Event-Triggered Interval Type-2 Fuzzy Control for Uncertain Space Teleoperation Systems with State Constraints

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***Abstract*—This paper is concerned with interval type-2 (IT2) fuzzy control design for a class of nonlinear space teleoperation systems with external disturbances and time-varying delays. IT2 fuzzy model based (FMB) control design with exponential-type Barrier Lyapunov function (EBLF) is presented to address state constraints, communication burden from ground stations to satellites (space-robot), and uncertain human/environment interaction parameters in a unified event-triggered control structure. We show that, with the proposed adaptive event-triggered control scheme, the exponential convergence performance of the synchronization tracking errors is guaranteed, while the prescribed constraint requirement is satisfied. Simulation results are provided to validate the effectiveness of the proposed controller.**

***Index Terms*—Interval type-2 fuzzy control, space teleoperation, state constraint, event-triggered communication.**

I. Introduction

Composed of ground and space manipulators connected via the Earth-Space communication channel, space teleoperation, as a typical cyber-physical system (CPS), can effectively project the perception and control capabilities of ground operators into on-orbit operation in space. Related technologies can be widely applied not only to aerospace [1], but also to remote surgery [2] and autonomous underwater vehicle [3], which thus leads to increasing attention of theoretical and industrial fields. Due to the complicated force interaction with the uncertain slave environment in the procedure of on-orbit operation, it is critical to address external disturbance and long-distance Earth-Space time delays in a unified framework. It is well known that the type-1 fuzzy model can be utilized to describe the nonlinear plants and unmodelled dynamics, featured by average weighted sum of local linear subsystems, where the weightings are characterized by the type-1 membership functions. Thus type-1 FMB control is a promising approach for nonlinear teleoperation systems in terms of stability analysis and control synthesis [4], [5]. With the help of universal approximation capability of fuzzy logic systems (FLS), an adaptive fuzzy finite-time control scheme [6] was developed to handle system uncertainties. In [7], the stochastic stability in mean square for multilateral teleoperation subject to random network-induced delays was achieved, where multiple stochastic delays in communication channels were modelled via Markov processes. Different from the above FLS utilized to compensate for the uncertainty, a T-S FMB control criteria [8] using the upper/lower boundary of time delay was proposed, leading to less conservative stability conditions and reducing the constraints on degree of freedom. Although the aforementioned control strategies could address teleoperation systems to some extent, certain coefficient information about interaction with environments is required. However, the slave environment in space is featured by uncertain and time-varying, especially in the task of capturing non-cooperative targets. Therefore, implementing the above controllers would result in limited performance in space teleoperation. In addition to this, the communication burden induced by Space-Earth long-distance signal transmission is not considered, which may increase the latency of time delay and packet loss. Event-triggered scheme is a promising tool for CPS to choose necessary signal transmission, and accordingly receives attention from the research community [9]–[11]. Nevertheless, to the best knowledge of the authors, none of the previous works have thoroughly discussed the above issues of space teleoperation systems in the framework of FMB control.

This research was supported by the National Natural Science Foundation of China (Grant No. 61673239, 61703228); Science and technology project of Shenzhen (Grant No. JCYJ20160428182227081, JCYJ20160301100921349); Science and Technology Planning Project of Guangdong Province (Grant No. 2017B010116001). (Corresponding author: Zhang Chen)

978-1-7281-6932-3/20/$31.00 ©2020 IEEE

Another important issue in practical space teleoperation is how to ensure constraint requirement for the sake of operation safety, especially in the presence of contact collision. Barrier Lyapunov function (BLF) provides an effective tool to address systems with state/output constraints, featured by explicitly containing prescribed constraint functions. Classic log-type BLF [12] and tan-type BLF [13] were proposed for stability analysis and control synthesis for constrained systems in the framework of back-stepping control. By virtue of favorable differentiation rules, the exponential-type BLF (EBLF) was developed for nonlinear systems subject to state constraints with applications to velocity observer design [14], master-slave synchronization [15], and fault-tolerant control [16]. However, among the aforementioned research works dealing with state constraints via BLF, no works discussed the constraint control issue for teleoperation systems with event-triggered mechanism. In addition to this, how to ensure superior convergence performance based on event-triggered approach, different from uniformly ultimately bounded stability [17], [18], is a challenging issue open to discuss.

Motivated by the above analysis, we propose a novel IT2 fuzzy model based control strategy for a class of space teleoperation systems with time-varying delays, external disturbance, and system uncertainty. We show that, under the proposed event-triggered control scheme, the exponential stability of synchronization tracking errors is realized, while the prescribed constraint range is never violated. The main contributions of this paper are summarized as follows.

1) The synchronization control issue for a class of space teleoperation systems subject to uncertain coefficients of interaction with slave environments is tackled via IT2 FMB approach, where time-varying delay, external disturbance, and system uncertainty are addressed in a unified framework of fuzzy control.

2) The exponentially stable performance of the closed-loop system is guaranteed, while the delay and packet loss caused by communication burden between the master and slave side are reduced by employing the event-triggered mechanism.

3) Time-varying state constraint requirement can be effectively handled by the proposed controller, incorporating EBLF in stability analysis and control synthesis, which achieves that the tracking errors never exceed the preassigned range.

The remainder of this paper is organized as follows. Sec. II introduces the dynamics model of space teleoperation systems and necessary lemmas. Event-triggered fuzzy control strategy is proposed in Sec. III. In Sec. IV simulation results show the effectiveness of the proposed controller, followed by the conclusion in Sec. V.

Notation. The subscript $i = m, s$ represents the master and slave manipulator, respectively. For $\forall A \in \mathbb{R}^{n\times n}$, $\|A\|$ is the Euclidean 2-norm of A; $\lambda_{min}(A)$ and $\lambda_{max}(A)$ denote the minimum and maximum eigenvalue of A, respectively; diag$\{a_j\}$ stands for a diagonal matrix with a_j as the j-th element; col$\{a_j\}$ stands for a column vector with a_j as the j-th element.

II. Problem Formulation

A. Dynamics of Space Teleoperation Systems

The space teleoperation system can be formulated as n degree-of-freedom (DOF) Euler-Lagrange model with gravity term omitted

$$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + f_{ci}(\dot{q}_i) + d_i = u_i + J_i^{\mathrm{T}}(q_i)F_i \quad (1)$$

where the subscript $i = m, s$ represents the master and slave manipulator, respectively. q_i, $\dot{q}_i$, $\ddot{q}_i \in \mathbb{R}^n$ stand for the position, velocity, and acceleration signals defined in joint space, respectively. $M_i(q_i) \in \mathbb{R}^{n\times n}$ is the positive-definite inertia matrix. $C_i(q_i,\dot{q}_i) \in \mathbb{R}^{n\times n}$ is the matrix denoting Centripetal and Coriolis torques. $f_{ci}(\dot{q}_i) \in \mathbb{R}^n$ and $d_i \in \mathbb{R}^n$ represent the Coulomb friction and external non-homogeneous disturbance, respectively. $u_i \in \mathbb{R}^n$ is the control input. The forces generated by human operator and environments are denoted as $F_{i=m} \in \mathbb{R}^m$ and $F_{i=s} \in \mathbb{R}^m$, respectively. $J_i^{\mathrm{T}}(q_i)$ is the force Jacobian matrix such that $\dot{x}_i = J_i(q_i)\dot{q}_i$, in which $x_i \in \mathbb{R}^m$ contains the position and orientation of end-effector for robots. Thus, the teleoperation system (1) can be transformed into

$$\mathcal{M}_i\ddot{x}_i + \mathcal{C}_i\dot{x}_i + \mathcal{F}_i = \mathcal{U}_i + F_i, \quad (2)$$

in which $\mathcal{M}_i = J_i^{\ddagger}(q_i)M_i(q_i)J_i^{\dagger}(q_i)$, $\mathcal{C}_i = J_i^{\ddagger}(q_i)(C_i(q_i,\dot{q}_i) - M_i(q_i)J_i^{\dagger}(q_i)\dot{J}_i(q_i))J_i^{\dagger}(q_i)$, $\mathcal{F}_i = J_i^{\ddagger}(q_i)(f_{ci}(\dot{q}_i) + d_i)$, $\mathcal{U}_i = J_i^{\ddagger}(q_i)u_i$, $J_i^{\ddagger}(q_i) = (J_i^{\dagger}(q_i))^{\mathrm{T}}$ with $J_i^{\dagger}(q_i)$ being the Moore-Penrose inverse of $J_i(q_i)$.

