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Network-Based T-S Fuzzy Dynamic Positioning Controller Design for Unmanned Marine Vehicles

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***Abstract*—This paper is concerned with Takagi-Sugeno (T-S) fuzzy dynamic positioning controller design for an unmanned marine vehicle in network environments. Network-based T-S fuzzy dynamic positioning system models for the unmanned marine vehicle are first established. Then stability and stabilization criteria are derived by taking into consideration an asynchronous difference between the normalized membership function of the T-S fuzzy dynamic positioning system and that of the controller. The proposed stabilization criteria can stabilize states of the unmanned marine vehicle. The dynamic positioning performance analysis verifies the effectiveness of the networked modelling and the controller design.**

***Index Terms*—Unmanned marine vehicle, dynamic positioning, network-based control, T-S fuzzy control.**

I. Introduction

Marine vehicles have found applications in broad areas including transportation, military operations, hydrographic, fishing, oil and gas exploration and construction, oceanographic data collection, and scientific characterization. Since marine vehicles are subject to disturbance induced by waves, wind, and current, it is of paramount importance to study the motion control of marine vehicles [1], [2]. There are some interesting results available in the literature, which cover research topics in roll stabilization [3], heading control [4], [5], containment maneuvering [6], [7], tracking control [8], mooring control [9], fault detection [10], model predictive control [11], and path planning [12]. Besides the topics mentioned above, dynamic positioning, which aims at regulating the horizontal position and heading of marine vehicles, has also attracted much attention in the literature [13]. For example, Kalman filtering-based positioning and heading control of ships were investigated in [14]. Output feedback control for a marine dynamic positioning system was addressed in [15], [16]. By using multiple unidirectional tugboats, robust dynamic positioning of an unactuated surface vessel was studied in [17]. In [18], robust controller design for dynamic positioning of ships and offshore rigs using H_∞ and mixed-μ techniques was considered. A novel continuous robust controller for dynamically positioned surface vessels with added mass terms was constructed in [19]. A robust nonlinear control law for the dynamic positioning system of ships subject to unknown time-varying disturbance and input saturation was proposed in [20]. Passivity-based controllers for dynamic positioning of ships were developed in [21]. Quadratic finite-horizon optimal controller design for T-S fuzzy-model-based dynamic ship positioning systems was addressed in [22]. It should be mentioned that the T-S fuzzy-control-based approach, which is different from those in [13], [16]–[21], was adopted in [22] to describe the dynamic positioning of a marine vehicle. There is a growing interest in applying a T-S fuzzy control approach to deal with nonlinear control systems. The main characteristic of T-S fuzzy control lies in utilizing a linear system model to describe the local dynamics of each fuzzy rule [22], [23]. Then the abundant linear control methodologies can be adopted to investigate each linear model. Since the dynamic positioning system (DPS) of a marine vehicle is a complex nonlinear system, how to propose an appropriate modelling and control scheme to improve the dynamic positioning performance is practically valuable and attractive.

This paper aims at providing good dynamic positioning performance for an unmanned marine vehicle (UMV). The dynamic positioning for the UMV is usually based on a remote land-based/mother ship-based control station. The communication between the UMV and the control station is completed through communication networks. Thus, the UMV, the remote land-based/mother ship-based control station, and communication networks constitute a network-based control system. Because of attractive advantages such as low cost in installation and maintenance, flexibility in communication architectures, and high reliability, network-based control systems have attracted increasing attention [24]–[31], see survey papers [32], [33] for recent developments. Despite of advantages of network-based control, introducing communication networks into control systems may induce packet dropouts, delays, and packet disordering. For the networked DPS of a UMV, how to take sampler-to-controller and controller-to-actuator packet dropouts, network-induced delays, and packet disordering into account, and to establish network-based T-S fuzzy models are of paramount importance and still unresolved. Answering these questions is the first motivation of the current work.

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For a T-S fuzzy system, if a communication network is introduced between the controlled plant and the controller, the membership functions of the controlled plant and the controller are not synchronous, and such a characteristic is not considered in [34]. The asynchronous difference between the normalized membership function of the controlled plant and that of the controller is taken into consideration in [35], [36]. Moreover, for the T-S fuzzy-control-based DPS of a UMV, the T-S fuzzy model is closely related to the variation scope of the yaw angle. Then how to take into account the variation scope of the yaw angle and the asynchronous difference between the normalized membership function of the UMV and that of the controller, and to derive a novel stability criterion are practically valuable. Addressing these issues is the second motivation of the current work.

In practical situations, the controlled plant states are not always measurable. Thus, it is of paramount importance to s-tudy observer-based control scheme for T-S fuzzy systems, and some nice results are available in the literature [37]–[40]. Note that only the sensor-to-observer network-induced delays are considered in [37], while packet dropouts and the controller-to-actuator network-induced delays are not considered. The work in [38] assumed that updating instants of the control input and the measured output are the same. In fact, if time-varying network-induced delays are considered, such an assumption may not be applicable. Moreover, packet dropouts are not considered in [38]. The Bernoulli stochastic process was adopted in [39] to describe packet dropouts in the sensor-to-observer channel and the controller-to-actuator channel with network-induced delays being neglected. The problem of observer-based output feedback control for T-S fuzzy systems under decentralized event triggering communication was discussed in [40] with packet dropouts and network-induced delays being neglected. For the observer-based T-S fuzzy DPS of a UMV, taking into account sampler-to-controller and controller-to-actuator network-induced characteristics will lead to much modelling and controller design complexity. How to solve these issues is the third motivation of the current work.

This paper investigates the network-based modelling, stability analysis, and controller design for observer-based T-S fuzzy DPS of a UMV. The T-S fuzzy dynamic positioning system model is established firstly by taking into consideration the variation scope of the yaw angle for a marine vehicle. Then networked T-S fuzzy models for the UMV are established by taking into consideration sampler-to-controller and controller-to-actuator network-induced characteristics and the asynchronous difference between the normalized membership function of the UMV and that of the controller. Based on these models, the stability analysis and observer-based controller design for the T-S fuzzy dynamic positioning systems are presented. The proposed observer-based controller design can provide good system performance, which is verified by the dynamic positioning performance analysis. The main contributions of this paper are summarized as follows:

- Novel network-based T-S fuzzy dynamic positioning system models for the UMV are established by taking into consideration the variation scope of the yaw angle, and the sampler-to-controller and controller-to-actuator network-induced characteristics.
- Appropriate observer-based controller design schemes are proposed to provide good dynamic positioning performance with the negative influences of wave-induced disturbance being reduced.

The remainder of this paper is organized as follows. Section II establishes novel network-based T-S fuzzy models for the UMV. Section III is concerned with stability analysis. Observer-based controller design is presented in Section IV. Dynamic positioning performance analysis is given in Section V. Conclusions are drawn in Section VI.

Notation: $\mathbb{R}^n$ denotes n-dimensional Euclidean space. $*$ denotes the entries of a matrix implied by symmetry. I and 0 represent an identity matrix and a zero matrix with appropriate dimensions, respectively. The superscripts '-1' and 'T' mean that the inverse of a nonsingular matrix and the transpose of a matrix (vector), respectively. Matrices and vectors, if not explicitly stated, are assumed to have appropriate dimensions.

II. Network-based T-S fuzzy modelling

This section aims to establish network-based T-S fuzzy models for the UMV. The dynamics of a marine vehicle in 6 degrees of freedom include surge, sway, heave, roll, pitch, and yaw. For the normalized model of horizontal motion in a DPS, motion components such as surge, sway and yaw were investigated in [1]. This paper investigates the dynamic positioning of a marine vehicle which is equipped with thrusters. Consider the body-fixed and earth-fixed reference frames presented in Fig. 1, where x, y, and z denote the longitudinal axis, transverse axis, and normal axis, respectively; X, Y, and Z denote earth-fixed reference frames. The origin of the coordinates is chosen to be at the center line of the marine vehicle.

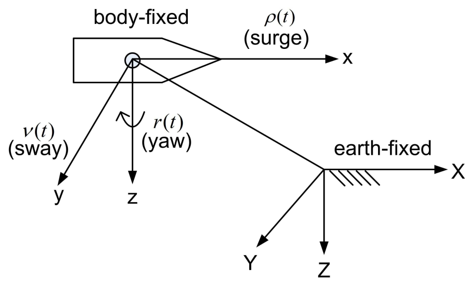

Fig. 1. Body-fixed and earth-fixed reference frames

The body-fixed equations of motion in surge, sway, and yaw are described as

$$M\dot{\nu}(t) + N\nu(t) + G\varphi(t) = u(t) + \omega(t) \tag{1}$$

where $\nu(t) = [\rho(t)\ \ \upsilon(t)\ \ r(t)]^T$ is the body-fixed linear and angular velocity vector with $\rho(t)$, $\upsilon(t)$, and $r(t)$ denoting the surge velocity, sway velocity, and yaw velocity, respectively; $\varphi(t) = [x(t)\ \ y(t)\ \ \psi(t)]^T$ is the earth-fixed orientation vector with $x(t)$ and $y(t)$ denoting positions and $\psi(t)$ denoting the yaw angle. The control input vector $u(t) = [u_1(t)\ u_2(t)\ u_3(t)]^T$ with $u_1(t)$ and $u_2(t)$ denoting the forces provided by main propellers aft of the marine vehicle and by tunnel thrusters, respectively, and $u_3(t)$ denoting the moment in yaw provided by azimuth thrusters; $\omega(t)$ is the wave-induced disturbance; M denotes the matrix of inertia which is invertible with $M = M^T > 0$; N introduces damping; the matrix $G = diag\{g_{11},\ g_{22},\ g_{33}\}$ represents mooring forces; and

$$\dot{\varphi}(t) = \Omega(\psi(t))\nu(t) \tag{2}$$

where

$$\Omega(\psi(t)) = \begin{bmatrix} cos(\psi(t)) & -sin(\psi(t)) & 0 \\ sin(\psi(t)) & cos(\psi(t)) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The starboard-port symmetry of the marine vehicle implies that M and N are of the following structure

$$M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{32} & m_{33} \end{bmatrix},\ N = \begin{bmatrix} n_{11} & 0 & 0 \\ 0 & n_{22} & n_{23} \\ 0 & n_{32} & n_{33} \end{bmatrix}$$

Let

$$A = -M^{-1}G = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix},$$

$$B = -M^{-1}N = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix},$$

$$D = M^{-1} = \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{bmatrix}.$$

Then the system (1) can be expressed as

$$\dot{\nu}(t) = A\varphi(t) + B\nu(t) + Du(t) + D\omega(t) \tag{3}$$

Define $\xi(t) = [\xi_1(t)\ \xi_2(t)\ \xi_3(t)\ \xi_4(t)\ \xi_5(t)\ \xi_6(t)]^T = [x(t)\ y(t)\ \psi(t)\ \rho(t)\ \upsilon(t)\ r(t)]^T$, where $\xi_1(t)$ and $\xi_4(t)$ denote the earth-fixed position on the X-axis and the body-fixed velocity on the x-axis, respectively; $\xi_2(t)$ and $\xi_5(t)$ denote the earth-fixed position on the Y-axis and the body-fixed velocity on the y-axis, respectively; $\xi_3(t)$ and $\xi_6(t)$ denote the yaw angle and yaw angular velocity, respectively. Combining (2) and (3) together, one can obtain state equations described as follows

$$\begin{aligned}
\dot{\xi}_1(t) =& cos(\xi_3(t))\xi_4(t) - sin(\xi_3(t))\xi_5(t) \\
\dot{\xi}_2(t) =& sin(\xi_3(t))\xi_4(t) + cos(\xi_3(t))\xi_5(t) \\
\dot{\xi}_3(t) =& \xi_6(t) \\
\dot{\xi}_4(t) =& a_{11}\xi_1(t) + a_{12}\xi_2(t) + a_{13}\xi_3(t) + b_{11}\xi_4(t) \\
& + b_{12}\xi_5(t) + b_{13}\xi_6(t) + d_{11}u_1(t) + d_{12}u_2(t) \\
& + d_{13}u_3(t) + d_{11}\omega_1(t) + d_{12}\omega_2(t) + d_{13}\omega_3(t) \\
\dot{\xi}_5(t) =& a_{21}\xi_1(t) + a_{22}\xi_2(t) + a_{23}\xi_3(t) + b_{21}\xi_4(t) \\
& + b_{22}\xi_5(t) + b_{23}\xi_6(t) + d_{21}u_1(t) + d_{22}u_2(t) \\
& + d_{23}u_3(t) + d_{21}\omega_1(t) + d_{22}\omega_2(t) + d_{23}\omega_3(t) \\
\dot{\xi}_6(t) =& a_{31}\xi_1(t) + a_{32}\xi_2(t) + a_{33}\xi_3(t) + b_{31}\xi_4(t) \\
& + b_{32}\xi_5(t) + b_{33}\xi_6(t) + d_{31}u_1(t) + d_{32}u_2(t) \\
& + d_{33}u_3(t) + d_{31}\omega_1(t) + d_{32}\omega_2(t) + d_{33}\omega_3(t)
\end{aligned} \tag{4}$$

Without loss of generality, suppose that the yaw angle $\psi(t)$, which is also known as $\xi_3(t)$, varies between $-\frac{\pi}{6}$ and $\frac{\pi}{6}$, and let $\theta_1(t) = sin(\xi_3(t))$, $\theta_2(t) = cos(\xi_3(t))$. Then $\theta_1(t) \in [-\frac{1}{2},\ \frac{1}{2}]$, $\theta_2(t) \in [\frac{\sqrt{3}}{2},\ 1]$. The T-S fuzzy DPS can be obtained by introducing the following rules

