:

$$\begin{cases} u_0(1) = 0.2\sin(0.02\pi t) + 0.1\cos(0.01\pi t) \\ u_0(2) = 0.4\cos(0.02\pi t) + 0.2\sin(0.01\pi t) \end{cases}$$

The initial conditions of the UUVs are listed as follows: $\eta_1(0) = [30,47,0]^T$, $\eta_2(0) = [22,11,0]^T$, and $\eta_3(0) = [40,20,0]^T$. The initial velocities are $u_i = 1m/s, (i = 1, 2, 3)$.

The following control gains are chosen:

$$K_p = 1.5, \quad K_v = 4, \; k_1 = 4, \; k_2 = 1, \; k_3 = 0.4.$$

Simulation results are shown in Figs. 2-6. Fig. 2 shows that the position error between the target and each UUV in the north (x-axis), which converges to zero. Fig. 3 illustrates that the position error in the east (y-axis) smoothly and rapidly converges. Figs. 4-5 show the corresponding velocity errors between each UUV and the target converge to 0. Fig. 6 shows the trajectories of the three UUVs and the target in the horizontal plane, which illustrate that UUVs that employ the target tracking law (7) and the parameter update rate (13) can smoothly cruise along and accurately track the target trajectory. Based on the simulation results, the control objectives are achieved.

$$\begin{bmatrix} \dot{E}(t) \\ \dot{\tilde{W}}(t) \end{bmatrix} = \begin{bmatrix} M \otimes I_n - (NK) \otimes L & (N \otimes I_n)\Phi^T(t) \\ \tau r\Phi(t)(K \otimes L) - \Phi(t)((N^T P') \otimes H) & -\rho_1 I - \rho_2(L \otimes I_2) \end{bmatrix} \begin{bmatrix} E(t) \\ \tilde{W}(t) \end{bmatrix} + \begin{bmatrix} -(NK) \otimes B & 0 \\ \tau r\Phi(t)(K \otimes I) & 0 \end{bmatrix} \begin{bmatrix} E(t-\tau) \\ \tilde{W}(t-\tau) \end{bmatrix} + \begin{bmatrix} 0 \\ -\Phi(t)((N^T P') \otimes I)\tau\mathbf{\Delta}(t) \end{bmatrix} \tag{53}$$

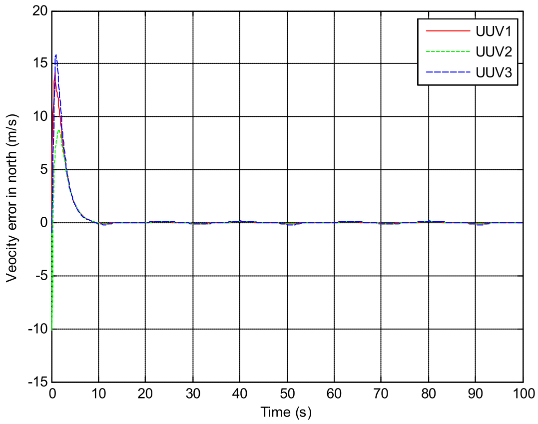

FIGURE 9. Velocity errors in north with time delays.

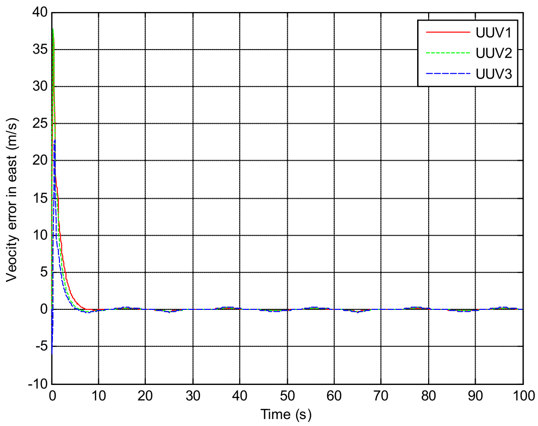

FIGURE 10. Velocity errors in east with time delays.

Example 2: In this scenario, the time delays of the target and UUVs are assumed to be $\tau = 0.1\ s$, and the input of the target is adopted as follows:

$$\begin{cases} u_0(1) = 0.4\sin(0.1\pi t) + 0.2\cos(0.05\pi t) \\ u_0(2) = 0.8\cos(0.1\pi t) + 0.4\sin(0.05\pi t) \end{cases}$$

The initial conditions of the UUVs are listed as follows: $\eta_1(0) = [30,47,0]^T$, $\eta_2(0) = [17,40,0]^T$, and $\eta_3(0) = [31,20,0]^T$. The initial velocities are $u_i = 1m/s, (i = 1, 2, 3)$.

The following control gains are chosen:

$$K_p = 1.5, \quad K_v = 3, \ \rho_1 = 6, \ \rho_2 = 2, \ r = 0.1.$$

The simulation results are shown in Figs. 7-11. Figs. 7-8 show the position errors between each UUV and the target in the north and east, respectively. Figs. 9-10 show the corresponding velocity errors in the north and east that are converged and stable. Fig. 11 shows the trajectories of UUVs and the target in the horizontal plane, which indicate that the UUV group can rapidly and accurately track the target using the controller (29) and the estimation (38). The simulation results reveal that the control objectives can be achieved.

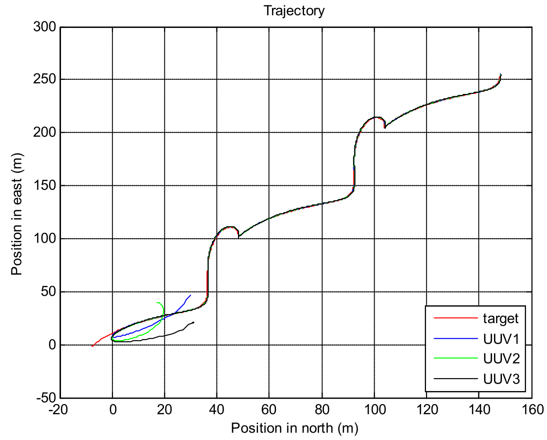

FIGURE 11. Trajectories of the target and UUVs with time delays.

V. CONCLUSIONS

This paper presents a target tracking strategy for multiple UUVs with time varying velocity and time delays based on a consensus algorithm. Neighboring state information and estimation of the target acceleration are employed to ensure that all UUVs can follow the target. Graph theory is applied to describe the communication topology, which is undirected connected in this paper. The design and analysis of the stability conditions for a multi-UUV system are developed using Lyapnov-Krasovskii functional, matrix theory and graph theories. Two simulations are presented to illustrate the theoretical results. In future studies, coordinated target tracking control with switching topologies and time-varying delays will be discussed.

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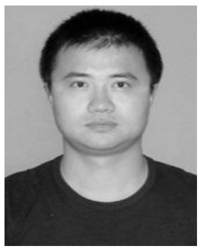

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