B. Ground Operator and Environmental Model

The interaction with operator and environment subject to time-varying parameters can be formulated as an inferred p-rule IT2 T-S fuzzy model (states of all variables will be omitted for brevity)

$$\begin{aligned} &\text{Rule } l: \text{IF } \mathcal{G}_1(x_i) \text{ is } \mathcal{Q}_1^l \text{ and...and } \mathcal{G}_a(x_i) \text{ is } \mathcal{Q}_a^l \\ &\qquad \text{THEN } F_i = f_{il} - M_{il}\ddot{x}_i - B_{il}\dot{x}_i - K_{il}x_i, \end{aligned} \quad (3)$$

where $\mathcal{Q}_\nu^l$ is an IT2 fuzzy set of rule l corresponding to the function $\mathcal{G}_\nu(x_i)$, $l = 1,2,...,p$, $\nu = 1,2,...,a$; a is a positive integer representing the number of fuzzy sets; $M_i \in \mathbb{R}^{m\times m}$, $B_{il} \in \mathbb{R}^{m\times m}$, and $K_{il} \in \mathbb{R}^{m\times m}$ are the equivalent positive-definite inertia, damping and stiffness of human arm and environments, respectively; f_{il} is the bounded exogenous force inserted at the corresponding side. Then combining (3) with (2) yields

$$\begin{aligned} &\text{Rule } l: \text{IF } \mathcal{G}_1(x_i) \text{ is } \mathcal{Q}_1^l \text{ and...and } \mathcal{G}_a(x_i) \text{ is } \mathcal{Q}_a^l \\ &\qquad \text{THEN } \mathfrak{M}_{il}\ddot{x}_i + \mathfrak{C}_{il}\dot{x}_i + K_{il}x_i = \mathcal{U}_i + \mathfrak{F}_{il}, \end{aligned} \quad (4)$$

where $\mathfrak{M}_{il} = \mathcal{M}_i + M_{il}$, $\mathfrak{C}_{il} = \mathcal{C}_i + B_{il}$, and $\mathfrak{F}_{il} = f_{il} - \mathcal{F}_i$. The firing strength of the Rule l is of the following interval set

$$W_{il}(x_i) = [\underline{\omega}_{il}(x_i), \bar{\omega}_{il}(x_i)],$$

where $\underline{\omega}_{il}(x_i) = \prod_{\nu=1}^{a}\underline{\mu}_{\mathcal{Q}_\nu^l}\mathcal{G}_\nu(x_i)$, $\bar{\omega}_{il}(x_i) = \prod_{\nu=1}^{a}\bar{\mu}_{\mathcal{Q}_\nu^l}\mathcal{G}_\nu(x_i)$, in which $\underline{\mu}_{\mathcal{Q}_\nu^l}\mathcal{G}_\nu(x_i)$ and $\bar{\mu}_{\mathcal{Q}_\nu^l}\mathcal{G}_\nu(x_i)$ denote the lower and upper membership function such that

$\bar{\mu}_{\mathcal{Q}_\nu^l}\mathcal{G}_\nu(x_i) \geq \underline{\mu}_{\mathcal{Q}_\nu^l}\mathcal{G}_\nu(x_i) \geq 0$; $\underline{\omega}_{il}(x_i)$ and $\bar{\omega}_{il}(x_i)$ are the lower and upper grade of membership, respectively, satisfying $\bar{\omega}_{il}(x_i) \geq \underline{\omega}_{il}(x_i) \geq 0$. Consequently, the inferred IT2 T-S fuzzy model is defined as

$$\ddot{x}_i = \sum_{l=1}^{p} \tilde{\omega}_{il}(x_i)\mathfrak{M}_{il}^{-1}\big(\mathcal{U}_i + \mathfrak{F}_{il} - \mathfrak{C}_{il}\dot{x}_i - K_{il}x_i\big), \quad (5)$$

$$\tilde{\omega}_{il}(x_i) = \underline{\omega}_{il}(x_i)\underline{\alpha}(x_i) + \bar{\omega}_{il}(x_i)\bar{\alpha}(x_i), \quad (6)$$

in which $\underline{\alpha}(x_i)$, $\bar{\alpha}(x_i) \in [0,1]$ such that $\underline{\alpha}(x_i) + \bar{\alpha}(x_i) = 1$.

The IT2 T-S fuzzy model (5) in Cartesian space shows the structural properties as follows [19], [20]

Property 1: $\mathfrak{M}_{il}$ is symmetric and positive-definite such that $\lambda_{min}\{\mathfrak{M}_{il}\}I \leq \mathfrak{M}_{il} \leq \lambda_{max}\{\mathfrak{M}_{il}\}I$.

Property 2: For $\forall y \in \mathbb{R}^m$, the dynamics can be written in linearly parameterizable form

$$\mathfrak{M}_{il}\dot{y} + \mathfrak{C}_{il}y = \Psi_{il}(q_i, \dot{q}_i, y, \dot{y})\varrho_{il} \quad (7)$$

where $\Psi_{il}(q_i, \dot{q}_i, \dot{y}, \dot{y}) \in \mathbb{R}^{m\times m_o}$ is a regressor matrix of known functions and $\varrho_{il} \in \mathbb{R}^{m_o}$ is a vector of unknown parameters.

Property 3: $\|\mathfrak{C}_{il}\| \leq c_{max}\|\dot{q}_i\|$ with c_{max} being a positive scalar.

III. Control Law Design

Define the synchronization tracking errors in Cartesian space as $e_m(t) = x_m(t) - x_s(t - T_s)$ and $e_s(t) = x_s(t) - x_m(t - T_m)$, where T_m and T_s stand for the bounded forward and backward time-varying delay between the ground station and space robot, respectively.

Design the IT2 fuzzy control input with q rules as

$$\begin{aligned}&\text{Rule } r: \text{IF } \mathcal{D}_1(\hat{x}_i) \text{ is } \mathcal{N}_1^r \text{ and...and } \mathcal{D}_c(\hat{x}_i) \text{ is } \mathcal{N}_c^r \\ &\qquad \text{THEN } \mathcal{U}_i = U_{ir},\end{aligned} \quad (8)$$

where $\hat{x}_i = [x_i^{\mathrm{T}}, x_j^{\mathrm{T}}(t - T_j)]^{\mathrm{T}}$, $j = m, s (i \neq j)$; $\mathcal{N}_w^l$ is an IT2 fuzzy set of rule r corresponding to the function $\mathcal{D}_w(\hat{x}_i)$, $r = 1, 2, ..., q$, $w = 1, 2, ..., c$; c is a positive integer representing the number of fuzzy sets. The firing strength of the Rule r is of the following interval set

$$M_{ir}(\hat{x}_i) = [\underline{m}_{ir}(\hat{x}_i), \bar{m}_{ir}(\hat{x}_i)],$$