Plant Rule i: IF $\theta_1(t)$ is W_{i1} and $\theta_2(t)$ is W_{i2}
THEN

$$\begin{cases} \dot{\xi}(t) = \widetilde{A}_i\xi(t) + \widetilde{D}_iu(t) + \widetilde{D}_i\omega(t) \\ z(t) = C_{2i}\xi(t) + F_i\omega(t) \\ y(t) = C_1\xi(t) \end{cases} \tag{5}$$

where $i = 1,\ 2,\ 3,$ and 4, $\theta_1(t) = sin(\xi_3(t))$ and $\theta_2(t) = cos(\xi_3(t))$ are premise variables, W_{i1} and W_{i2} are fuzzy sets, $z(t)$ and $y(t)$ denote the controlled output and the measured output, respectively, C_{2i}, F_i, and C_1 are known matrices with appropriate dimensions, while

$$\widetilde{A}_1 = \begin{bmatrix} 0 & 0 & 0 & 1 & -\frac{1}{2} & 0 \\ 0 & 0 & 0 & \frac{1}{2} & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ a_{11} & a_{12} & a_{13} & b_{11} & b_{12} & b_{13} \\ a_{21} & a_{22} & a_{23} & b_{21} & b_{22} & b_{23} \\ a_{31} & a_{32} & a_{33} & b_{31} & b_{32} & b_{33} \end{bmatrix},$$

$$\widetilde{A}_2 = \begin{bmatrix} 0 & 0 & 0 & \frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 \\ 0 & 0 & 0 & \frac{1}{2} & \frac{\sqrt{3}}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ a_{11} & a_{12} & a_{13} & b_{11} & b_{12} & b_{13} \\ a_{21} & a_{22} & a_{23} & b_{21} & b_{22} & b_{23} \\ a_{31} & a_{32} & a_{33} & b_{31} & b_{32} & b_{33} \end{bmatrix},$$

$$\widetilde{A}_3 = \begin{bmatrix} 0 & 0 & 0 & 1 & \frac{1}{2} & 0 \\ 0 & 0 & 0 & -\frac{1}{2} & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ a_{11} & a_{12} & a_{13} & b_{11} & b_{12} & b_{13} \\ a_{21} & a_{22} & a_{23} & b_{21} & b_{22} & b_{23} \\ a_{31} & a_{32} & a_{33} & b_{31} & b_{32} & b_{33} \end{bmatrix},$$

$$\widetilde{A}_4 = \begin{bmatrix} 0 & 0 & 0 & \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ 0 & 0 & 0 & -\frac{1}{2} & \frac{\sqrt{3}}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ a_{11} & a_{12} & a_{13} & b_{11} & b_{12} & b_{13} \\ a_{21} & a_{22} & a_{23} & b_{21} & b_{22} & b_{23} \\ a_{31} & a_{32} & a_{33} & b_{31} & b_{32} & b_{33} \end{bmatrix},$$

$$\widetilde{D}_1 = \widetilde{D}_2 = \widetilde{D}_3 = \widetilde{D}_4 = \widetilde{D} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{bmatrix}$$

Remark 1: Note that the measured output $y(t)$ is described as $y(t) = C_1\xi(t)$ instead of $y(t) = C_{1i}\xi(t)$. In fact, when dealing with observer-based controller design, an equality constraint $JC_{1i}^T = C_{1i}^T\bar{J}$ is usually introduced with J and $\bar{J}$ denoting unknown matrices. This equality constraint leads to much difficulty for designing the observer-based controller. Thus, this paper chooses $C_{1i} = C_1$.

From the definition of $\widetilde{A}_i$, one can conclude that $W_{11}(\theta_1(t)) = W_{21}(\theta_1(t))$, $W_{31}(\theta_1(t)) = W_{41}(\theta_1(t))$, $W_{12}(\theta_2(t)) = W_{32}(\theta_2(t))$, $W_{22}(\theta_2(t)) = W_{42}(\theta_2(t))$. Note that

$$\begin{aligned} & W_{11}(\theta_1(t)) + W_{31}(\theta_1(t)) = 1 \\ & \tfrac{1}{2}W_{11}(\theta_1(t)) - \tfrac{1}{2}W_{31}(\theta_1(t)) = \theta_1(t) \end{aligned} \tag{6}$$

Then one has

$$\begin{array}{l} W_{11}(\theta_1(t)) = W_{21}(\theta_1(t)) = \frac{1}{2} + \theta_1(t) \\ W_{31}(\theta_1(t)) = W_{41}(\theta_1(t)) = \frac{1}{2} - \theta_1(t) \end{array} \quad (7)$$

Similarly,

$$\begin{array}{l} W_{12}(\theta_2(t)) = W_{32}(\theta_2(t)) = -3 - 2\sqrt{3} + (4 + 2\sqrt{3})\theta_2(t) \\ W_{22}(\theta_2(t)) = W_{42}(\theta_2(t)) = 4 + 2\sqrt{3} - (4 + 2\sqrt{3})\theta_2(t) \end{array} \quad (8)$$

From (5), one can derive the following T-S fuzzy DPS

$$\begin{cases} \dot{\xi}(t) = \sum_{i=1}^{4} h_i(\theta(t))[\widetilde{A}_i\xi(t) + \widetilde{D}_i u(t) + \widetilde{D}_i\omega(t)] \\ z(t) = \sum_{i=1}^{4} h_i(\theta(t))[C_{2i}\xi(t) + F_i\omega(t)] \\ y(t) = C_1\xi(t) \end{cases} \quad (9)$$

where

$$h_i(\theta(t)) = \frac{\vartheta_i(\theta(t))}{\sum_{j=1}^{4}\vartheta_j(\theta(t))}, \ \vartheta_i(\theta(t)) = W_{i1}(\theta_1(t))W_{i2}(\theta_2(t))$$

$$h_i(\theta(t)) \geq 0, \ \sum_{i=1}^{4} h_i(\theta(t)) = 1$$

Remark 2: As observed from (5), a different variation scope of the yaw angle $\psi(t)$ will lead to different $\widetilde{A}_i$. This paper assumes that the yaw angle $\psi(t)$ varies between $-\frac{\pi}{6}$ and $\frac{\pi}{6}$. If a different variation scope for the yaw angle $\psi(t)$ is chosen, the corresponding T-S fuzzy DPS is also different from (9) in this paper.

Since communication networks are introduced between the UMV and the observer-based controller, the premise membership function structure of the observer may be different from that of the fuzzy system (9). Thus, it is of paramount importance to construct an observer-based controller under imperfect premise matching. The rule of the observer is given as follows

Observer Rule j: IF $\hat{\theta}_1(t)$ is $\hat{W}_{j1}$ and $\hat{\theta}_2(t)$ is $\hat{W}_{j2}$ THEN

$$\begin{cases} \dot{\hat{\xi}}(t) = \widetilde{A}_j\hat{\xi}(t) + \widetilde{D}_j\hat{u}(t) + L_j(\bar{y}(t) - \hat{y}(t)) \\ \hat{y}(t) = C_1\hat{\xi}(t) \end{cases} \quad (10)$$

where $\hat{\theta}_1(t) = sin(\hat{\xi}_3(t))$ and $\hat{\theta}_2(t) = cos(\hat{\xi}_3(t))$ are premise variables, $\hat{W}_{j1}$ and $\hat{W}_{j2}$ are fuzzy sets, $j = 1, 2, 3,$ and 4; $\hat{\xi}(t)$ is the estimated observer state, $\bar{y}(t)$ is the measured output received by the observer, L_j is the observer gain to be designed. The global dynamics of the observer can be described as

$$\begin{cases} \dot{\hat{\xi}}(t) = \sum_{j=1}^{4} \phi_j(\hat{\theta}(t))[\widetilde{A}_j\hat{\xi}(t) + \widetilde{D}_j\hat{u}(t) + L_j(\bar{y}(t) - \hat{y}(t))] \\ \hat{y}(t) = C_1\hat{\xi}(t) \end{cases} \quad (11)$$

where

$$\phi_j(\hat{\theta}(t)) = \frac{\hat{\vartheta}_j(\hat{\theta}(t))}{\sum_{s=1}^{4}\hat{\vartheta}_s(\hat{\theta}(t))}, \ \hat{\vartheta}_j(\hat{\theta}(t)) = \hat{W}_{j1}(\hat{\theta}_1(t))\hat{W}_{j2}(\hat{\theta}_2(t))$$

$$\phi_j(\hat{\theta}(t)) \geq 0, \ \sum_{j=1}^{4} \phi_j(\hat{\theta}(t)) = 1$$

Note that no communication network is introduced between the observer and the controller. It is reasonable to assume that premise variables of the fuzzy observer and the controller are the same. Then the observer-based fuzzy control law can be represented as

Controller Rule l: IF $\hat{\theta}_1(t)$ is $\hat{W}_{l1}$ and $\hat{\theta}_2(t)$ is $\hat{W}_{l2}$ THEN

$$\hat{u}(t) = K_l\hat{\xi}(t) \quad (12)$$

where $\hat{\theta}_1(t) = sin(\hat{\xi}_3(t))$ and $\hat{\theta}_2(t) = cos(\hat{\xi}_3(t))$ are premise variables, $\hat{W}_{l1}$ and $\hat{W}_{l2}$ are fuzzy sets, $l = 1, 2, 3,$ and 4; K_l is the controller gain to be determined. Then the fuzzy controller is

$$\hat{u}(t) = \sum_{l=1}^{4} \phi_l(\hat{\theta}(t))K_l\hat{\xi}(t) \quad (13)$$

where the definition for $\phi_l(\hat{\theta}(t))$ is similar to that of $\phi_j(\hat{\theta}(t))$, here it is omitted for brevity.

In what follows, we turn to network-based modelling for the UMV.

Throughout this paper, we consider the case that the UMV and the remote control station are connected through communication networks; there exist packet dropouts, network-induced delays, and packet disordering; if packet disordering occurs, the latest available data packets will be utilized by the observer or the actuator, and disordered packets will be dropped; the sampler is time-driven, while the observer-based controller and the actuator are event-driven; the actuator is chosen as the zero order hold which is connected to the propeller and thruster system; the sampler, the observer-based controller, and the actuator are assumed to be clock synchronized. The networked structure for the T-S fuzzy DPS of a UMV is presented in Fig. 2, where the UMV is the C-Stat station keeping vessel of ASV Global in United Kingdom.

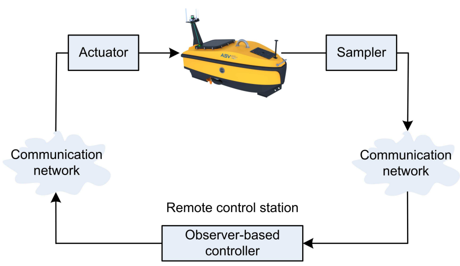

Fig. 2. Networked structure for the T-S fuzzy DPS of a UMV

Fig. 3 depicts the signal transmission for the UMV subject to sampler-to-controller and controller-to-actuator packet dropouts, network-induced delays, and packet disordering, where the solid lines denote successful data packet transmission, while the dashed lines and the dotted lines denote packet dropouts and packet disordering, respectively.

As observed from Fig. 3, sampled data based on the measured outputs at the instants $t_kh, \ t_{k+1}h, \ \cdots \ (k = 0, \ 1, \ 2, \ \cdots)$ are transmitted to the receivers successfully, while the data sampled at the instants $\tilde{t}_{k1}h$ and $\tilde{t}_{k2}h$ are dropped due to communication network unreliability and packet disordering, respectively; h denotes the length of the sampling period; $\varrho-1$ denotes the upper bound of consecutive packet dropouts; τ_k^{sc} and τ_k denotes the length of sampler-to-controller and sampler-to-actuator network-induced delays, respectively; τ_k^{ca} is defined as $\tau_k-\tau_k^{sc}$; $\tau_m^{sc}\le\tau_k^{sc}\le\tau_M^{sc}$, $\tau_m^{ca}\le\tau_k^{ca}\le\tau_M^{ca}$, $\tau_m\le\tau_k\le\tau_M$, where $\tau_m^{sc}\ge 0$, $\tau_m^{ca}\ge 0$, $\tau_m\ge 0$, and $\tau_m=\tau_m^{sc}+\tau_m^{ca}$.

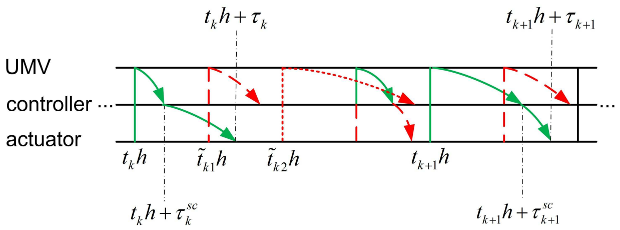

Fig. 3. Signal transmission for the UMV

Thus, for $t\in[t_kh+\tau_k^{sc},\ t_{k+1}h+\tau_{k+1}^{sc})$, the measurement output utilized by the observer is described as

$$\bar{y}(t)=y(t_kh) \tag{14}$$

For $t\in[t_kh+\tau_k,\ t_{k+1}h+\tau_{k+1})$, the control input available to the actuator is

$$u(t)=\hat{u}(t_kh+\tau_k^{sc}) \tag{15}$$

Remark 3: Note that for $t\in[t_kh+\tau_k,\ t_{k+1}h+\tau_{k+1})$, the measurement outputs available to the observer are variable. Then one should choose an appropriate measurement output for the observer. At the instant $t_kh+\tau_k$, the measurement outputs utilized by the observer may be sampled at instants $t_kh,\ t_kh+h,\ \cdots,\ t_kh+\lfloor\frac{\tau_k}{h}\rfloor h$, where $\lfloor\frac{\tau_k}{h}\rfloor$ is the largest integer smaller than or equal to $\frac{\tau_k}{h}$. A similar conclusion can be drawn for the instant $t_{k+1}h+\tau_{k+1}$. When the control input $\hat{u}(t_kh+\tau_k^{sc})$ is received by the actuator at the instant $t_k+\tau_k$, the actuator sends an acknowledgement signal to the observer-based controller. The acknowledgement signal is assigned the highest transmission priority and its network-induced delays are negligible. Thus, for $t\in[t_kh+\tau_k,\ t_{k+1}h+\tau_{k+1})$, the observer can choose to use the measurement output $y(t_kh)$ as its input.

Define $d(t)=t-t_kh$ and $\tau(t)=t-t_kh-\tau_k^{sc}$. Then one has $d(t)\in[\underline{d},\ \bar{d})$ and $\tau(t)\in[\underline{\tau},\ \bar{\tau})$ with $\underline{d}=\tau_m$, $\bar{d}=\varrho h+\tau_M$, $\underline{\tau}=\tau_m^{ca}$, and $\bar{\tau}=\varrho h+\tau_M-\tau_m^{sc}$. Define $\tilde{\xi}(t)=\xi(t)-\hat{\xi}(t)$, and $\bar{\xi}(t)=[\hat{\xi}^T(t)\quad\tilde{\xi}^T(t)]^T$. The following networked T-S fuzzy DPS can be established readily

$$\begin{cases}\dot{\bar{\xi}}(t)=\sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{l=1}^{4}\sum_{s=1}^{4}h_i(\theta(t))\phi_j(\hat{\theta}(t))\phi_l(\hat{\theta}(t))\\ \qquad\phi_s(\hat{\theta}(t-\tau(t)))[\Pi_{1ijl}\bar{\xi}(t)+\Pi_{2s}\bar{\xi}(t-\tau(t))\\ \qquad+\Pi_{3j}\bar{\xi}(t-d(t))+\bar{D}\omega(t)]\\ z(t)=\sum_{i=1}^{4}h_i(\theta(t))[C_{2i}\tilde{I}\bar{\xi}(t)+F_i\omega(t)]\end{cases} \tag{16}$$

where

$$\Pi_{1ijl}=\begin{bmatrix}\tilde{A}_j+\tilde{D}K_l-L_jC_1 & 0\\ \tilde{A}_i-\tilde{A}_j-\tilde{D}K_l+L_jC_1 & \tilde{A}_i\end{bmatrix},\Pi_{2s}=\begin{bmatrix}0 & 0\\ \tilde{D}K_s & 0\end{bmatrix},$$
$$\Pi_{3j}=\begin{bmatrix}L_jC_1 & L_jC_1\\ -L_jC_1 & -L_jC_1\end{bmatrix},\ \bar{D}=\begin{bmatrix}0\\ \tilde{D}\end{bmatrix},\ \tilde{I}=[I\quad I]$$

Remark 4: Note that $\tilde{D}_1=\tilde{D}_2=\tilde{D}_3=\tilde{D}_4=\tilde{D}$. Then $\tilde{D}_i$ $(i=1,\ 2,\ 3,\ 4)$ is written as $\tilde{D}$ in (16) and the followed expressions for brevity.

If communication networks are introduced between the UMV and the observer-based controller, it is natural to take into account the imperfect premise matching. However, this will lead to increased computational complexity inevitably, which statement is verified by the stability criterion in Theorem 1. Without loss of generality, we turn to consider the case of premise matching, and the rule of the observer is described as

Observer Rule i: IF $\theta_1(t)$ is W_{i1} and $\theta_2(t)$ is W_{i2} THEN

$$\begin{cases}\dot{\hat{\xi}}(t)=\tilde{A}_i\hat{\xi}(t)+\tilde{D}\hat{u}(t)+L_i(\bar{y}(t)-\hat{y}(t))\\ \hat{y}(t)=C_1\hat{\xi}(t)\end{cases} \tag{17}$$

where $\theta_1(t)$, $\theta_2(t)$, W_{i1}, and W_{i2} are the same as the corresponding items in Plant Rule i; $\hat{\xi}(t)$, $\bar{y}(t)$, and L_i are the same as the corresponding items in (10). The global dynamics of the observer is described as

$$\begin{cases}\dot{\hat{\xi}}(t)=\sum_{j=1}^{4}h_j(\theta(t))[\tilde{A}_j\hat{\xi}(t)+\tilde{D}\hat{u}(t)+L_j(\bar{y}(t)-\hat{y}(t))]\\ \hat{y}(t)=C_1\hat{\xi}(t)\\ \hat{u}(t)=K\hat{\xi}(t)\end{cases} \tag{18}$$

where the definition of $h_j(\theta(t))$ is similar to $h_i(\theta(t))$ in (9).

Motivated by the networked T-S fuzzy DPS in (16), one can establish the fuzzy DPS under premise matching as follows

$$\begin{cases}\dot{\bar{\xi}}(t)=\sum_{i=1}^{4}\sum_{j=1}^{4}h_i(\theta(t))h_j(\theta(t))[\Pi_{1ij}\bar{\xi}(t)\\ \qquad+\Pi_2\bar{\xi}(t-\tau(t))+\Pi_{3j}\bar{\xi}(t-d(t))+\bar{D}\omega(t)]\\ z(t)=\sum_{i=1}^{4}h_i(\theta(t))[C_{2i}\tilde{I}\bar{\xi}(t)+F_i\omega(t)]\end{cases} \tag{19}$$

where

$$\Pi_{1ij}=\begin{bmatrix}\tilde{A}_j+\tilde{D}K-L_jC_1 & 0\\ \tilde{A}_i-\tilde{A}_j-\tilde{D}K+L_jC_1 & \tilde{A}_i\end{bmatrix},\Pi_2=\begin{bmatrix}0 & 0\\ \tilde{D}K & 0\end{bmatrix},$$
$$\Pi_{3j}=\begin{bmatrix}L_jC_1 & L_jC_1\\ -L_jC_1 & -L_jC_1\end{bmatrix},\ \bar{D}=\begin{bmatrix}0\\ \tilde{D}\end{bmatrix},\ \tilde{I}=[I\quad I]$$

Note that sampler-to-controller and controller-to-actuator network-induced characteristics are taken into full consideration in closed-loop systems (16) and (19). If one considers only controller-to-actuator network-induced characteristics, the global dynamics of the observer in (18) reduces to

$$\begin{cases} \dot{\hat{\xi}}(t) = \sum_{j=1}^{4} h_j(\theta(t))[\widetilde{A}_j\hat{\xi}(t) + \widetilde{D}\hat{u}(t) + L_j(y(t) - \hat{y}(t))] \\ \hat{y}(t) = C_1\hat{\xi}(t) \\ \hat{u}(t) = K\hat{\xi}(t) \end{cases} \tag{20}$$

where $h_j(\theta(t))$ is similar to $h_i(\theta(t))$ in (9). Then the networked T-S fuzzy DPS in (19) is converted to

$$\begin{cases} \dot{\bar{\xi}}(t) = \sum_{i=1}^{4}\sum_{j=1}^{4} h_i(\theta(t))h_j(\theta(t))[\widetilde{\Pi}_{1ij}\bar{\xi}(t) \\ \qquad +\Pi_2\bar{\xi}(t-\tau(t)) + \bar{D}\omega(t)] \\ z(t) = \sum_{i=1}^{4} h_i(\theta(t))[C_{2i}\widetilde{I}\bar{\xi}(t) + F_i\omega(t)] \end{cases} \tag{21}$$

where

$$\widetilde{\Pi}_{1ij} = \begin{bmatrix} \widetilde{A}_j + \widetilde{D}K & L_jC_1 \\ \widetilde{A}_i - \widetilde{A}_j - \widetilde{D}K & \widetilde{A}_i - L_jC_1 \end{bmatrix},$$
$$\Pi_2 = \begin{bmatrix} 0 & 0 \\ \widetilde{D}K & 0 \end{bmatrix}, \ \bar{D} = \begin{bmatrix} 0 \\ \widetilde{D} \end{bmatrix}, \ \widetilde{I} = \begin{bmatrix} I & I \end{bmatrix}$$

and $\tau(t) \in [\tau_l,\ \tau^u)$, where $\tau_l = \tau_m^{ca}$, $\tau^u = \varrho h + \tau_M^{ca}$.

Remark 5: Note that the T-S fuzzy-model-based dynamic positioning of a marine vehicle is investigated in [22] by using a state feedback fuzzy controller. In this paper, we consider an observer-based output feedback fuzzy control for dynamic positioning of a marine vehicle in network environments. As a consequence, network-induced characteristics are taken into account to establish network-based models and then investigate the stability analysis and controller design for networked T-S fuzzy DPSs. The proposed modelling and observer-based output feedback fuzzy control schemes can be extended to deal with general T-S fuzzy systems.

III. Stability analysis for networked T-S fuzzy DPSs

In this section, we analyse stability of network-based T-S fuzzy DPSs (16) and (19) for the UMV. In doing so, we construct the Lyapunov-Krasovskii functional as

$$V(t,\bar{\xi}_t) = \sum_{i=1}^{4} V_i(t,\bar{\xi}_t) \tag{22}$$

where

$$\begin{aligned} V_1(t,\bar{\xi}_t) =& \bar{\xi}^T(t)P\bar{\xi}(t), \\ V_2(t,\bar{\xi}_t) =& (\bar{\tau} - \tau(t))\int_{t-\tau(t)}^{t} \dot{\bar{\xi}}^T(s)Q_1\dot{\bar{\xi}}(s)ds \\ &+ (\bar{d} - d(t))\int_{t-d(t)}^{t} \dot{\bar{\xi}}^T(s)Q_2\dot{\bar{\xi}}(s)ds, \end{aligned}$$

$$\begin{aligned} V_3(t,\bar{\xi}_t) =& \int_{t-\underline{\tau}}^{t} \bar{\xi}^T(s)R_1\bar{\xi}(s)ds + \int_{t-\bar{\tau}}^{t-\underline{\tau}} \bar{\xi}^T(s)R_2\bar{\xi}(s)ds \\ &+ \int_{t-\underline{d}}^{t} \bar{\xi}^T(s)R_3\bar{\xi}(s)ds + \int_{t-\bar{d}}^{t-\underline{d}} \bar{\xi}^T(s)R_4\bar{\xi}(s)ds, \\ V_4(t,\bar{\xi}_t) =& \int_{-\bar{\tau}}^{-\underline{\tau}}\int_{t+s}^{t} \dot{\bar{\xi}}^T(\theta)S_1\dot{\bar{\xi}}(\theta)d\theta ds \\ &+ \int_{-\bar{d}}^{-\underline{d}}\int_{t+s}^{t} \dot{\bar{\xi}}^T(\theta)S_2\dot{\bar{\xi}}(\theta)d\theta ds \end{aligned}$$

and $\bar{\xi}_t = \bar{\xi}(t+\varsigma)$ with $\varsigma \in [t_0h + \tau_0 - max\{\bar{\tau},\ \bar{d}\},\ t_0h + \tau_0]$, while P, Q_1, Q_2, R_1, R_2, R_3, R_4, S_1, and S_2 are symmetric positive definite matrices of appropriate dimensions. We now state and establish the following stability criterion for the network-based system (16).

Theorem 1: For given scalars $\tau_m^{ca} \geq 0$, $\tau_m^{sc} \geq 0$, $\tau_M > 0$, $h > 0$, $\varrho > 0$, $\gamma > 0$, $\sigma_m \in [0,\ 1]$, membership functions $\phi_m(\hat{\theta}(t-\tau(t)))$ and $\phi_m(\hat{\theta}(t))$ satisfying $|\phi_m(\hat{\theta}(t-\tau(t))) - \phi_m(\hat{\theta}(t))| \leq \sigma_m$, and matrices L_j and K of appropriate dimensions, the network-based T-S fuzzy DPS (16) is asymptotically stable with an H_∞ norm bound γ, if there exist symmetric positive definite matrices P, Q_1, Q_2, R_1, R_2, R_3, R_4, S_1, S_2, and Z_{ijl} such that

$$\Gamma_{ijlm} + \Xi_{ijlm} + Z_{ijl} > 0 \tag{23}$$

$$\Gamma_{ijjs} + \Xi_{ijjs} + \sum_{m=1}^{4}\sigma_m(\Gamma_{ijjm} + \Xi_{ijjm} + Z_{ijj}) < 0 \tag{24}$$

$$\begin{aligned} &\Gamma_{ijls} + \Gamma_{iljs} + \Xi_{ijls} + \Xi_{iljs} + \sum_{m=1}^{4}\sigma_m(\Gamma_{ijlm} + \Gamma_{iljm} \\ &+\Xi_{ijlm} + \Xi_{iljm} + Z_{ijl} + Z_{ilj}) < 0, \quad j < l \end{aligned} \tag{25}$$

where $i,\ j,\ l,\ s,\ m = 1,\ 2,\ 3,$ and 4, and

$$\begin{aligned} \Gamma_{ijls} =& \begin{bmatrix} \Gamma_{1,ijls} & \Gamma_2 \\ * & \Gamma_3 \end{bmatrix}, \\ \Xi_{ijls} =& U_{1ijls}^T\Theta U_{1ijls} + \gamma^{-1}U_{2i}^TU_{2i}, \end{aligned}$$

$$\Gamma_{1,ijls} = \begin{bmatrix} \Gamma_{ijl}^{11} & 0 & 0 & 0 & 0 & \Gamma_s^{16} & \Gamma_j^{17} \\ * & \Gamma^{22} & 0 & 0 & 0 & \Gamma^{26} & 0 \\ * & * & \Gamma^{33} & 0 & 0 & \Gamma^{36} & 0 \\ * & * & * & \Gamma^{44} & 0 & 0 & \Gamma^{47} \\ * & * & * & * & \Gamma^{55} & 0 & \Gamma^{57} \\ * & * & * & * & * & \Gamma^{66} & 0 \\ * & * & * & * & * & 0 & \Gamma^{77} \end{bmatrix},$$