where $\underline{m}_{ir}(\hat{x}_i) = \prod_{w=1}^{c}\underline{\mu}_{\mathcal{N}_w^r}\mathcal{D}_w(\hat{x}_i)$, $\bar{m}_{ir}(\hat{x}_i) = \prod_{w=1}^{c}\bar{\mu}_{\mathcal{N}_w^r}\mathcal{D}_w(\hat{x}_i)$, in which $\underline{\mu}_{\mathcal{N}_w^r}\mathcal{D}_w(\hat{x}_i)$ and $\bar{\mu}_{\mathcal{N}_w^r}\mathcal{D}_w(\hat{x}_i)$ denote the lower and upper membership function such that $\bar{\mu}_{\mathcal{N}_w^r}\mathcal{D}_w(\hat{x}_i) \geq \underline{\mu}_{\mathcal{N}_w^r}\mathcal{D}_w(\hat{x}_i) \geq 0$; $\underline{m}_{ir}(\hat{x}_i)$ and $\bar{m}_{ir}(\hat{x}_i)$ are the lower and upper grade of membership, respectively, satisfying $\bar{m}_{ir}(\hat{x}_i) \geq \underline{m}_{ir}(\hat{x}_i) \geq 0$. Then the inferred IT2 fuzzy controller is represented by

$$\mathcal{U}_i = \sum_{r=1}^{q} \tilde{m}_{ir}(\hat{x}_i)U_{ir}, \quad (9)$$

where

$$\tilde{m}_{ir}(\hat{x}_i) = \frac{\underline{\theta}_{ir}(\hat{x}_i)\underline{m}_{ir}(\hat{x}_i) + \bar{\theta}_{ir}(\hat{x}_i)\bar{m}_{ir}(\hat{x}_i)}{\sum_{r=1}^{q}\left(\underline{\theta}_{ir}(\hat{x}_i)\underline{m}_{ir}(\hat{x}_i) + \bar{\theta}_{ir}(\hat{x}_i)\bar{m}_{ir}(\hat{x}_i)\right)},$$

with $\tilde{m}_{ir}(\hat{x}_i)$ is the grade of the embedded membership function such that $\sum_{r=1}^{q}\tilde{m}_{ir}(\hat{x}_i) = 1$. $\underline{\theta}_{ir}(\hat{x}_i), \bar{\theta}_{ir}(\hat{x}_i) \in [0,1]$ are predefined functions satisfying $\underline{\theta}_{ir}(\hat{x}_i) + \bar{\theta}_{ir}(\hat{x}_i) = 1$.

In order to reduce computing burden induced by long-distance signal transmission, we need to design a mechanism to determine whether to send updated status information to the slave manipulator. Thus, a time-varying threshold event-triggered control scheme is developed as follows

$$U_{ir}^j(t) = \tau_{ir}^j(t_k), \forall t \in [t_k, t_{k+1}), k \in \mathbb{Z}_+ \quad (10)$$

$$t_{k+1} = \inf\left\{t > t_k \middle| \left|\tau_{ir}^j(t) - U_{ir}^j(t)\right| \geq \varpi_i\left|U_{ir}^j(t)\right| + \eta_i\right\} \quad (11)$$

where $\varpi_i \in (0,1)$ and $\eta_i \in (0,1)$ are positive design parameters; t_k is the update time; $U_{ir}^j(t)$ and $\tau_{ir}^j(t_k)$ are the jth element of $U_{ir}(t)$ and $\tau_{ir}(t_k)$, respectively, for $j = 1, 2, ..., n$. Once the mechanism (11) is triggered, the control input $U_{ir}(t)$ will be updated by the intermediate control $\tau_{ir}(t_{k+1})$. Thus, for $t \in [t_k, t_{k+1})$, $U_{ir}(t)$ remains at $\tau_{ir}(t)$ updated at the last moment such that

$$\left|\tau_{ir}^j(t) - U_{ir}^j(t)\right| \leq \varpi_i\left|U_{ir}^j(t)\right| + \eta_i, \quad (12)$$

which further indicates

$$U_{ir}^j(t) = \frac{\tau_{ir}^j(t)}{1 + \bar{\varrho}_{1ir}^j(t)\varpi_i} - \frac{\bar{\varrho}_{2ir}^j(t)\eta_i}{1 + \bar{\varrho}_{1ir}^j(t)\varpi_i} \quad (13)$$

where $\bar{\varrho}_{1ir}^j(t) \in [-1,1]$ and $\bar{\varrho}_{2ir}^j(t) \in [-1,1]$ are time-varying parameters. Denote $\Gamma_{ir} = \mathrm{diag}\{1/1 + \bar{\varrho}_{1ir}^j(t)\varpi_i\}$ and $\Omega_{ir} = \mathrm{col}\{\bar{\varrho}_{2ir}^j(t)\eta_i/1 + \bar{\varrho}_{1ir}^j(t)\varpi_i\}$, one has a more compact form of (13) as

$$U_{ir}(t) = \Gamma_{ir}\tau_{ir}(t) - \Omega_{ir}. \quad (14)$$

Combining (5), (9), and (14), we can obtain the IT2 T-S FMB control system

$$\begin{aligned}\ddot{x}_i &= \sum_{l=1}^{p}\tilde{\omega}_{il}(x_i)\mathfrak{M}_{il}^{-1}\left(\sum_{r=1}^{q}\tilde{m}_{ir}(\hat{x}_i)U_{ir} + \mathfrak{F}_{il} - \mathfrak{C}_{il}\dot{x}_i - K_{il}x_i\right)\\ &= \sum_{l=1}^{p}\sum_{r=1}^{q}\tilde{h}_{ilr}\mathfrak{M}_{il}^{-1}\Big(\Gamma_{ir}\tau_{ir} - \Omega_{ir} + \mathfrak{F}_{il} - \mathfrak{C}_{il}\dot{x}_i - K_{il}x_i\Big)\end{aligned} \quad (15)$$

where $\tilde{h}_{ilr} \triangleq \tilde{h}_{ilr}(\hat{x}_i) = \tilde{\omega}_{il}(x_i)\tilde{m}_{ir}(\hat{x}_i)$ and the property $\sum_{l=1}^{p}\tilde{\omega}_{il}(x_i) = \sum_{r=1}^{q}\tilde{m}_{ir}(\hat{x}_i) = \sum_{l=1}^{p}\sum_{r=1}^{q}\tilde{h}_{ilr}(\hat{x}_i) = 1$ is utilized.

Define the following auxiliary variable

$$S_i = \dot{e}_i + \kappa_{1i}e_i \quad (16)$$

where κ_{1i} is a positive constant. With *Property 2* and $v_i = \dot{x}_i - S_i$, we can obtain from (2) that

$$\begin{aligned}\dot{S}_i = &\sum_{l=1}^{p}\sum_{r=1}^{q}\tilde{h}_{ilr}\mathfrak{M}_{il}^{-1}\Big(\Gamma_{ir}\tau_{ir} - \Omega_{ir} + \mathfrak{F}_{il} - \mathfrak{C}_{il}S_i - K_{il}x_i\\ &- \Psi_{il}(q_i, \dot{q}_i, v_i, \dot{v}_i)\varrho_{il}\Big).\end{aligned} \quad (17)$$