$$\Gamma_2 = \begin{bmatrix} \frac{6Q_1}{\bar{\tau}} & \frac{6Q_2}{\bar{d}} & 0 & 0 & 0 & 0 & P\bar{D} \\ 0 & 0 & \hat{S}_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \hat{S}_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \hat{S}_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \hat{S}_2 & 0 \\ \frac{6Q_1}{\bar{\tau}} & 0 & \hat{S}_1 & \hat{S}_1 & 0 & 0 & 0 \\ 0 & \frac{6Q_2}{\bar{d}} & 0 & 0 & \hat{S}_2 & \hat{S}_2 & 0 \end{bmatrix},$$

$$\begin{aligned} \Gamma_3 =& diag\{-\frac{12Q_1}{\bar{\tau}},\ -\frac{12Q_2}{\bar{d}},\ -\frac{12S_1}{\bar{\tau}-\underline{\tau}}, \\ &-\frac{12S_1}{\bar{\tau}-\underline{\tau}},\ -\frac{12S_2}{\bar{d}-\underline{d}},\ -\frac{12S_2}{\bar{d}-\underline{d}},\ -\gamma I\}, \end{aligned}$$

$$
\begin{aligned}
\Gamma_{ijl}^{11} =& P\Pi_{1ijl} + \Pi_{1ijl}^T P - \frac{4Q_1}{\bar{\tau}} - \frac{4Q_2}{\bar{d}} + R_1 + R_3,\\
\Gamma_s^{16} =& P\Pi_{2s} - \frac{2Q_1}{\bar{\tau}},\ \Gamma_j^{17} = P\Pi_{3j} - \frac{2Q_2}{\bar{d}},\\
\Gamma^{22} =& R_2 - R_1 - \frac{4S_1}{\bar{\tau}-\underline{\tau}},\ \Gamma^{26} = -\frac{2S_1}{\bar{\tau}-\underline{\tau}},\\
\Gamma^{33} =& -R_2 - \frac{4S_1}{\bar{\tau}-\underline{\tau}},\ \Gamma^{36} = -\frac{2S_1}{\bar{\tau}-\underline{\tau}},\\
\Gamma^{44} =& R_4 - R_3 - \frac{4S_2}{\bar{d}-\underline{d}},\ \Gamma^{47} = -\frac{2S_2}{\bar{d}-\underline{d}},\\
\Gamma^{55} =& -R_4 - \frac{4S_2}{\bar{d}-\underline{d}},\ \Gamma^{57} = -\frac{2S_2}{\bar{d}-\underline{d}},\\
\Gamma^{66} =& -\frac{4Q_1}{\bar{\tau}} - \frac{8S_1}{\bar{\tau}-\underline{\tau}},\ \Gamma^{77} = -\frac{4Q_2}{\bar{d}} - \frac{8S_2}{\bar{d}-\underline{d}},\\
\hat{S}_1 =& \frac{6S_1}{\bar{\tau}-\underline{\tau}},\ \hat{S}_2 = \frac{6S_2}{\bar{d}-\underline{d}},\\
U_{1ijls} =& \begin{bmatrix} \Pi_{1ijl} & \underbrace{0,\ \cdots,\ 0}_{4} & \Pi_{2s} & \Pi_{3j} & \underbrace{0,\ \cdots,\ 0}_{6} & \bar{D} \end{bmatrix},\\
U_{2i} =& \begin{bmatrix} C_{2i}\widetilde{I} & \underbrace{0,\ \cdots,\ 0}_{12} & F_i \end{bmatrix},\ \widetilde{I} = \begin{bmatrix} I & I \end{bmatrix},\\
\Theta =& (\bar{\tau}-\underline{\tau})(Q_1+S_1) + (\bar{d}-\underline{d})(Q_2+S_2),
\end{aligned}
\tag{26}
$$

while Γ_{ijlm} and Ξ_{ijlm} are derived from Γ_{ijls} and Ξ_{ijls}, respectively, by substituting the subscript s with m; Γ_{ijjs}, Ξ_{ijjs}, Γ_{ijjm}, Ξ_{ijjm}, and Z_{ijj} are derived from Γ_{ijls}, Ξ_{ijls}, Γ_{ijlm}, Ξ_{ijlm}, and Z_{ijl}, respectively, by substituting the subscript l with j; Γ_{iljs}, Ξ_{iljs}, Γ_{iljm}, Ξ_{iljm}, and Z_{ilj} are derived from Γ_{ijls}, Ξ_{ijls}, Γ_{ijlm}, Ξ_{ijlm}, and Z_{ijl}, respectively, by interchanging the subscripts j and l.

Proof: See the Appendix. ■

Remark 6: Note that the assumption $|\phi_m(\hat{\theta}(t-\tau(t))) - \phi_m(\hat{\theta}(t))| \le \sigma_m$ is introduced in the proof Theorem 1. As discussed in [35], considering the asynchronous difference between the normalized membership function of the controlled plant and that of the controller will lead to less conservatism. Thus, the stability criterion in Theorem 1 is expected to provide good dynamic positioning performance. On the other hand, the T-S fuzzy systems and the stability criterion in Theorem 1 of this paper are totally different from those in [35], the comparison between this paper and [35] is omitted.

If the networked T-S fuzzy DPS (19) under the premise matching is considered, the following stability criterion is followed immediately.

Theorem 2: For given scalars $\tau_m^{ca} \ge 0$, $\tau_m^{sc} \ge 0$, $\tau_M > 0$, $h > 0$, $\varrho > 0$, $\gamma > 0$, and matrices L_j and K of appropriate dimensions, the network-based T-S fuzzy DPS (19) is asymptotically stable with an H_∞ norm bound γ, if there exist symmetric positive definite matrices P, Q_1, Q_2, R_1, R_2, R_3, R_4, S_1, and S_2 such that the inequalities (27) and (28) hold for $1 \le i \ne j \le 4$,

$$
\begin{bmatrix} \Gamma_{ii} & \Gamma_{4,ii} \\ * & \Gamma_5 \end{bmatrix} < 0 \tag{27}
$$

$$
\begin{bmatrix} \bar{\Gamma}_{ij} & \Gamma_{4,ii} & \Gamma_{4,ij} & \Gamma_{4,ji} \\ * & 3\Gamma_5 & 0 & 0 \\ * & * & 2\Gamma_5 & 0 \\ * & * & * & 2\Gamma_5 \end{bmatrix} < 0 \tag{28}
$$

where

$$
\begin{aligned}
\bar{\Gamma}_{ij} =& \frac{1}{3}\Gamma_{ii} + \frac{1}{2}\Gamma_{ij} + \frac{1}{2}\Gamma_{ji},\\
\Gamma_{4,ij} =& \begin{bmatrix} U_{3ij} & U_{3ij} & U_{3ij} & U_{3ij} & U_{2i} \end{bmatrix},\\
\Gamma_5 =& diag\{-(\bar{\tau}-\underline{\tau})^{-1}Q_1^{-1},\ -(\bar{\tau}-\underline{\tau})^{-1}S_1^{-1},\\
& -(\bar{d}-\underline{d})^{-1}Q_2^{-1},\ -(\bar{d}-\underline{d})^{-1}S_2^{-1},\ -\gamma I\},\\
U_{3ij} =& \begin{bmatrix} \Pi_{1ij} & \underbrace{0,\ \cdots,\ 0}_{4} & \Pi_2 & \Pi_{3j} & \underbrace{0,\ \cdots,\ 0}_{6} & \bar{D} \end{bmatrix},\\
U_{2i} =& \begin{bmatrix} C_{2i}\widetilde{I} & \underbrace{0,\ \cdots,\ 0}_{12} & F_i \end{bmatrix},\ \widetilde{I} = \begin{bmatrix} I & I \end{bmatrix},
\end{aligned}
$$

while Γ_{ij} is derived from Γ_{ijls} in (26) by substituting Π_{1ijl} and Π_{2s} with Π_{1ij} and Π_2 in (19), respectively; Γ_{ii} and $\Gamma_{4,ii}$ are derived from Γ_{ij} and $\Gamma_{4,ij}$, respectively, by substituting the subscript j with i; Γ_{ji} and $\Gamma_{4,ji}$ are derived from Γ_{ij} and $\Gamma_{4,ij}$, respectively, by interchanging the subscripts i and j.

Proof: By combining Theorem 2.2 in [43] and the proof of Theorem 1 in this paper, one can derive the stability criterion presented above. The detailed proof is omitted here for brevity. This completes the proof. ■

IV. CONTROLLER DESIGN FOR NETWORKED T-S FUZZY DPSS

This section is concerned with controller design for network-based T-S fuzzy DPSs of the UMV.

We state and establish the following controller design criterion for the closed-loop system (19).

Theorem 3: For given scalars $\tau_m^{ca} \ge 0$, $\tau_m^{sc} \ge 0$, $\tau_M > 0$, $h > 0$, $\varrho > 0$, $\gamma > 0$, the network-based T-S fuzzy DPS (19) is asymptotically stable with an H_∞ norm bound γ and the controller gain $K = V_1^T J^{-1}$, and the observer gain $L_j = V_{2j}^T \bar{J}^{-T}$, if there exist symmetric positive definite matrices J, $\widetilde{Q}_1$, $\widetilde{Q}_2$, $\widetilde{R}_1$, $\widetilde{R}_2$, $\widetilde{R}_3$, $\widetilde{R}_4$, $\widetilde{S}_1$, and $\widetilde{S}_2$, matrices V_1, V_{2j}, and $\bar{J}$ such that

$$
\begin{bmatrix} \widetilde{\Gamma}_{ii} & \widetilde{\Gamma}_{4,ii} \\ * & \widetilde{\Gamma}_5 \end{bmatrix} < 0 \tag{29}
$$

$$
\begin{bmatrix} \widetilde{\Gamma}_{ij}^{com} & \widetilde{\Gamma}_{4,ii} & \widetilde{\Gamma}_{4,ij} & \widetilde{\Gamma}_{4,ji} \\ * & 3\widetilde{\Gamma}_5 & 0 & 0 \\ * & * & 2\widetilde{\Gamma}_5 & 0 \\ * & * & * & 2\widetilde{\Gamma}_5 \end{bmatrix} < 0 \tag{30}
$$

$$
JC_1^T = C_1^T \bar{J} \tag{31}
$$

where

$$
\widetilde{\Gamma}_{ij} = \begin{bmatrix} \widetilde{\Gamma}_{1,ij} & \widetilde{\Gamma}_2 \\ * & \widetilde{\Gamma}_3 \end{bmatrix},
$$

$$
\widetilde{\Gamma}_{1,ij} = \begin{bmatrix}
\widetilde{\Gamma}_{ij}^{11} & 0 & 0 & 0 & 0 & \widetilde{\Gamma}^{16} & \widetilde{\Gamma}_j^{17} \\
* & \widetilde{\Gamma}^{22} & 0 & 0 & 0 & \widetilde{\Gamma}^{26} & 0 \\
* & * & \widetilde{\Gamma}^{33} & 0 & 0 & \widetilde{\Gamma}^{36} & 0 \\
* & * & * & \widetilde{\Gamma}^{44} & 0 & 0 & \widetilde{\Gamma}^{47} \\
* & * & * & * & \widetilde{\Gamma}^{55} & 0 & \widetilde{\Gamma}^{57} \\
* & * & * & * & * & \widetilde{\Gamma}^{66} & 0 \\
* & * & * & * & * & 0 & \widetilde{\Gamma}^{77}
\end{bmatrix}, \tag{32}
$$

$$\widetilde{\Gamma}_2=\begin{bmatrix}\frac{6\widetilde{Q}_1}{\bar{\tau}} & \frac{6\widetilde{Q}_2}{\bar{d}} & 0 & 0 & 0 & 0 & \bar{D}\\ 0 & 0 & \bar{S}_1 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & \bar{S}_1 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & \bar{S}_2 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & \bar{S}_2 & 0\\ \frac{6\widetilde{Q}_1}{\bar{\tau}} & 0 & \bar{S}_1 & \bar{S}_1 & 0 & 0 & 0\\ 0 & \frac{6\widetilde{Q}_2}{\bar{d}} & 0 & 0 & \bar{S}_2 & \bar{S}_2 & 0\end{bmatrix},$$

$$\begin{aligned}
\widetilde{\Gamma}_3 =& diag\{-\frac{12\widetilde{Q}_1}{\bar{\tau}},\ -\frac{12\widetilde{Q}_2}{\bar{d}},\ -\frac{12\widetilde{S}_1}{\bar{\tau}-\underline{\tau}},\\
&-\frac{12\widetilde{S}_1}{\bar{\tau}-\underline{\tau}},\ -\frac{12\widetilde{S}_2}{\bar{d}-\underline{d}},\ -\frac{12\widetilde{S}_2}{\bar{d}-\underline{d}},\ -\gamma I\},\\
\widetilde{\Gamma}_{ij}^{11} =& H_{1ij}+H_{1ij}^T-\frac{4\widetilde{Q}_1}{\bar{\tau}}-\frac{4\widetilde{Q}_2}{\bar{d}}+\widetilde{R}_1+\widetilde{R}_3,\\
\widetilde{\Gamma}^{16} =& H_2^T-\frac{2\widetilde{Q}_1}{\bar{\tau}},\ \widetilde{\Gamma}_j^{17}=H_{3j}^T-\frac{2\widetilde{Q}_2}{\bar{d}},\\
\widetilde{\Gamma}^{22} =& \widetilde{R}_2-\widetilde{R}_1-\frac{4\widetilde{S}_1}{\bar{\tau}-\underline{\tau}},\ \widetilde{\Gamma}^{26}=-\frac{2\widetilde{S}_1}{\bar{\tau}-\underline{\tau}},\\
\widetilde{\Gamma}^{33} =& -\widetilde{R}_2-\frac{4\widetilde{S}_1}{\bar{\tau}-\underline{\tau}},\ \widetilde{\Gamma}^{36}=-\frac{2\widetilde{S}_1}{\bar{\tau}-\underline{\tau}},\\
\widetilde{\Gamma}^{44} =& \widetilde{R}_4-\widetilde{R}_3-\frac{4\widetilde{S}_2}{\bar{d}-\underline{d}},\ \widetilde{\Gamma}^{47}=-\frac{2\widetilde{S}_2}{\bar{d}-\underline{d}},\\
\widetilde{\Gamma}^{55} =& -\widetilde{R}_4-\frac{4\widetilde{S}_2}{\bar{d}-\underline{d}},\ \widetilde{\Gamma}^{57}=-\frac{2\widetilde{S}_2}{\bar{d}-\underline{d}},\\
\widetilde{\Gamma}^{66} =& -\frac{4\widetilde{Q}_1}{\bar{\tau}}-\frac{8\widetilde{S}_1}{\bar{\tau}-\underline{\tau}},\ \widetilde{\Gamma}^{77}=-\frac{4\widetilde{Q}_2}{\bar{d}}-\frac{8\widetilde{S}_2}{\bar{d}-\underline{d}},\\
\bar{S}_1 =& \frac{6\widetilde{S}_1}{\bar{\tau}-\underline{\tau}},\ \bar{S}_2=\frac{6\widetilde{S}_2}{\bar{d}-\underline{d}},\\
\widetilde{\Gamma}_{4,ij} =& \begin{bmatrix}\widetilde{U}_{3ij} & \widetilde{U}_{3ij} & \widetilde{U}_{3ij} & \widetilde{U}_{3ij} & \widetilde{U}_{2i}\end{bmatrix},\\
\widetilde{\Gamma}_5 =& diag\{(\bar{\tau}-\underline{\tau})^{-1}(\widetilde{Q}_1-2\Upsilon),\ (\bar{\tau}-\underline{\tau})^{-1}(\widetilde{S}_1-2\Upsilon),\\
&(\bar{d}-\underline{d})^{-1}(\widetilde{Q}_2-2\Upsilon),\ (\bar{d}-\underline{d})^{-1}(\widetilde{S}_2-2\Upsilon),\ -\gamma I\},\\
\widetilde{U}_{3ij} =& \begin{bmatrix}H_{1ij}^T & \underbrace{0,\ \cdots,\ 0}_{4} & H_2^T & H_{3j}^T & \underbrace{0,\ \cdots,\ 0}_{6} & \bar{D}\end{bmatrix}^T,\\
\widetilde{U}_{2i} =& \begin{bmatrix}H_{4i}^T & \underbrace{0,\ \cdots,\ 0}_{12} & F_i\end{bmatrix}^T,\\
\widetilde{\Gamma}_{ij}^{com} =& \frac{1}{3}\widetilde{\Gamma}_{ii}+\frac{1}{2}\widetilde{\Gamma}_{ij}+\frac{1}{2}\widetilde{\Gamma}_{ji},\ \Upsilon=diag\{J,\ J\},\\
H_{1ij} =& \begin{bmatrix}\Lambda_1 & \Lambda_2\\ 0 & J\widetilde{A}_i^T\end{bmatrix},\ H_2=\begin{bmatrix}0 & V_1\widetilde{D}^T\\ 0 & 0\end{bmatrix},\\
H_{3j} =& \begin{bmatrix}C_1^TV_{2j} & -C_1^TV_{2j}\\ C_1^TV_{2j} & -C_1^TV_{2j}\end{bmatrix},\ H_{4i}=\begin{bmatrix}JC_{2i}^T\\ JC_{2i}^T\end{bmatrix},\\
\Lambda_1 =& J\widetilde{A}_j^T+V_1\widetilde{D}^T-C_1^TV_{2j},\\
\Lambda_2 =& J\widetilde{A}_i^T-J\widetilde{A}_j^T-V_1\widetilde{D}^T+C_1^TV_{2j},
\end{aligned}$$

while $\widetilde{\Gamma}_{ii}$ and $\widetilde{\Gamma}_{4,ii}$ are derived from $\widetilde{\Gamma}_{ij}$ and $\widetilde{\Gamma}_{4,ij}$, respectively, by substituting the subscript j with i; $\widetilde{\Gamma}_{ji}$ and $\widetilde{\Gamma}_{4,ji}$ are derived from $\widetilde{\Gamma}_{ij}$ and $\widetilde{\Gamma}_{4,ij}$, respectively, by interchanging the subscripts i and j.

Proof: Let $P = diag\{\hat{P},\ \hat{P}\}$, and $\hat{P}^{-1} = J$. Pre- and post-multiplying both sides of (27) with $diag\{\underbrace{P^{-1},\ \cdots,\ P^{-1}}_{13},\ \underbrace{I,\ \cdots,\ I}_{6}\}$ and its transpose, and pre- and post-multiplying both sides of (28) with $diag\{\underbrace{P^{-1},\ \cdots,\ P^{-1}}_{13},\ \underbrace{I,\ \cdots,\ I}_{16}\}$ and its transpose, supposing that there exists a matrix $\bar{J}$ such that $JC_1^T = C_1^T\bar{J}$, defining $P^{-1}Q_1P^{-1} = \widetilde{Q}_1$, $P^{-1}Q_2P^{-1} = \widetilde{Q}_2$, $P^{-1}R_1P^{-1} = \widetilde{R}_1$, $P^{-1}R_2P^{-1} = \widetilde{R}_2$, $P^{-1}R_3P^{-1} = \widetilde{R}_3$, $P^{-1}R_4P^{-1} = \widetilde{R}_4$, $P^{-1}S_1P^{-1} = \widetilde{S}_1$, $P^{-1}S_2P^{-1} = \widetilde{S}_2$, $JK^T = V_1$, $\bar{J}L_j^T = V_{2j}$, and considering that $-Q_1^{-1} \le \widetilde{Q}_1 - 2\Upsilon$, $-Q_2^{-1} \le \widetilde{Q}_2 - 2\Upsilon$, $-S_1^{-1} \le \widetilde{S}_1 - 2\Upsilon$, $-S_2^{-1} \le \widetilde{S}_2 - 2\Upsilon$, one can see that if (29)-(31) are satisfied, the stability criterion in Theorem 2 is also satisfied. This completes the proof. ■

It should be mentioned that the equality constraint in (31) induces some difficulty for numerical calculation. We turn to eliminate the equality constraint in (31). For the matrix C_1^T of full column rank, there always exist two orthogonal matrices $X \in \mathbb{R}^{6\times 6}$ and $Y \in \mathbb{R}^{3\times 3}$ such that

$$XC_1^TY=\begin{bmatrix}X_1\\ X_2\end{bmatrix}C_1^TY=\begin{bmatrix}\Phi\\ 0\end{bmatrix} \tag{33}$$

where $X_1 \in \mathbb{R}^{3\times 6}$, $X_2 \in \mathbb{R}^{3\times 6}$, $\Phi = diag\{\alpha_1,\ \alpha_2,\ \alpha_3\}$, and $\alpha_1,\ \alpha_2,\ \alpha_3$ are nonzero singular values of C_1^T. By using Lemma 2 in [44], one can conclude that if the matrix J can be written as

$$J=X^T\begin{bmatrix}J_{11} & 0\\ 0 & J_{22}\end{bmatrix}X=X_1^TJ_{11}X_1+X_2^TJ_{22}X_2 \tag{34}$$

where J_{11} and J_{22} are symmetric positive definite matrices with appropriate dimensions, then there exists a nonsingular matrix $\bar{J}$ such that $JC_1^T = C_1^T\bar{J}$.

Based on Theorem 3 and the statement presented above, one can derive the following observer-based controller design criterion.

Corollary 1: For given scalars $\tau_m^{ca} \ge 0$, $\tau_m^{sc} \ge 0$, $\tau_M > 0$, $h > 0$, $\varrho > 0$, $\gamma > 0$, the network-based T-S fuzzy DPS (19) is asymptotically stable with an H_∞ norm bound γ and the controller gain $K = V_1^T(X_1^TJ_{11}X_1 + X_2^TJ_{22}X_2)^{-1}$, and the observer gain $L_j = V_{2j}^TY\Phi J_{11}^{-1}\Phi^{-1}Y^T$, if there exist symmetric positive definite matrices J_{11}, J_{22}, $\widetilde{Q}_1$, $\widetilde{Q}_2$, $\widetilde{R}_1$, $\widetilde{R}_2$, $\widetilde{R}_3$, $\widetilde{R}_4$, $\widetilde{S}_1$, and $\widetilde{S}_2$, matrices V_1, and V_{2j} such that

$$\begin{bmatrix}\widetilde{\Gamma}_{ii,J} & \widetilde{\Gamma}_{4,ii,J}\\ * & \widetilde{\Gamma}_{5,J}\end{bmatrix}<0 \tag{35}$$

$$\begin{bmatrix}\widetilde{\Gamma}_{ij,J}^{com} & \widetilde{\Gamma}_{4,ii,J} & \widetilde{\Gamma}_{4,ij,J} & \widetilde{\Gamma}_{4,ji,J}\\ * & 3\widetilde{\Gamma}_{5,J} & 0 & 0\\ * & * & 2\widetilde{\Gamma}_{5,J} & 0\\ * & * & * & 2\widetilde{\Gamma}_{5,J}\end{bmatrix}<0 \tag{36}$$

where $\widetilde{\Gamma}_{ii,J}$, $\widetilde{\Gamma}_{4,ii,J}$, $\widetilde{\Gamma}_{5,J}$, $\widetilde{\Gamma}_{ij,J}^{com}$, $\widetilde{\Gamma}_{4,ij,J}$, and $\widetilde{\Gamma}_{4,ji,J}$ are derived from $\widetilde{\Gamma}_{ii}$, $\widetilde{\Gamma}_{4,ii}$, $\widetilde{\Gamma}_5$, $\widetilde{\Gamma}_{ij}^{com}$, $\widetilde{\Gamma}_{4,ij}$, and $\widetilde{\Gamma}_{4,ji}$ in (29)-(30), respectively, by substituting J with $X_1^TJ_{11}X_1 + X_2^TJ_{22}X_2$.

If the networked closed-loop system (21) is investigated, the controller design criterion in Theorem 4 is followed readily.

Theorem 4: For given scalars $\tau_m^{ca} \ge 0$, $\tau_M^{ca} > 0$, $h > 0$, $\varrho > 0$, $\gamma > 0$, the network-based T-S fuzzy DPS (21) is asymptotically stable with an H_∞ norm bound γ and the controller gain $K = V_1^T(X_1^T J_{11} X_1 + X_2^T J_{22} X_2)^{-1}$, and the observer gain $L_j = V_{2j}^T Y \Phi J_{11}^{-1} \Phi^{-1} Y^T$, if there exist symmetric positive definite matrices J_{11}, J_{22}, $\widetilde{Q}_1$, $\widetilde{R}_1$, $\widetilde{R}_2$, and $\widetilde{S}_1$, matrices V_1, and V_{2j} such that

$$\begin{bmatrix} \hat{\Gamma}_{ii} & \widetilde{\Gamma}_{6,ii} \\ * & \widetilde{\Gamma}_7 \end{bmatrix} < 0 \tag{37}$$

$$\begin{bmatrix} \hat{\Gamma}_{ij}^{com} & \widetilde{\Gamma}_{6,ii} & \widetilde{\Gamma}_{6,ij} & \widetilde{\Gamma}_{6,ji} \\ * & 3\widetilde{\Gamma}_7 & 0 & 0 \\ * & * & 2\widetilde{\Gamma}_7 & 0 \\ * & * & * & 2\widetilde{\Gamma}_7 \end{bmatrix} < 0 \tag{38}$$

where

$$\hat{\Gamma}_{ij} = \begin{bmatrix} \hat{\Gamma}_{ij}^{11} & 0 & 0 & \hat{\Gamma}^{14} & \hat{\Gamma}^{15} & 0 & 0 & \bar{D} \\ * & \hat{\Gamma}^{22} & 0 & \hat{\Gamma}^{24} & 0 & \hat{\Gamma}^{26} & 0 & 0 \\ * & * & \hat{\Gamma}^{33} & \hat{\Gamma}^{34} & 0 & 0 & \hat{\Gamma}^{37} & 0 \\ * & * & * & \hat{\Gamma}^{44} & \hat{\Gamma}^{45} & \hat{\Gamma}^{46} & \hat{\Gamma}^{47} & 0 \\ * & * & * & * & \hat{\Gamma}^{55} & 0 & 0 & 0 \\ * & * & * & * & * & \hat{\Gamma}^{66} & 0 & 0 \\ * & * & * & * & * & * & \hat{\Gamma}^{77} & 0 \\ * & * & * & * & * & * & * & -\gamma I \end{bmatrix},$$