Design the intermediate bilateral control input as

$$\tau_{ilr} = -(1+\varpi_i)\frac{\mathfrak{M}_{il} S_i \bar{\tau}_{ilr}^{\mathrm{T}} \bar{\tau}_{ilr}}{\sqrt{S_i^{\mathrm{T}} S_i \bar{\tau}_{ilr}^{\mathrm{T}} \bar{\tau}_{ilr} + \epsilon^2}}, \tag{18}$$

and $\bar{\tau}_{ilr}$ is designed as

$$\bar{\tau}_{ilr} = \big(\bar{\mu}_i + \kappa_{3i}\,\|\dot{q}_i\|\big) S_i - K_{il}\mathfrak{M}_{il}^{-1} x_i - \bar{\tau}_{ilr}^{\star}, \tag{19}$$

in which $\bar{\mu}_i = \mu_i + \kappa_{4i}/\xi_i + \frac{(k_i^2 - S_i^{\mathrm{T}} S_i)^2}{2k_i^2\|S_i\|^2} + \frac{\xi_i}{2\|S_i\|^2}$, and

$$\bar{\tau}_{ilr}^{\star} = \mathfrak{M}_{il}^{-1}\Psi_i(q_i,\dot{q}_i,v_i,\dot{v}_i)\hat{\varrho}_{il} - \frac{\xi_i\hat{\psi}_{ilr}}{\sqrt{\xi_i^2 S_i^{\mathrm{T}} S_i + \epsilon^2}} S_i - \frac{\kappa_{2i}}{\xi_i} e_i, \tag{20}$$

with the following adaptive update laws

$$\dot{\hat{\varrho}}_{ilr} = -\tilde{h}_{ilr}\delta_{1ilr}\xi_i\Psi_{il}^{\mathrm{T}}(q_i,\dot{q}_i,v_i,\dot{v}_i)\mathfrak{M}_{il}^{-\mathrm{T}} S_i - \tilde{h}_{ilr}\delta_{3ilr}\hat{\varrho}_{ilr}, \tag{21}$$

$$\dot{\hat{\psi}}_{ilr} = \tilde{h}_{ilr}\delta_{2ilr}\frac{\xi_i^2 S_i^{\mathrm{T}} S_i}{\sqrt{\xi_i^2 S_i^{\mathrm{T}} S_i + \epsilon^2}} - \tilde{h}_{ilr}\delta_{4ilr}\hat{\psi}_{ilr}, \tag{22}$$

where κ_{3i} is a positive tuning parameter such that $\kappa_{3i} > \frac{c_{max}}{\lambda_{min}\{\mathfrak{M}_i\}}$; δ_{1ilr} and δ_{2ilr} are positive scalars; κ_{2i}, κ_{4i}, δ_{3ilr} and δ_{4ilr} are positive scalars to be designed; ξ_i will be defined later; $\mu_i = \sup\sqrt{(\frac{\dot{k}_i}{k_i})^2 + \epsilon}$ with ϵ being a positive constant; $k_i \in \mathbb{R}_+$ denoting the prescribed n-order differentiable time-varying constraint function such that $k_i(t_0) > \|S_i(t_0)\|$; $\hat{\varrho}_{ilr}$ and $\hat{\psi}_{ilr}$ are the estimations of ϱ_{ilr} and ψ_{ilr}, respectively; ψ_{ilr} will be defined later.

Theorem 1: For the nonlinear space teleoperation system (15), if the bilateral control input (18) triggered by (10)-(11) and adaptive laws (21)-(22) are adopted, the following properties will hold.

1) All signals of the closed-loop teleoperation system are bounded.

2) The constraint requirement on the synchronization tracking errors is satisfied. That is, the preassigned constraint will never be violated.

3) The exponential convergence performance of the tracking errors can be guaranteed.

Proof. Choose the following Lyapunov-Krasovskii functional

$$V = V_1 + V_2 + V_3, \tag{23}$$

$$V_1 = \sum_{i=m,s}\frac{1}{2}k_i^2\big(\exp(k_i \circ S_i) - 1\big), \tag{24}$$

$$V_2 = \sum_{i=m,s}\sum_{l=1}^{p}\sum_{r=1}^{q}\frac{1}{2\delta_{1ilr}}\tilde{\varrho}_{ilr}^{\mathrm{T}}\tilde{\varrho}_{ilr} + \frac{1}{2\delta_{2ilr}}\tilde{\psi}_{ilr}^2, \tag{25}$$

$$V_3 = \sum_{i=m,s}\frac{\kappa_{2i}}{2}\left(\int_{t-\bar{T}_i}^{t}\tanh\big(\alpha(\tau - t + \bar{T}_i)\big)\mathcal{X}_i^{\mathrm{T}}(\tau) \times R_i\mathcal{X}_i(\tau)d\tau + e_i^{\mathrm{T}} e_i\right), \tag{26}$$

where $k_i \circ S_i = S_i^{\mathrm{T}} S_i/(k_i^2 - S_i^{\mathrm{T}} S_i)$. In general, the constraint function k_i is set to be monotonically decreasing for the sake of transient-state convergence performance. $\tilde{\varrho}_{ilr} = \hat{\varrho}_{ilr} - \varrho_{ilr}$ denotes the estimation error of ϱ_{ilr}. $\tilde{\psi}_{ilr} = \psi_{ilr} - \hat{\psi}_{ilr}$ represents the estimation error of ψ_{ilr}; $\mathcal{X}_i = [S_i^{\mathrm{T}}, \tilde{\varrho}_{ilr}^{\mathrm{T}}, \tilde{\psi}_{ilr}^{\mathrm{T}}, e_i^{\mathrm{T}}]^{\mathrm{T}}$; R_i is a symmetric positive-definite matrix of appropriate dimension; $\alpha \in \mathbb{R}_+$ is a tunable parameter; tanh$(\cdot)$ denotes the hyperbolic tangent function; $\bar{T}_i$ is the upper boundary of T_i. Then taking time derivative of V_1 gives

$$\begin{aligned}\dot{V}_1 = &\sum_{i=m,s}\dot{k}_i k_i\big(\exp(k_i\circ S_i) - 1\big) + k_i^2\exp(k_i\circ S_i)\\ &\times\frac{S_i^{\mathrm{T}}\dot{S}_i k_i^2 - S_i^{\mathrm{T}} S_i\dot{k}_i k_i}{(k_i^2 - S_i^{\mathrm{T}} S_i)^2}\\ \le &\sum_{i=m,s} -\dot{k}_i k_i - \frac{\dot{k}_i k_i^3 S_i^{\mathrm{T}} S_i}{(k_i^2 - S_i^{\mathrm{T}} S_i)^2}\exp(k_i\circ S_i)\\ &+ k_i^4\exp(k_i\circ S_i)\frac{S_i^{\mathrm{T}}\dot{S}_i}{(k_i^2 - S_i^{\mathrm{T}} S_i)^2}.\end{aligned} \tag{27}$$

Recalling $\mu_i = \sup\sqrt{(\frac{\dot{k}_i}{k_i})^2 + \epsilon}$, then (27) can be rewritten as

$$\dot{V}_1 \le \sum_{i=m,s}\mu_i k_i^2 + \mu_i\xi_i S_i^{\mathrm{T}} S_i + \xi_i S_i^{\mathrm{T}}\dot{S}_i \tag{28}$$

where $\xi_i = k_i^4\exp(k_i\circ S_i)/(k_i^2 - S_i^{\mathrm{T}} S_i)^2$. Substituting (17) into (28) yields

$$\begin{aligned}\dot{V}_1 \le &\sum_{i=m,s}\mu_i k_i^2 + \mu_i\xi_i S_i^{\mathrm{T}} S_i + \xi_i S_i^{\mathrm{T}}\Bigg(\sum_{l=1}^{p}\sum_{r=1}^{q}\tilde{h}_{ilr}\mathfrak{M}_{il}^{-1}\\ &\times\Big(\Gamma_{ir}\tau_{ir} - \Omega_{ir} + \mathfrak{F}_{il} - \mathfrak{C}_{il} S_i - K_{il}x_i\\ &- \Psi_{il}(q_i,\dot{q}_i,v_i,\dot{v}_i)\varrho_{il}\Big)\Bigg).\end{aligned} \tag{29}$$

Note that we can obtain from (29) that

$$\begin{aligned}\xi_i S_i^{\mathrm{T}}\mathfrak{M}_{il}^{-1}(\mathfrak{F}_{il} - \Omega_{ir}) &\le \xi_i\,\|S_i\|\,\big\|\mathfrak{M}_{il}^{-1}\big\|\,(\bar{\mathfrak{F}}_{il} + \bar{\Omega}_{ir})\\ &\le \psi_{ilr}\epsilon + \psi_{ilr}\frac{\xi_i^2 S_i^{\mathrm{T}} S_i}{\sqrt{\xi_i^2 S_i^{\mathrm{T}} S_i + \epsilon^2}},\end{aligned} \tag{30}$$

in which $\psi_{ilr} = \bar{\mathfrak{F}}_{il} + \bar{\Omega}_{ir}/\lambda_{min}\{\mathfrak{M}_{il}\}$ is an unknown scalar to be estimated; $\bar{\mathfrak{F}}_{il}$ and $\bar{\Omega}_{ir}$ stand for unknown upper bounds of $\mathfrak{F}_{il}$ and Ω_{ir}, respectively.

Similarly with (30), according to *Property 1* and *Property 3*, one can derive that

$$-\xi_i S_i^{\mathrm{T}}\mathfrak{M}_{il}^{-1}\mathfrak{C}_{il} S_i \le \frac{\xi_i c_{max}}{\lambda_{min}\{\mathfrak{M}_{il}\}}\,\|\dot{q}_i\|\,S_i^{\mathrm{T}} S_i. \tag{31}$$

Then substituting (30) and (31) into (29) and further simplifying yield

$$\dot{V}_1 \leq \sum_{i=m,s} \mu_i k_i^2 + \mu_i \xi_i S_i^{\mathrm{T}} S_i + \sum_{i=m,s} \sum_{l=1}^{p} \sum_{r=1}^{q} \tilde{h}_{ilr} \Bigg(\xi_i \times S_i^{\mathrm{T}} \mathfrak{M}_{il}^{-1} \Gamma_{ir} \tau_{ilr} + \psi_{ilr} \epsilon + \psi_{ilr} \frac{\xi_i^2 S_i^{\mathrm{T}} S_i}{\sqrt{\xi_i^2 S_i^{\mathrm{T}} S_i + \epsilon^2}} + \frac{\xi_i c_{max}}{\lambda_{min}\{\mathfrak{M}_{il}\}} \|\dot{q}_i\| S_i^{\mathrm{T}} S_i - \xi_i S_i^{\mathrm{T}} \mathfrak{M}_{il}^{-1} \Big(K_{il} x_i + \Psi_{il}(q_i, \dot{q}_i, v_i, \dot{v}_i) \varrho_{il} \Big) \Bigg), \tag{32}$$

which further indicates

$$\begin{aligned} \xi_i S_i^{\mathrm{T}} \mathfrak{M}_{il}^{-1} \Gamma_{ir} \tau_{ilr} &\leq -\frac{\xi_i S_i^{\mathrm{T}} S_i \bar{\tau}_{ilr}^{\mathrm{T}} \bar{\tau}_{ilr}}{\sqrt{S_i^{\mathrm{T}} S_i \bar{\tau}_{ilr}^{\mathrm{T}} \bar{\tau}_{ilr} + \epsilon^2}} \\ &\leq \xi_i \epsilon - \xi_i S_i^{\mathrm{T}} \bar{\tau}_{ilr} \\ &\leq \frac{\xi_i^2}{2} + \frac{\epsilon^2}{2} - \xi_i S_i^{\mathrm{T}} \bar{\tau}_{ilr}. \end{aligned} \tag{33}$$

Combining (32)-(33) with (18)-(19), we have

$$\dot{V}_1 \leq \sum_{i=m,s} \sum_{l=1}^{p} \sum_{r=1}^{q} \tilde{h}_{ilr} \Bigg(\mu_i k_i^2 + \psi_{ilr} \epsilon - \frac{(k_i^2 - S_i^{\mathrm{T}} S_i)^2}{2k_i^2} \xi_i + \frac{\xi_i^2 S_i^{\mathrm{T}} S_i}{\sqrt{\xi_i^2 S_i^{\mathrm{T}} S_i + \epsilon^2}} \tilde{\psi}_{ilr} + \xi_i S_i^{\mathrm{T}} \mathfrak{M}_{il}^{-1} \Psi_{il}(q_i, \dot{q}_i, v_i, \dot{v}_i) \tilde{\varrho}_{il} - \kappa_{2i} S_i^{\mathrm{T}} e_i - \kappa_{4i} S_i^{\mathrm{T}} S_i + \frac{\epsilon^2}{2} \Bigg). \tag{34}$$

Note that the time-derivative of V_2 gives

$$\dot{V}_2 = \sum_{i=m,s} \sum_{l=1}^{p} \sum_{r=1}^{q} \frac{1}{\delta_{1ilr}} \tilde{\varrho}_{ilr}^{\mathrm{T}} \dot{\tilde{\varrho}}_{ilr} + \frac{1}{\delta_{2ilr}} \tilde{\psi}_{ilr} \dot{\tilde{\psi}}_{ilr}. \tag{35}$$

Then substituting (21) and (22) into (35) and (34), we have

$$\begin{aligned} \dot{V}_1 + \dot{V}_2 \leq & \sum_{i=m,s} \sum_{l=1}^{p} \sum_{r=1}^{q} \tilde{h}_{ilr} \Bigg(\mu_i k_i^2 + \psi_{ilr} \epsilon - \frac{k_i^2}{2} \exp(k_i \circ S_i) \\ & + \frac{\xi_i^2 S_i^{\mathrm{T}} S_i \tilde{\psi}_{ilr}}{\sqrt{\xi_i^2 S_i^{\mathrm{T}} S_i + \epsilon^2}} + \xi_i S_i^{\mathrm{T}} \mathfrak{M}_{il}^{-1} \Psi_{il}(q_i, \dot{q}_i, v_i, \dot{v}_i) \tilde{\varrho}_{il} \\ & - \kappa_{2i} S_i^{\mathrm{T}} e_i - \kappa_{4i} S_i^{\mathrm{T}} S_i + \frac{\epsilon^2}{2} \Bigg) - \sum_{i=m,s} \sum_{l=1}^{p} \sum_{r=1}^{q} \tilde{h}_{ilr} \\ & \times \Bigg(\xi_i \tilde{\varrho}_{il}^{\mathrm{T}} \Psi_{il}^{\mathrm{T}}(q_i, \dot{q}_i, v_i, \dot{v}_i) \mathfrak{M}_{il}^{-\mathrm{T}} S_i + \frac{\delta_{3ilr}}{\delta_{1ilr}} \tilde{\varrho}_{ilr}^{\mathrm{T}} \hat{\varrho}_{ilr} \\ & + \frac{\xi_i^2 S_i^{\mathrm{T}} S_i}{\sqrt{\xi_i^2 S_i^{\mathrm{T}} S_i + \epsilon^2}} \tilde{\psi}_{ilr} - \frac{\delta_{4ilr}}{\delta_{2ilr}} \tilde{\psi}_{ilr} \hat{\psi}_{ilr} \Bigg), \end{aligned} \tag{36}$$

which can be further simplified as

$$\begin{aligned} \dot{V}_1 + \dot{V}_2 \leq & \sum_{i=m,s} \sum_{l=1}^{p} \sum_{r=1}^{q} \tilde{h}_{ilr} \Bigg(\mu_i k_i^2 + \psi_{ilr} \epsilon + \frac{\epsilon^2}{2} \\ & - \frac{k_i^2}{2} \exp(k_i \circ S_i) - \kappa_{2i} S_i^{\mathrm{T}} e_i \\ & - \kappa_{4i} S_i^{\mathrm{T}} S_i - \frac{\delta_{3ilr}}{\delta_{1ilr}} \tilde{\varrho}_{ilr}^{\mathrm{T}} \hat{\varrho}_{ilr} + \frac{\delta_{4ilr}}{\delta_{2ilr}} \tilde{\psi}_{ilr} \hat{\psi}_{ilr} \Bigg) \end{aligned} \tag{37}$$

where the last two terms of the right hand of (37) follow

$$\begin{aligned} -\frac{\delta_{3ilr}}{\delta_{1ilr}} \tilde{\varrho}_{ilr}^{\mathrm{T}} \hat{\varrho}_{ilr} &= -\frac{\delta_{3ilr}}{\delta_{1ilr}} \tilde{\varrho}_{ilr}^{\mathrm{T}} (\tilde{\varrho}_{ilr} + \varrho_{ilr}) \\ &\leq -\frac{\delta_{3ilr}}{2\delta_{1ilr}} \tilde{\varrho}_{ilr}^{\mathrm{T}} \tilde{\varrho}_{ilr} + \frac{\delta_{3ilr}}{2\delta_{1ilr}} \varrho_{ilr}^{\mathrm{T}} \varrho_{ilr}. \end{aligned} \tag{38}$$