$$\begin{aligned}
\hat{\Gamma}_{ij}^{11} =& H_{5ij} + H_{5ij}^T - \frac{4\widetilde{Q}_1}{\tau^u} + \widetilde{R}_1,\ \hat{\Gamma}^{14} = H_2^T - \frac{2\widetilde{Q}_1}{\tau^u}, \\
\hat{\Gamma}^{15} =& \frac{6\widetilde{Q}_1}{\tau^u},\ \hat{\Gamma}^{22} = \widetilde{R}_2 - \widetilde{R}_1 - \frac{4\widetilde{S}_1}{\tau^u - \tau_l},\ \hat{\Gamma}^{24} = -\frac{2\widetilde{S}_1}{\tau^u - \tau_l}, \\
\hat{\Gamma}^{26} =& \frac{6\widetilde{S}_1}{\tau^u - \tau_l},\ \hat{\Gamma}^{33} = -\widetilde{R}_2 - \frac{4\widetilde{S}_1}{\tau^u - \tau_l},\ \hat{\Gamma}^{34} = -\frac{2\widetilde{S}_1}{\tau^u - \tau_l}, \\
\hat{\Gamma}^{37} =& \frac{6\widetilde{S}_1}{\tau^u - \tau_l},\ \hat{\Gamma}^{44} = -\frac{4\widetilde{Q}_1}{\tau^u} - \frac{8\widetilde{S}_1}{\tau^u - \tau_l},\ \hat{\Gamma}^{45} = \frac{6\widetilde{Q}_1}{\tau^u}, \\
\hat{\Gamma}^{46} =& \hat{\Gamma}^{47} = \frac{6\widetilde{S}_1}{\tau^u - \tau_l},\ \hat{\Gamma}^{55} = -\frac{12\widetilde{Q}_1}{\tau^u}, \\
\hat{\Gamma}^{66} =& \hat{\Gamma}^{77} = -\frac{12\widetilde{S}_1}{\tau^u - \tau_l},\ \widetilde{\Gamma}_{6,ij} = \begin{bmatrix} \widetilde{U}_{4ij} & \widetilde{U}_{4ij} & \widetilde{U}_{5i} \end{bmatrix}, \\
\widetilde{\Gamma}_7 =& diag\{(\tau^u - \tau_l)^{-1}(\widetilde{Q}_1 - 2\Upsilon), \\
& (\tau^u - \tau_l)^{-1}(\widetilde{S}_1 - 2\Upsilon),\ -\gamma I\}, \\
\widetilde{U}_{4ij} =& \begin{bmatrix} H_{5ij}^T & 0 & 0 & H_2^T & 0 & 0 & 0 & \bar{D} \end{bmatrix}^T, \\
\widetilde{U}_{5i} =& \begin{bmatrix} H_{4i}^T & \underbrace{0, \cdots, 0}_{6} & F_i \end{bmatrix}^T, \\
\hat{\Gamma}_{ij}^{com} =& \frac{1}{3}\hat{\Gamma}_{ii} + \frac{1}{2}\hat{\Gamma}_{ij} + \frac{1}{2}\hat{\Gamma}_{ji},\ \Upsilon = diag\{\widetilde{J},\ \widetilde{J}\}, \\
H_{5ij} =& \begin{bmatrix} \widetilde{J}\widetilde{A}_j^T + V_1\widetilde{D}^T & \widetilde{J}\widetilde{A}_i^T - \widetilde{J}\widetilde{A}_j^T - V_1\widetilde{D}^T \\ C_1^T V_{2j} & \widetilde{J}\widetilde{A}_i^T - C_1^T V_{2j} \end{bmatrix}, \\
\widetilde{J} =& X_1^T J_{11} X_1 + X_2^T J_{22} X_2,
\end{aligned}$$

while H_2 and H_{4i} are the same as the corresponding items in Theorem 3; $\hat{\Gamma}_{ii}$ and $\widetilde{\Gamma}_{6,ii}$ are derived from $\hat{\Gamma}_{ij}$ and $\widetilde{\Gamma}_{6,ij}$, respectively, by substituting the subscript j with i; $\hat{\Gamma}_{ji}$ and $\widetilde{\Gamma}_{6,ji}$ are derived from $\hat{\Gamma}_{ij}$ and $\widetilde{\Gamma}_{6,ij}$, respectively, by interchanging the subscripts i and j.

Remark 7: Note that observer-based controller design, which can stabilize states of the UMV, for network-based T-S fuzzy DPSs (19) and (21) are investigated in Corollary 1 and Theorem 4, respectively. The proposed design methods can be extended to investigate the system (16), and the corresponding result is omitted here for brevity.

V. PERFORMANCE ANALYSIS AND DISCUSSION

In this section, we show the effectiveness of the proposed observer-based dynamic positioning controller design for the network-based T-S fuzzy DPS (21). In fact, the dynamic positioning controller design scheme in Corollary 1 is also applicable. The detailed performance analysis corresponding to the design scheme in Corollary 1 is omitted here.

Choose the matrices M, N, and G in the system (1) as (see [4], [22])

$$M = \begin{bmatrix} 1.0852 & 0 & 0 \\ 0 & 2.0575 & -0.4087 \\ 0 & -0.4087 & 0.2153 \end{bmatrix},$$
$$N = \begin{bmatrix} 0.0865 & 0 & 0 \\ 0 & 0.0762 & 0.1510 \\ 0 & 0.0151 & 0.0031 \end{bmatrix},$$
$$G = \begin{bmatrix} 0.0389 & 0 & 0 \\ 0 & 0.0266 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Noting that $A = -M^{-1}G$, $B = -M^{-1}N$, $D = M^{-1}$, one has

$$\begin{aligned}
A =& \begin{bmatrix} -0.0358 & 0 & 0 \\ 0 & -0.0208 & 0 \\ 0 & -0.0394 & 0 \end{bmatrix}, \\
B =& \begin{bmatrix} -0.0797 & 0 & 0 \\ 0 & -0.0818 & -0.1224 \\ 0 & -0.2254 & -0.2468 \end{bmatrix}, \\
D =& \begin{bmatrix} 0.9215 & 0 & 0 \\ 0 & 0.7802 & 1.4811 \\ 0 & 1.4811 & 7.4562 \end{bmatrix}
\end{aligned} \tag{39}$$

Without loss of generality, let

$$\begin{aligned}
C_{21} =& \begin{bmatrix} 0.5 & 1 & 0 & 0.1 & 0 & -0.7 \end{bmatrix}, \\
C_{22} =& \begin{bmatrix} 1 & 0 & 1 & 2.1 & -1.6 & 0 \end{bmatrix}, \\
C_{23} =& \begin{bmatrix} 0.2 & 0 & 2 & 1 & 0 & -0.8 \end{bmatrix}, \\
C_{24} =& \begin{bmatrix} -1 & 0 & -0.7 & 0 & 1 & 0.6 \end{bmatrix}, \\
F_1 =& \begin{bmatrix} 0.8 & 1 & 0.3 \end{bmatrix},\ F_2 = \begin{bmatrix} 1 & -1 & 2 \end{bmatrix}, \\
F_3 =& \begin{bmatrix} 0.6 & 1 & -0.5 \end{bmatrix},\ F_4 = \begin{bmatrix} 1 & 0.9 & -2 \end{bmatrix}, \\
C_1 =& \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}
\end{aligned} \tag{40}$$

For Theorem 4, let $\tau_m^{ca} = 0$s, $\tau_M^{ca} = 0.03$s, $h = 0.02$s, $\varrho = 2$.

By using matrix singular value decomposition and from (33), one has

$$X_1 = \begin{bmatrix} -0.7071 & 0 & 0 & -0.7071 & 0 & 0 \\ 0 & -0.7071 & 0 & 0 & -0.7071 & 0 \\ 0 & 0 & -0.7071 & 0 & 0 & -0.7071 \end{bmatrix},$$
$$X_2 = \begin{bmatrix} -0.7071 & 0 & 0 & 0.7071 & 0 & 0 \\ 0 & -0.7071 & 0 & 0 & 0.7071 & 0 \\ 0 & 0 & -0.7071 & 0 & 0 & 0.7071 \end{bmatrix},$$
$$Y = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix},\ \Phi = \begin{bmatrix} 1.4142 & 0 & 0 \\ 0 & 1.4142 & 0 \\ 0 & 0 & 1.4142 \end{bmatrix}$$

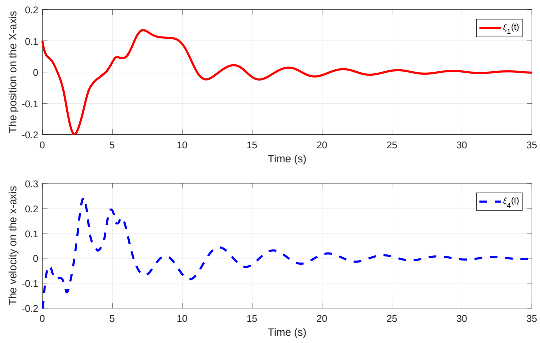

Fig. 4. The responses of the earth-fixed position on the X-axis and the body-fixed velocity on the x-axis.

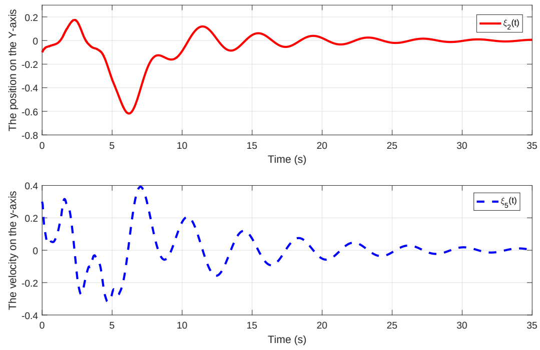

Fig. 5. The responses of the earth-fixed position on the Y-axis and the body-fixed velocity on the y-axis.

Suppose that the initial state of the closed-loop system (21) is $\bar{\xi}(t) = [0.1 \ \ -0.1 \ \ 0.2 \ \ -0.2 \ \ 0.3 \ \ -0.3 \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0]^T$. The disturbance of surge, sway and yaw motions $\omega_1(t)$, $\omega_2(t)$, and $\omega_3(t)$ is given as

$$\begin{cases} \omega_1(t) = 0.27F_1(s)N_1(t)N_2(t) \\ \omega_2(t) = -0.6cos(1.6t)e^{-0.12t} \\ \omega_3(t) = 0.58F_2(s)N_3(t)N_4(t) \end{cases} \tag{41}$$

where $F_1(s)$ and $F_2(s)$ are shaping filters described by $\frac{K_{\omega 1}s}{s^2+2\epsilon_1\sigma_1 s+\sigma_1^2}$ and $\frac{K_{\omega 2}s}{s^2+2\epsilon_2\sigma_2 s+\sigma_2^2}$, respectively; $K_{\omega 1}$ and $K_{\omega 2}$ denote the dominate wave strength coefficients with $K_{\omega 1} =$

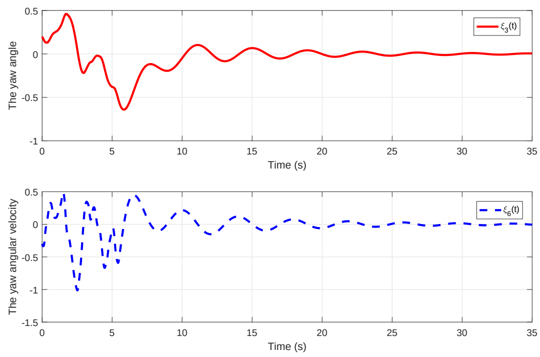

Fig. 6. The responses of the yaw angle and yaw angular velocity.

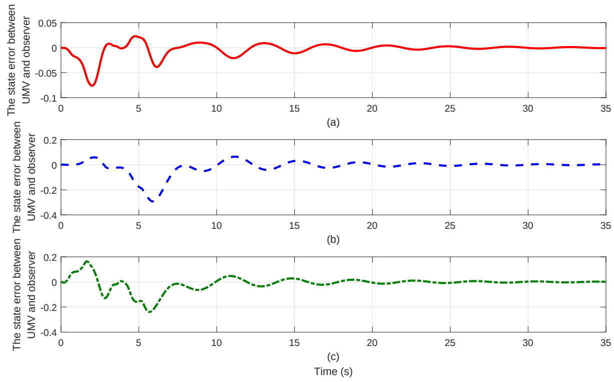

Fig. 7. The responses of state error between the UMV and the observer. (a), (b), and (c) are corresponding to $\tilde{\xi}_1(t)$, $\tilde{\xi}_2(t)$, and $\tilde{\xi}_3(t)$, respectively.

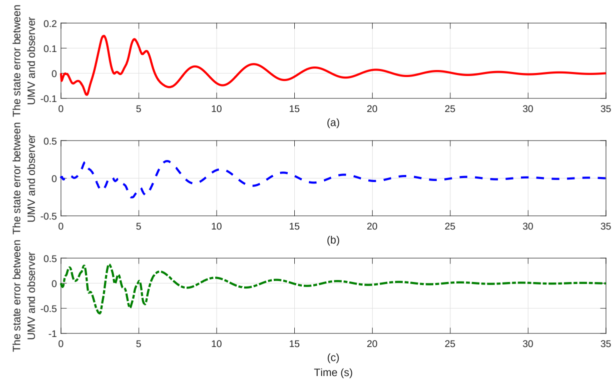

Fig. 8. The responses of state error between the UMV and the observer. (a), (b), and (c) are corresponding to $\tilde{\xi}_4(t)$, $\tilde{\xi}_5(t)$, and $\tilde{\xi}_6(t)$, respectively.

0.26 and $K_{\omega 2} = 0.8$; ϵ_1 and ϵ_2 denote the damping coefficients with $\epsilon_1 = 0.2$ and $\epsilon_2 = 1.7$; σ_1 and σ_2 denote the encountering wave frequencies with $\sigma_1 = 1.3$ and $\sigma_2 = 0.9$; $N_1(t)$ and $N_3(t)$ are band-limited white noise with noise powers 2.69

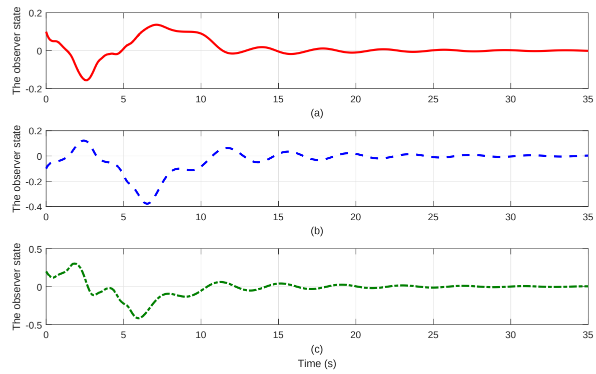

Fig. 9. The responses of observer state. (a), (b), and (c) are corresponding to $\hat{\xi}_1(t)$, $\hat{\xi}_2(t)$, and $\hat{\xi}_3(t)$, respectively.

and 1.56, respectively; while

$$N_2(t) = \begin{cases} 1, & t \in [0s,\ 6s] \\ 0, & otherwise \end{cases}$$
$$N_4(t) = \begin{cases} 1, & t \in [0s,\ 5.5s] \\ 0, & otherwise \end{cases}$$

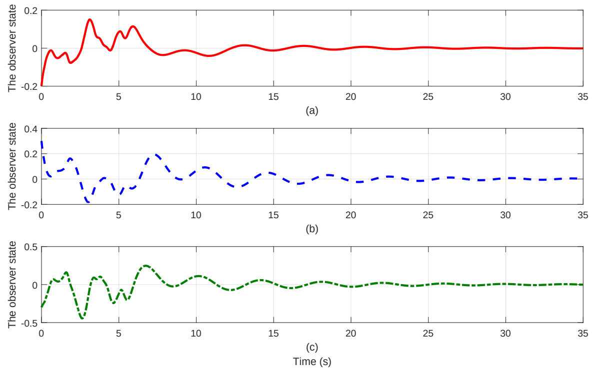

Fig. 10. The responses of observer state. (a), (b), and (c) are corresponding to $\hat{\xi}_4(t)$, $\hat{\xi}_5(t)$, and $\hat{\xi}_6(t)$, respectively.