Similarly, we have $\frac{\delta_{4ilr}}{\delta_{2ilr}} \tilde{\psi}_{ilr} \hat{\psi}_{ilr} \leq -\frac{\delta_{4ilr}}{2\delta_{2ilr}} \tilde{\psi}_{ilr}^2 + \frac{\delta_{4ilr}}{2\delta_{2ilr}} \psi_{ilr}^2$, which indicates the time-derivative of V is given by

$$\begin{aligned} \dot{V} =& \dot{V}_1 + \dot{V}_2 + \dot{V}_3 \\ \leq & \sum_{i=m,s} \sum_{l=1}^{p} \sum_{r=1}^{q} \tilde{h}_{ilr} \Bigg(-\frac{\delta_{3ilr}}{2\delta_{1ilr}} \tilde{\varrho}_{ilr}^{\mathrm{T}} \tilde{\varrho}_{ilr} - \frac{\delta_{4ilr}}{2\delta_{2ilr}} \tilde{\psi}_{ilr}^2 - \frac{k_i^2}{2} \\ & \times \exp(k_i \circ S_i) + \kappa_{2i} e_i^{\mathrm{T}} \dot{e}_i - \kappa_{2i} S_i^{\mathrm{T}} e_i - \kappa_{4i} S_i^{\mathrm{T}} S_i \\ & + \frac{\kappa_{2i}}{2} \tanh(\alpha \bar{T}_i) \mathcal{X}_i^{\mathrm{T}} R_i \mathcal{X}_i - \frac{\kappa_{2i}}{2} \int_{t-\bar{T}_i}^{t} \Big(\alpha - \alpha \tanh\big(\alpha \\ & \times (\tau - t + \bar{T}_i)\big)^2 \Big) \mathcal{X}_i^{\mathrm{T}}(t) R_i \mathcal{X}_i(t) d\tau + \gamma_{ilr} \Bigg) \end{aligned} \tag{39}$$

where $\gamma_{ilr} = \mu_i k_i^2 + \psi_{ilr} \epsilon + \frac{\epsilon^2}{2} + \frac{\delta_{3ilr}}{2\delta_{1ilr}} \varrho_{ilr}^{\mathrm{T}} \varrho_{ilr} + \frac{\delta_{4ilr}}{2\delta_{2ilr}} \psi_{ilr}^2$. Recalling $S_i = \dot{e}_i + \kappa_{1i} e_i$, (39) can be further simplified as

$$\begin{aligned} \dot{V} \leq & \sum_{i=m,s} \sum_{l=1}^{p} \sum_{r=1}^{q} -\tilde{h}_{ilr} \Bigg(\Big(\frac{\delta_{3ilr}}{2\delta_{1ilr}} - \frac{\kappa_{2i}}{2} \bar{R}_i \Big) \tilde{\varrho}_{ilr}^{\mathrm{T}} \tilde{\varrho}_{ilr} \\ & + \Big(\frac{\delta_{4ilr}}{2\delta_{2ilr}} - \frac{\kappa_{2i}}{2} \bar{R}_i \Big) \tilde{\psi}_{ilr}^2 + \Big(\kappa_{1i} \kappa_{2i} - \frac{\kappa_{2i}}{2} \bar{R}_i \Big) e_i^{\mathrm{T}} e_i \\ & + \Big(\kappa_{4i} - \frac{\kappa_{2i}}{2} \bar{R}_i \Big) S_i^{\mathrm{T}} S_i + \frac{k_i^2}{2} \exp(k_i \circ S_i) + \frac{\kappa_{2i}}{2} \int_{t-\bar{T}_i}^{t} \\ & \Big(\alpha - \alpha \tanh\big(\alpha(\tau - t + \bar{T}_i)\big)^2 \Big) \mathcal{X}_i^{\mathrm{T}}(t) R_i \mathcal{X}_i(t) d\tau - \gamma_{il} \Bigg) \\ \leq & \sum_{i=m,s} \sum_{l=1}^{p} \sum_{r=1}^{q} -\tilde{h}_{ilr} \Bigg(\Big(\frac{\delta_{3ilr}}{2\delta_{1ilr}} - \frac{\kappa_{2i}}{2} \bar{R}_i \Big) \tilde{\varrho}_{ilr}^{\mathrm{T}} \tilde{\varrho}_{ilr} \\ & + \Big(\frac{\delta_{4ilr}}{2\delta_{2ilr}} - \frac{\kappa_{2i}}{2} \bar{R}_i \Big) \tilde{\psi}_{ilr}^2 + \Big(\kappa_{1i} \kappa_{2i} - \frac{\kappa_{2i}}{2} \bar{R}_i \Big) e_i^{\mathrm{T}} e_i \\ & + \Big(\kappa_{4i} - \frac{\kappa_{2i}}{2} \bar{R}_i \Big) S_i^{\mathrm{T}} S_i + \frac{k_i^2}{2} \Big(\exp(k_i \circ S_i) - 1 \Big) + \frac{\kappa_{2i}}{2} \\ & \times \int_{t-\bar{T}_i}^{t} \tanh\big(\alpha(\tau - t + \bar{T}_i)\big) \mathcal{X}_i^{\mathrm{T}}(t) R_i \mathcal{X}_i(t) d\tau - \gamma_{ilr} \Bigg) \\ \leq & -\beta V + \gamma \end{aligned} \tag{40}$$

where $\bar{R}_i = \lambda_{\max}\{R_i\}$; $\gamma = \sum_{i=m,s} \sum_{l=1}^{p} \sum_{r=1}^{q} \tilde{h}_{ilr} \gamma_{ilr}$; $\kappa_{5i} = \min\{\delta_{3ilr}/2\delta_{1ilr} - \kappa_{2i}\bar{R}_i/2, \delta_{4ilr}/2\delta_{2ilr} -$

$\kappa_{2i}\bar{R}_i/2, \kappa_{1i}\kappa_{2i} - \kappa_{2i}\bar{R}_i/2, \kappa_{4i} - \kappa_{2i}\bar{R}_i/2, 1\}$; $\beta = \sum_{l=1}^{p}\sum_{r=1}^{q}\tilde{h}_{ilr}\kappa_{5i} \times \min\{1, 2\delta_{1ilr}, 2\delta_{2ilr}\}$. Then it follows from (40) that

$$V_1 \le V \le e^{-\beta t}V(0) + \frac{\gamma}{\beta}(1 - e^{-\beta t}), \tag{41}$$

which indicates the uniformly ultimately boundedness of the space teleoperation system can be guaranteed such that S_i, e_i, $\tilde{\varrho}_{il}$, $\tilde{\psi}_{il} \in \mathcal{L}_\infty$. Since $S_i = \dot{e}_i + \kappa_{1i}e_i$, the boundedness of $\dot{e}_i$ is ensured. Then all signals of the closed-loop system are bounded. That completes the proof.

Remark 1: The hyperbolic tangent function with a tunable parameter used in the integral quadratic term, as stated in (26), plays an important role in stability analysis, where the saturation characteristic of the hyperbolic tangent function reduces the delay dependence of the stability condition. It further implies that extra estimate of the upper bound of delay is not required in the proposed scheme.

Remark 2: The parameter α in the designed Lyapunov-Krasovskii functional (26) shows the flexible application to teleoperation systems with different upper bounds of time-delays. For the derivation of (40) to hold, the inequality $\alpha - \alpha\tanh\big(\alpha(\tau - t + \bar{T}_i)\big)^2 \ge \tanh\big(\alpha(\tau - t + \bar{T}_i)\big)$ needs to be satisfied for $\forall\tau \in [t - \bar{T}_i, t]$, which is equivalent to

$$\begin{aligned}\alpha &\ge \frac{\tanh\big(\alpha\bar{T}_i\big)}{1 - \tanh\big(\alpha\bar{T}_i\big)^2} \\ &\ge \frac{\tanh\big(\alpha(\tau - t + \bar{T}_i)\big)}{1 - \tanh\big(\alpha(\tau - t + \bar{T}_i)\big)^2},\end{aligned} \tag{42}$$

in which the monotonically increasing nature of the hyperbolic tangent function is used. It means that, with appropriate selection of α satisfying (42), the proposed control structure is unified with respect to multiple delay scenarios. For example, the measured round-trip delay in FORROST-ASTRA W3L space mission implemented by German Aerospace Center (DLR) is on average 570 ms [21]. Then α can be set as 1 for this geostationary teleoperation.

Remark 3: For $\forall t \in [t_k, t_{k+1})$, we have $\frac{d}{dt}\left|\tau_{ir}^j(t) - U_{ir}^j(t)\right| = \frac{d}{dt}((\tau_{ir}^j(t) - U_{ir}^j(t)) \times (\tau_{ir}^j(t) - U_{ir}^j(t)))^{\frac{1}{2}} = \mathrm{sign}(\tau_{ir}^j(t) - U_{ir}^j(t))(\dot{\tau}_{ir}^j(t) - \dot{U}_{ir}^j(t)) \le \left|\dot{\tau}_{ir}^j(t)\right|$. It follows from (18) that $\tau_{ir}^j(t)$ is bounded and continuously differentiable such that $\left|\dot{\tau}_{ir}^j(t)\right| \le \chi_{ir}^j$. In view of the fact that $\tau_{ir}^j(t_k) - U_{ir}^j(t_k) = 0$ and $\lim_{t\to t_{k+1}}\tau_{ir}^j(t) - U_{ir}^j(t) = \eta_{ir}^j$, there exists a positive scalar $t^\star$ such that $\{t_{k+1} - t_k\} \ge t^\star \ge \eta_{ir}^j/\chi_{ir}^j$. Hence Zeno behaviour can be effectively eliminated in the proposed scheme.

Remark 4: It is worth mentioning that, when $k_i \to +\infty$, according to L'Hopital rule, the EBLF (24) will degenerate into a commonly used quadratic form

$$\lim_{k_i\to+\infty} V_1 = \lim_{k_i\to+\infty}\frac{1}{2}\frac{k_i^2 S_i^{\mathrm{T}}S_i}{k_i^2 - S_i^{\mathrm{T}}S_i} = \frac{1}{2}S_i^{\mathrm{T}}S_i. \tag{43}$$

The EBLF (24) can be still used for stability analysis and control synthesis in the case of no constraint, which is essentially different from conventional BLF approaches [22], [23]. Therefore, compared with log-type BLF [22] and tangent-type BLF [23], the exponential-type BLF (24) is a more generalized form used in a unified framework to handle nonlinear systems with and without constraint requirements simultaneously.

IV. Simulation Results

To validate the effectiveness of the developed adaptive event-triggered control strategy, two identical 2-DOF manipulators are set as the master and slave part, respectively. The body parameters of the space teleoperation system are given as $m_{m1} = 1.5$kg, $m_{m2} = 0.5$kg, $m_{s1} = 1.5$kg, $m_{s2} = 0.5$kg, $l_{m1} = 1.0$m, $l_{m2} = 0.8$m, $l_{s1} = 1.0$m, $l_{s2} = 0.8$m. The initial states are set as $q_m(0) = [0.4\pi\ \ 0.3\pi]^{\mathrm{T}}$(rad), $q_s(0) = [0.2\pi\ 0.05\pi]^{\mathrm{T}}$(rad), $\dot{q}_m(0) = [0\ 0]^{\mathrm{T}}$(rad/s), $\dot{q}_s(0) = [0\ \ 0]^{\mathrm{T}}$(rad/s). d_m and d_s are external disturbances with $d_i = [d_{i1}\ d_{i2}]^{\mathrm{T}}$, where d_{i1} and d_{i2} are random numbers in the range of $[-0.2, 0.2]$. The control parameters are chosen as $\kappa_{1m} = \kappa_{1s} = 0.5$, $\varpi_m = \varpi_s = 0.2$, $\eta_m = \eta_s = 1$, $\epsilon = 0.1$, $\kappa_{2m} = \kappa_{2s} = 2$, $\kappa_{3m} = \kappa_{3s} = 4$, $\kappa_{4m} = \kappa_{4s} = 5$, $\delta_{1m} = \delta_{2m} = 1$, $\delta_{1s} = \delta_{2s} = 1$, $\delta_{3m} = \delta_{3s} = 4$, $\delta_{4m} = \delta_{4s} = 4$. The time-varying constraint function is designed as $k_m = k_s = 1.6\exp(-t) + 0.25$. The time delays are composed of jittering delays and constant Earth-Space delay measured by DLR in the FORROST-ASTRA W3L mission [21], as shown in Fig. 1. A 4-rule IT2 T-S fuzzy model is developed to describe the force interaction (3) with $K_{i1} = K_{i3} = \begin{bmatrix}0.01 & 0\\ 0 & 0.01\end{bmatrix}$, $K_{i2} = K_{i4} = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$, $B_{i1} = B_{i2} = \begin{bmatrix}0.01 & 0\\ 0 & 0.01\end{bmatrix}$, $B_{i3} = B_{i4} = \begin{bmatrix}0.1 & 0\\ 0 & 0.1\end{bmatrix}$, $M_{i1} = M_{i2} = \begin{bmatrix}0.01 & 0\\ 0 & 0.01\end{bmatrix}$, $M_{i3} = M_{i4} = \begin{bmatrix}0.1 & 0\\ 0 & 0.1\end{bmatrix}$, where the operating domain is characterized by $x_i^j \in [-2, 2]$ and $\dot{x}_i^j \in [-5, 5]$ for $i \in \{m, s\}$, $j \in \{1, 2\}$. A 2-rule IT2 fuzzy controller is designed with

$$\begin{aligned}&\underline{m}_{i1}(x) = \underline{\mu}_{\mathcal{N}_1^1}(x) = \bar{m}_{i1}(x) = \bar{\mu}_{\mathcal{N}_1^1}(x) = \exp(-\frac{\|x\|^2}{3.5})\\ &\underline{m}_{i2}(x) = \underline{\mu}_{\mathcal{N}_1^2}(x) = \bar{m}_{i2}(x) = \bar{\mu}_{\mathcal{N}_1^2}(x) = 1 - \bar{\mu}_{\mathcal{N}_1^1}(x)\\ &\underline{\theta}_{i1}(x) = \bar{\theta}_{i1}(x) = \frac{1}{2}, \quad \underline{\theta}_{i2}(x) = \bar{\theta}_{i2}(x) = \frac{1}{2}.\end{aligned}$$