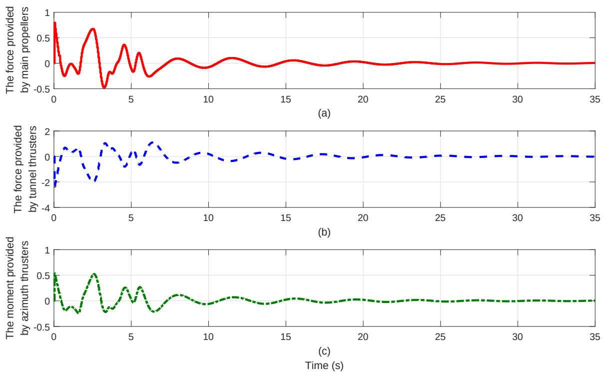

Fig. 11. The responses of the control forces and moment provided by the thruster system. (a), (b), and (c) are corresponding to the force $u_1(t)$ provided by main propellers, the force $u_2(t)$ provided by tunnel thrusters, and the moment $u_3(t)$ provided by azimuth thrusters, respectively.

The number of packet dropouts and the network-induced delays τ_k vary stochastically.

The responses of the UMV state are given in Fig. 4, Fig. 5, and Fig. 6, from which figures one can see that the proposed dynamic positioning scheme can guarantee satisfying performance for the UMV. The responses of state error between the UMV and the observer are presented in Fig. 7 and Fig. 8. In fact, the observer-based dynamic positioning controller design scheme can provide a small state error between the UMV and the observer, which is verified by Fig. 7 and Fig. 8. The responses of observer state are described by Fig. 9 and Fig. 10, while Fig. 11, and Fig. 12 present the responses of the control forces and moment provided by the thruster system, and the wave-induced disturbance, respectively. Even if the wave-induced disturbance is imposed on the UMV, the control cost is still acceptable. This statement is verified by Fig. 11 and Fig. 12.

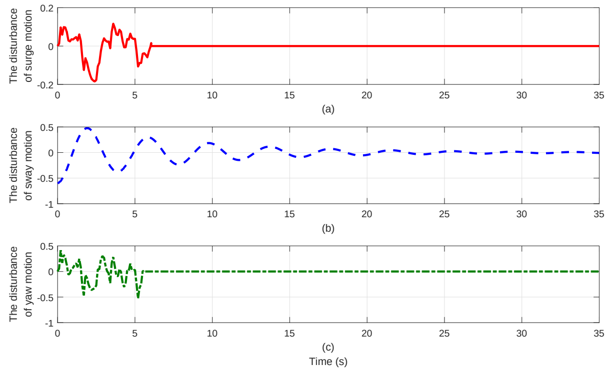

Fig. 12. The responses of the disturbance. (a), (b), and (c) are corresponding to the disturbance of surge motion $\omega_1(t)$, the disturbance of sway motion $\omega_2(t)$, and the disturbance of yaw motion $\omega_3(t)$, respectively.

VI. Conclusions

The networked modelling, stability analysis, and observer-based controller design for the T-S fuzzy dynamic positioning system of a UMV subject to wave-induced disturbance have been investigated. Network-based T-S fuzzy models for the DPS have been established by making full use of the variation scope of the yaw angle, and the sampler-to-controller and controller-to-actuator network-induced characteristics. A novel stability criterion has been derived by taking the asynchronous difference between the normalized membership function of the UMV and that of the controller into consideration. The proposed observer-based controller design has been shown to be effective in providing good dynamic positioning performance.

Future research includes network-based filtering [26], [45] for the T-S fuzzy dynamic positioning system of a UMV in network environments.

Appendix
Proof of Theorem 1

Taking the time derivative of the Lyapunov functional $V(t, \bar{\xi}_t)$ given in (22) along the trajectory of the system (16), we have

$$\dot{V}_1(t, \bar{\xi}_t) = 2\bar{\xi}^T(t)P\dot{\bar{\xi}}(t) \tag{42}$$

Applying the Wirtinger-based integral inequality [41], [42], one has

$$\begin{aligned} &\dot{V}_2(t, \bar{\xi}_t) \\ &= (\bar{\tau} - \tau(t))\dot{\bar{\xi}}^T(t)Q_1\dot{\bar{\xi}}(t) + (\bar{d} - d(t))\dot{\bar{\xi}}^T(t)Q_2\dot{\bar{\xi}}(t) \\ &\quad - \int_{t-\tau(t)}^{t} \dot{\bar{\xi}}^T(s)Q_1\dot{\bar{\xi}}(s) - \int_{t-d(t)}^{t} \dot{\bar{\xi}}^T(s)Q_2\dot{\bar{\xi}}(s) \\ &\leq (\bar{\tau} - \underline{\tau})\dot{\bar{\xi}}^T(t)Q_1\dot{\bar{\xi}}(t) + (\bar{d} - \underline{d})\dot{\bar{\xi}}^T(t)Q_2\dot{\bar{\xi}}(t) \\ &\quad - \frac{1}{\bar{\tau}}\zeta_1^TQ_1\zeta_1 - \frac{3}{\bar{\tau}}\zeta_2^TQ_1\zeta_2 - \frac{1}{\bar{d}}\zeta_3^TQ_2\zeta_3 - \frac{3}{\bar{d}}\zeta_4^TQ_2\zeta_4 \end{aligned} \tag{43}$$

$$\begin{aligned}&\dot{V}_3(t,\bar{\xi}_t)\\&=\bar{\xi}^T(t)R_1\bar{\xi}(t)+\bar{\xi}^T(t-\underline{\tau})(R_2-R_1)\bar{\xi}(t-\underline{\tau})\\&\quad-\bar{\xi}^T(t-\bar{\tau})R_2\bar{\xi}(t-\bar{\tau})+\bar{\xi}^T(t)R_3\bar{\xi}(t)\\&\quad+\bar{\xi}^T(t-\underline{d})(R_4-R_3)\bar{\xi}(t-\underline{d})-\bar{\xi}^T(t-\bar{d})R_4\bar{\xi}(t-\bar{d})\end{aligned}\tag{44}$$

Similar to the inequality in (43), we have

$$\begin{aligned}&\dot{V}_4(t,\bar{\xi}_t)\\&\leq(\bar{\tau}-\underline{\tau})\dot{\bar{\xi}}^T(t)S_1\dot{\bar{\xi}}(t)+(\bar{d}-\underline{d})\dot{\bar{\xi}}^T(t)S_2\dot{\bar{\xi}}(t)\\&\quad-\frac{1}{\bar{\tau}-\underline{\tau}}\zeta_5^TS_1\zeta_5-\frac{3}{\bar{\tau}-\underline{\tau}}\zeta_6^TS_1\zeta_6-\frac{1}{\bar{\tau}-\underline{\tau}}\zeta_7^TS_1\zeta_7\\&\quad-\frac{3}{\bar{\tau}-\underline{\tau}}\zeta_8^TS_1\zeta_8-\frac{1}{\bar{d}-\underline{d}}\zeta_9^TS_2\zeta_9-\frac{3}{\bar{d}-\underline{d}}\zeta_{10}^TS_2\zeta_{10}\\&\quad-\frac{1}{\bar{d}-\underline{d}}\zeta_{11}^TS_2\zeta_{11}-\frac{3}{\bar{d}-\underline{d}}\zeta_{12}^TS_2\zeta_{12}\end{aligned}\tag{45}$$

where

$$\begin{aligned}\zeta_1&=\bar{\xi}(t)-\bar{\xi}(t-\tau(t)),\\\zeta_2&=\bar{\xi}(t)+\bar{\xi}(t-\tau(t))-\frac{2}{\tau(t)}\int_{t-\tau(t)}^{t}\bar{\xi}(s)ds,\\\zeta_3&=\bar{\xi}(t)-\bar{\xi}(t-d(t)),\\\zeta_4&=\bar{\xi}(t)+\bar{\xi}(t-d(t))-\frac{2}{d(t)}\int_{t-d(t)}^{t}\bar{\xi}(s)ds,\\\zeta_5&=\bar{\xi}(t-\underline{\tau})-\bar{\xi}(t-\tau(t)),\\\zeta_6&=\bar{\xi}(t-\underline{\tau})+\bar{\xi}(t-\tau(t))-\frac{2}{\tau(t)-\underline{\tau}}\int_{t-\tau(t)}^{t-\underline{\tau}}\bar{\xi}(s)ds,\\\zeta_7&=\bar{\xi}(t-\tau(t))-\bar{\xi}(t-\bar{\tau}),\\\zeta_8&=\bar{\xi}(t-\tau(t))+\bar{\xi}(t-\bar{\tau})-\frac{2}{\bar{\tau}-\tau(t)}\int_{t-\bar{\tau}}^{t-\tau(t)}\bar{\xi}(s)ds,\\\zeta_9&=\bar{\xi}(t-\underline{d})-\bar{\xi}(t-d(t)),\\\zeta_{10}&=\bar{\xi}(t-\underline{d})+\bar{\xi}(t-d(t))-\frac{2}{d(t)-\underline{d}}\int_{t-d(t)}^{t-\underline{d}}\bar{\xi}(s)ds,\\\zeta_{11}&=\bar{\xi}(t-d(t))-\bar{\xi}(t-\bar{d}),\\\zeta_{12}&=\bar{\xi}(t-d(t))+\bar{\xi}(t-\bar{d})-\frac{2}{\bar{d}-d(t)}\int_{t-\bar{d}}^{t-d(t)}\bar{\xi}(s)ds\end{aligned}\tag{46}$$

Define

$$\begin{aligned}&\eta(t)=\\&[\bar{\xi}^T(t),\ \bar{\xi}^T(t-\underline{\tau}),\ \bar{\xi}^T(t-\bar{\tau}),\ \bar{\xi}^T(t-\underline{d}),\ \bar{\xi}^T(t-\bar{d}),\\&\bar{\xi}^T(t-\tau(t)),\ \bar{\xi}^T(t-d(t)),\ \frac{1}{\tau(t)}\int_{t-\tau(t)}^{t}\bar{\xi}^T(s)ds,\\&\frac{1}{d(t)}\int_{t-d(t)}^{t}\bar{\xi}^T(s)ds,\ \frac{1}{\tau(t)-\underline{\tau}}\int_{t-\tau(t)}^{t-\underline{\tau}}\bar{\xi}^T(s)ds,\\&\frac{1}{\bar{\tau}-\tau(t)}\int_{t-\bar{\tau}}^{t-\tau(t)}\bar{\xi}^T(s)ds,\ \frac{1}{d(t)-\underline{d}}\int_{t-d(t)}^{t-\underline{d}}\bar{\xi}^T(s)ds,\\&\frac{1}{\bar{d}-d(t)}\int_{t-\bar{d}}^{t-d(t)}\bar{\xi}^T(s)ds,\ \omega^T(t)]^T.\end{aligned}$$

Then we obtain the following inequality

$$\begin{aligned}&\dot{V}(t,\bar{\xi}_t)+\gamma^{-1}z^T(t)z(t)-\gamma\omega^T(t)\omega(t)\\&\leq\sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{l=1}^{4}\sum_{s=1}^{4}h_i(\theta(t))\phi_j(\hat{\theta}(t))\phi_l(\hat{\theta}(t))\phi_s(\hat{\theta}(t-\tau(t)))\\&\quad\eta^T(t)[\Gamma_{ijls}+\Xi_{ijls}]\eta(t)\end{aligned}\tag{47}$$

where Γ_{ijls} and Ξ_{ijls} are the same as the corresponding items in (26).

Note that the right side of the inequality (47) can be rewritten as

$$\begin{aligned}\Delta=&\sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{l=1}^{4}\sum_{s=1}^{4}h_i(\theta(t))\phi_j(\hat{\theta}(t))\phi_l(\hat{\theta}(t))\phi_s(\hat{\theta}(t))\\&\eta^T(t)[\Gamma_{ijls}+\Xi_{ijls}]\eta(t)+\sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{l=1}^{4}\sum_{s=1}^{4}h_i(\theta(t))\\&\phi_j(\hat{\theta}(t))\phi_l(\hat{\theta}(t))(\phi_s(\hat{\theta}(t-\tau(t)))-\phi_s(\hat{\theta}(t)))\\&\eta^T(t)[\Gamma_{ijls}+\Xi_{ijls}+Z_{ijl}]\eta(t)\end{aligned}\tag{48}$$

By assuming that $|\phi_m(\hat{\theta}(t-\tau(t)))-\phi_m(\hat{\theta}(t))|\leq\sigma_m$, one can see that

$$\begin{aligned}&\sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{l=1}^{4}\sum_{m=1}^{4}h_i(\theta(t))\phi_j(\hat{\theta}(t))\phi_l(\hat{\theta}(t))(\phi_m(\hat{\theta}(t-\tau(t)))\\&-\phi_m(\hat{\theta}(t)))\eta^T(t)[\Gamma_{ijlm}+\Xi_{ijlm}+Z_{ijl}]\eta(t)\\&\leq\sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{l=1}^{4}\sum_{s=1}^{4}h_i(\theta(t))\phi_j(\hat{\theta}(t))\phi_l(\hat{\theta}(t))\phi_s(\hat{\theta}(t))\\&\quad\eta^T(t)[\sum_{m=1}^{4}\sigma_m(\Gamma_{ijlm}+\Xi_{ijlm}+Z_{ijl})]\eta(t)\end{aligned}\tag{49}$$

Thus, the Δ in (48) satisfies

$$\begin{aligned}\Delta\leq&\sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{l=1}^{4}\sum_{s=1}^{4}h_i(\theta(t))\phi_j(\hat{\theta}(t))\phi_l(\hat{\theta}(t))\phi_s(\hat{\theta}(t))\\&\eta^T(t)[\Gamma_{ijls}+\Xi_{ijls}+\sum_{m=1}^{4}\sigma_m(\Gamma_{ijlm}\\&+\Xi_{ijlm}+Z_{ijl})]\eta(t)\\=&\sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{s=1}^{4}h_i(\theta(t))\phi_j(\hat{\theta}(t))\phi_j(\hat{\theta}(t))\phi_s(\hat{\theta}(t))\\&\eta^T(t)[\Gamma_{ijjs}+\Xi_{ijjs}+\sum_{m=1}^{4}\sigma_m(\Gamma_{ijjm}\\&+\Xi_{ijjm}+Z_{ijj})]\eta(t)\\&+\sum_{i=1}^{4}\sum_{j=1}^{3}\sum_{s=1}^{4}\sum_{j<l}h_i(\theta(t))\phi_j(\hat{\theta}(t))\phi_l(\hat{\theta}(t))\phi_s(\hat{\theta}(t))\\&\eta^T(t)[\Gamma_{ijls}+\Gamma_{iljs}+\Xi_{ijls}+\Xi_{iljs}+\sum_{m=1}^{4}\sigma_m(\Gamma_{ijlm}\\&+\Gamma_{iljm}+\Xi_{ijlm}+\Xi_{iljm}+Z_{ijl}+Z_{ilj})]\eta(t)\end{aligned}\tag{50}$$

From the inequalities presented above, one can conclude that if the inequalities in (23)-(25) are satisfied, then $\dot{V}(t,\bar{\xi}_t)+\gamma^{-1}z^T(t)z(t)-\gamma\omega^T(t)\omega(t)<0$. Based on the definition for H_∞ performance, one can get the stability criterion in Theorem 1. This completes the proof. ■

REFERENCES

[1] T. I. Fossen, *Handbook of Marine Craft Hydrodynamics and Motion Control*. Chichester, U.K.: John Wiley & Sons Ltd, 2011.

[2] Y.-L. Wang and Q.-L. Han, "Network-based modelling and dynamic output feedback control for unmanned marine vehicles in network environments," *Automatica*, vol. 91, pp. 43-53, May 2018.

[3] R.-Y. Ren, Z.-J. Zou, and X.-G. Wang, "A two-time scale control law based on singular perturbations used in rudder roll stabilization of ships," *Ocean Engineering*, vol. 88, pp. 488-498, Sep. 2014.

[4] N. E. Kahveci and P. A. Ioannou, "Adaptive steering control for uncertain ship dynamics and stability analysis," *Automatica*, vol. 49, no. 3, pp. 685-697, Mar. 2013.

[5] Y.-L. Wang and Q.-L. Han, "Network-based heading control and rudder oscillation reduction for unmanned surface vehicles," *IEEE Transactions on Control Systems Technology*, vol. 25, no. 5, pp. 1609-1620, Sep. 2017.

[6] Z. Peng, J. Wang, and D. Wang, "Distributed containment maneuvering of multiple marine vessels via neurodynamics-based output feedback," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 5, pp. 3831-3839, May 2017.

[7] Z. Peng, J. Wang, and D. Wang, "Containment maneuvering of marine surface vehicles with multiple parameterized paths via spatial-temporal decoupling," *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 2, pp. 1026-1036, Apr. 2017.

[8] H. Katayama and H. Aoki, "Straight-line trajectory tracking control for sampled-data underactuated ships," *IEEE Transactions on Control Systems Technology*, vol. 22, no. 4, pp. 1638-1645, Jul. 2014.

[9] M. Chen, S. S. Ge, B. V. E. How, and Y. S. Choo, "Robust adaptive position mooring control for marine vessels," *IEEE Transactions on Control Systems Technology*, vol. 21, no, 2, pp. 395-409, Mar. 2013.

[10] Y.-L. Wang and Q.-L. Han, "Network-based fault detection filter and controller coordinated design for unmanned surface vehicles in network environments," *IEEE Transactions on Industrial Informatics*, vol. 12, no. 5, pp. 1753-1765, Oct. 2016.

[11] Z. Yan and J. Wang, "Model predictive control for tracking of under-actuated vessels based on recurrent neural networks," *IEEE Journal of Oceanic Engineering*, vol. 37, no. 4, pp. 717-726, Oct. 2012.

[12] Y. Wang, S. Wang, and M. Tan, "Path generation of autonomous approach to a moving ship for unmanned vehicles," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 9, pp. 5619-5629, Sep. 2015.

[13] T. A. Johansen, T. I. Bø, E. Mathiesen, A. Veksler, and A. J. Sørensen, "Dynamic positioning system as dynamic energy storage on diesel-electric ships," *IEEE Transactions on Power Systems*, vol. 29, no. 6, pp. 3086-3091, Nov. 2014.

[14] Z. Peng, D. Wang, and J. Wang, "Cooperative dynamic positioning of multiple marine offshore vessels: a modular design," *IEEE/ASME Transactions on Mechatronics*, vol. 21, no. 3, pp. 1210-1221, May 2016.

[15] Z. Peng, D. Wang, and J. Wang, "Predictor-based neural dynamic surface control for uncertain nonlinear systems in strict-feedback form," *IEEE Transactions on Neural Networks and Learning Systems*, vol. 28, no. 9, pp. 2156-2167, Sep. 2017.

[16] J. Du, X. Hu, H. Liu, and C. L. P. Chen, "Adaptive robust output feedback control for a marine dynamic positioning system based on a high-gain observer," *IEEE Transactions on Neural Networks and Learning Systems*, vol. 26, no. 11, pp. 2775-2786, Nov. 2015.

[17] B. Bidikli, E. Tatlicioglu, and E. Zergeroglu, "Robust dynamic positioning of surface vessels via multiple unidirectional tugboats," *Ocean Engineering*, vol. 113, pp. 237-245, Feb. 2016.

[18] V. Hassani, A. J. Sørensen, A. M. Pascoal, and M. Athans, "Robust dynamic positioning of offshore vessels using mixed-μ synthesis modeling, design, and practice," *Ocean Engineering*, vol. 129, pp. 389-400, Jan. 2017.

[19] B. Bidikli, E. Tatlicioglu, and E. Zergeroglu, "Compensating of added mass terms in dynamically positioned surface vehicles: a continuous robust control approach," *Ocean Engineering*, vol. 139, pp. 198-204, Jul. 2017.

[20] J. Du, X. Hu, M. Krstić, and Y. Sun, "Robust dynamic positioning of ships with disturbances under input saturation," *Automatica*, vol. 73, pp. 207-214, Nov. 2016.

[21] S. Muhammad and A. Dòria-Cerezo, "Passivity-based control applied to the dynamic positioning of ships," *IET Control Theory & Applications*, vol. 6, no. 5, pp. 680-688, May 2012.

[22] W.-H. Ho, S.-H. Chen, and J.-H. Chou, "Optimal control of Takagi–Sugeno fuzzy-model-based systems representing dynamic ship positioning systems," *Applied Soft Computing*, vol. 13, no. 7, pp. 3197-3210, Jul. 2013.

[23] W.-B. Xie, Y.-L. Wang, J. Zhang, and M.-Y. Fu, "Novel separation principle based H_∞ observer-controller design for a class of T-S fuzzy systems," *IEEE Transactions on Fuzzy Systems*, DOI: 10.1109/TFUZZ.2018.2814610, Mar. 2018.

[24] N. A. M. Subha and G.-P. Liu, "Design and practical implementation of external consensus protocol for networked multiagent systems with communication delays," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 2, pp. 619-631, Mar. 2015.

[25] C. Peng, J. Zhang, and H. Yan, "Adaptive event-triggering H_∞ load frequency control for network-based power systems," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 2, pp. 1685-1694, Feb. 2018.

[26] X.-M. Zhang and Q.-L. Han, "Network-based H_∞ filtering using a logic jumping-like trigger," *Automatica*, vol. 49, no. 5, pp. 1428-1435, May 2013.

[27] C. Peng, E. Tian, J. Zhang, and D. Du, "Decentralized event-triggering communication scheme for large-scale systems under network environments," *Information Sciences*, vol. 380, pp. 132-144, Feb. 2017.

[28] X.-M. Sun, D. Wu, G.-P. Liu, and W. Wang, "Input-to-state stability for networked predictive control with random delays in both feedback and forward channels," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 7, pp. 3519-3526, Jul. 2014.

[29] Z.-H. Pang, G.-P. Liu, and D. Zhou, "Design and performance analysis of incremental networked predictive control systems," *IEEE Transactions on Cybernetics*, vol. 46, no. 6, pp. 1400-1410, Jun. 2016.

[30] G.-P. Liu, "Consensus and stability analysis of networked multiagent predictive control systems," *IEEE Transactions on Cybernetics*, vol. 47, no. 4, pp. 1114-1119, Apr. 2017.

[31] Y.-L. Wang, T.-B. Wang, and Q.-L. Han, "Fault detection filter design for data reconstruction-based continuous-time networked control systems," *Information Sciences*, vol. 328, pp. 577-594, Jan. 2016.

[32] X.-M. Zhang, Q.-L. Han, and X. Yu, "Survey on recent advances in networked control systems," *IEEE Transactions on Industrial Informatics*, vol. 12, no. 5, pp. 1740-1752, Oct. 2016.

[33] X.-M. Zhang, Q.-L. Han, and B.-L. Zhang, "An overview and deep investigation on sampled-data-based event-triggered control and filtering for networked systems," *IEEE Transactions on Industrial Informatics*, vol. 13, no. 1, pp. 4-16, Jan. 2017.

[34] X. Jia, D. Zhang, X. Hao, and N. Zheng, "Fuzzy H_∞ tracking control for nonlinear networked control systems in T-S fuzzy model," *IEEE Transactions on Systems, Man, and Cybernetics-Part B: Cybernetics*, vol. 39, no. 4, pp. 1073-1079, Aug. 2009.

[35] D. Zhang, Q.-L. Han, and X. Jia, "Network-based output tracking control for a class of T-S fuzzy systems that can not be stabilized by nondelayed output feedback controllers," *IEEE Transactions on Cybernetics*, vol. 45, no. 8, pp. 1511-1524, Aug. 2015.

[36] D. Zhang, Q.-L. Han, and X. Jia, "Network-based output tracking control for TCS fuzzy systems using an event-triggered communication scheme," *Fuzzy Sets and Systems*, vol. 273, pp. 26-48, Aug. 2015.

[37] C. Peng, S. Ma, and X. Xie, "Observer-based non-PDC control for networked T–S fuzzy systems with an event-triggered communication," *IEEE Transactions on Cybernetics*, vol. 47, no. 8, pp. 2279-2287, Aug. 2017.

[38] Z. Zhong and Y. Zhu, "Observer-based output-feedback control of large-scale networked fuzzy systems with two-channel event-triggering," *Journal of the Franklin Institute*, vol. 354, no. 13, pp. 5398-5420, Sep. 2017.

[39] H. Li, C. Wu, S. Yin, and H.-K. Lam, "Observer-based fuzzy control for nonlinear networked systems under unmeasurable premise variables," *IEEE Transactions on Fuzzy Systems*, vol. 24, no. 5, pp. 1233-1245, Oct. 2016.

[40] C. Zhang, J. Hu, J. Qiu, and Q. Chen, "Reliable output feedback control for T-S fuzzy systems with decentralized event triggering communication and actuator failures," *IEEE Transactions on Cybernetics*, vol. 47, no. 9, pp. 2592-2602, Sep. 2017.

[41] A. Seuret and F. Gouaisbaut, "Wirtinger-based integral inequality: application to time-delay systems," *Automatica*, vol. 49, no. 9, pp. 2860-2866, Sep. 2013.

[42] X.-M. Zhang, Q.-L. Han, A. Seuret, and F. Gouaisbaut, "An improved reciprocally convex inequality and an augmented Lyapunov-Krasovskii

functional for stability of linear systems with time-varying delay," *Automatica*, vol. 84, pp. 221-226, Oct. 2017.
[43] H. D. Tuan, P. Apkarian, T. Narikiyo, and Y. Yamamoto, "Parameterized linear matrix inequality techniques in fuzzy control system design," *IEEE Transactions on Fuzzy Systems*, vol. 9, no. 2, pp. 324-332, Apr. 2001.
[44] F. Yang, Z. Wang, Y. S. Hung, and M. Gani, "H_∞ control for networked systems with random communication delays," *IEEE Transactions on Automatic Control*, vol. 51, no. 3, pp. 511-518, Mar. 2006.
[45] S. Zhu, Q.-L. Han, and C. Zhang, "l_1-gain performance analysis and positive filter design for positive discrete-time Markov jump linear systems: a linear programming approach," *Automatica*, vol. 50, no. 8, pp. 2098-2107, Aug. 2014.

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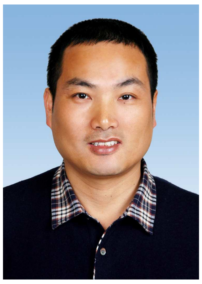

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