The synchronization position errors are illustrated in Fig. 2, where x_{ij} denotes the position response in Cartesian space for i manipulator with respect to j direction. $j = 1$ and $j = 2$ represent the x and y direction in Cartesian space, respectively. It can be seen that the tracking performance can be guaranteed despite the existence of time-varying delay, uncertain external disturbance and force interaction, and the prescribed constraint requirement is satisfied. Thus, We can indirectly obtain the constraint on synchronization tracking errors by constraining the sliding mode. Due to limited number of pages, we have omitted the simulation results of the sliding

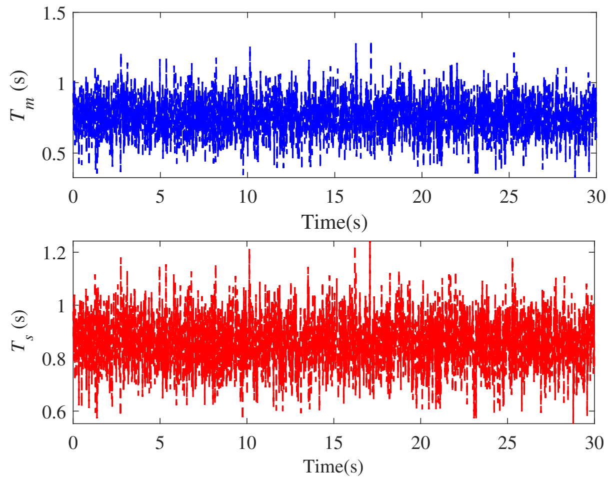

Fig. 1. Forward and backward time delays.

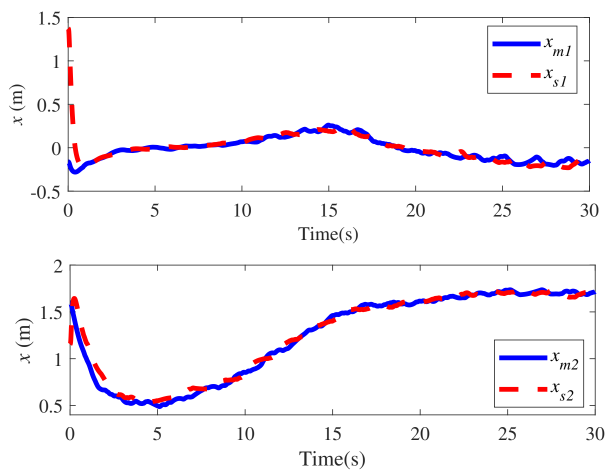

Fig. 2. Synchronization tracking errors.

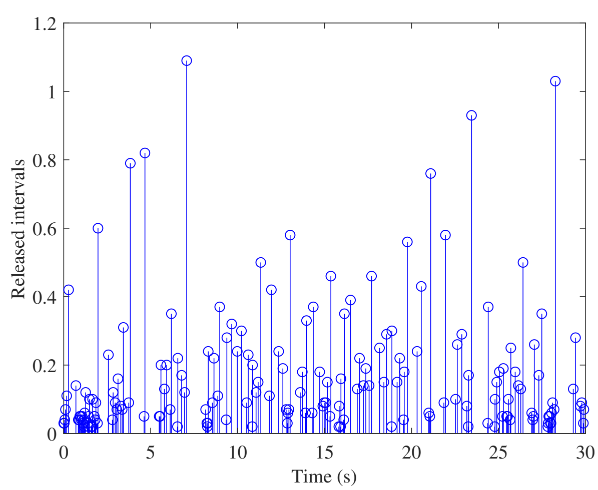

Fig. 3. Released intervals of the proposed event-triggered controller for the master manipulator with respect to Joint 1.

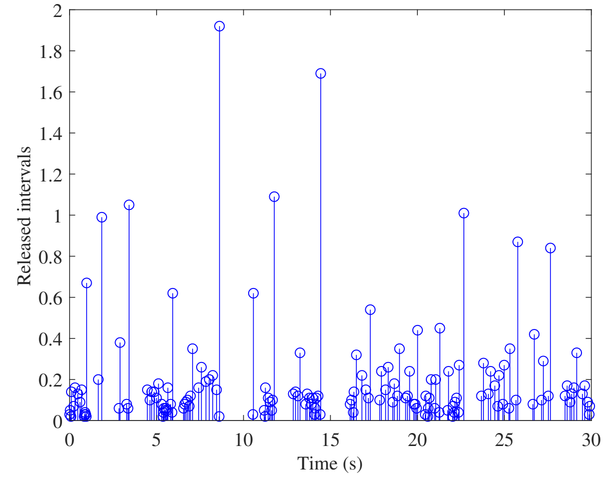

Fig. 4. Released intervals of the proposed event-triggered controller for the master manipulator with respect to Joint 2.

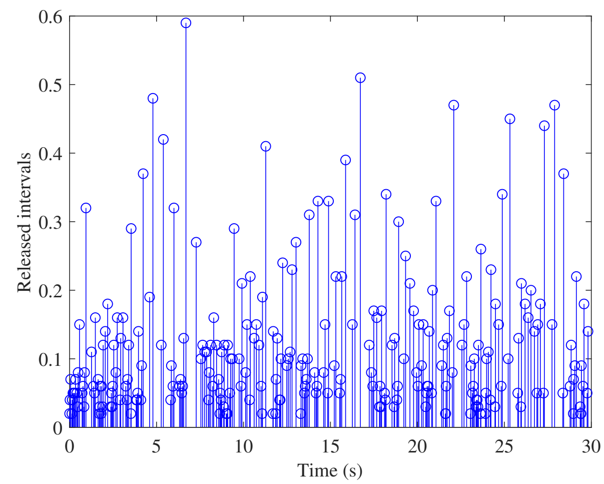

Fig. 5. Released intervals of the proposed event-triggered controller for the slave manipulator with respect to Joint 1.

mode. Figs. 3-6 show that the communication burden can be effectively reduced by employing the proposed event-triggered mechanism.

V. Conclusion

In this paper, an adaptive event-triggered fuzzy control scheme is proposed for a class of uncertain space teleoperation systems subject to time-varying delay, external disturbance, and state constraint. With the help of interval type-2 fuzzy model, we firstly address the uncertain dynamic parameters in the process of force interaction in a unified control structure. We rigorously show that, with the developed event-triggered fuzzy controller incorporating the exponential-type barrier Lyapunov function technique, the exponential convergence performance of tracking errors is ensured while the state constraint is never violated. Future works will aim at dealing

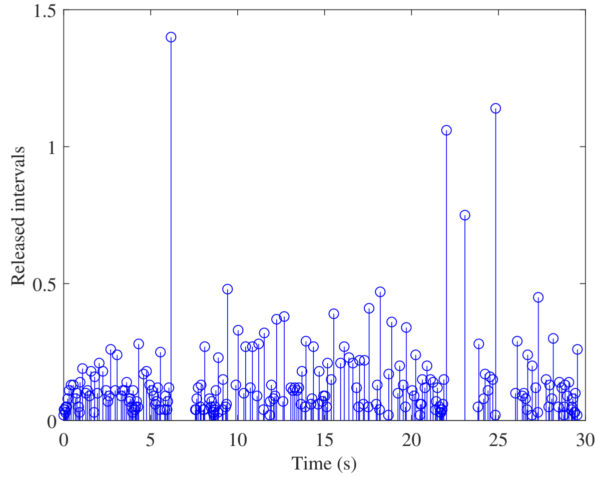

Fig. 6. Released intervals of the proposed event-triggered controller for the slave manipulator with respect to Joint 2.

with output feedback control issue in the current framework of event-triggered fuzzy control.

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