https://doi.org/10.1109/LRA.2021.3061976

Delay-Robust Nonlinear Control of Bounded-Input Telerobotic Systems with Synchronization Enhancement

Amir Zakerimanesh[1], Mojtaba Sharifi[1], *Member, IEEE*, Farzad Hashemzadeh[2], and Mahdi Tavakoli[1], *Senior Member, IEEE*

***Abstract*—This paper puts forward a novel controller for joint position tracking of bilateral teleoperation systems subjected simultaneously to time-varying communication delays and bounded actuation. Enhancing such systems' robustness to the larger time delays comes prevalently at the cost of increased settling time for position synchronization. To this end, we propose a general and refined form of nP+D controller that not only mitigates the trade-off between settling time of synchronization and magnitude of time-delay but also exhibits better transient error in position convergence. These advantages are brought along through using capped joint-velocity in the controller, which offers a blessing in disguise in our presented Lyapunov-based stability analysis and allows disposing of the limitation that was originally considered on the nonlinear function's amplitude in previous nP+D controllers. We have shown that by setting conditions on the controller parameters obtained from the analytical study, the closed-loop dynamics' asymptotic stability is ensured. The proposed controller's efficacy and outperformance are validated through numerical simulations and experimental evaluations on a bilateral teleoperation system with multi-DOF robots as the leader and follower.**

***Index Terms*—Bilateral Teleoperation, Bounded Input, Time-Varying Delay, Stability and Robustness.**

I. INTRODUCTION

THE bilateral teleoperation systems enable operators to implement tasks remotely through a controlled coupling between leader and follower robots, where information is exchanged bidirectionally through the communication channel between local and remote sites. With teleoperation, the physical presence in hazardous environments is no longer necessary for the operators, and the system can provide a safe and stable platform for remote operations. The advantages of telemanipulating has consolidated the teleoperation systems standing in a wide range of applications such as remote medical operation [1], [2], underwater telemanipulation [3], haptics-assisted training [4], telerehabilitation [5], space exploration [6] and beyond.

Teleoperation comes with distance between robots which in turn inevitably render exchanged signals delayed when passing through the communication channels. This can destabilize/degrade the system performance and therefore should be taken into account [7]–[11]. As far as time-varying delay goes, it is mostly assumed to be asymmetric in the forward and backward communication avenues between the operator and the remote environment [12], [13]. A number of control schemes have been proposed in the literature to address the time-varying delay. An LMI-based stability analysis is adopted in [13] for a proportional plus damping (P+D) controller proposed for bilateral teleoperation system with time-varying delays. In [14], based on subsystem decomposition, an adaptive control framework is developed for finite-time stability in bilateral teleoperation with asymmetric time-varying delays. In [15], a controller based on an extended state observer, a continuous terminal sliding mode control strategy and a time-delay part observer is investigated for a bilateral teleoperation system with time-varying delays. In [16], [17], nP+D like controllers are developed for nonlinear bilateral teleoperation with time-varying delays.

In almost all applications of Robotics, the joint actuators are the key and predominant components of the robotic manipulators and pragmatically speaking, their output have a limited amplitude, i.e., they are subject to saturation. In this regard, input control signals may exceed the saturation threshold and result in degradation of system's performance and even closed-loop instability [18]. It is possible to avoid the actuators saturation by using sufficiently high-torque actuators in robots, however, it inevitably will come at the cost of having large and heavy actuators. This, in turn, will cause further problems in robot design and control. Therefore, putting forward a control scheme in which the actuators saturation are taken into account is of crucial importance and will decrease the cost of the overall system significantly. In the context of teleoperation systems, the saturation control has recently received some attention. In [19], a nonlinear proportional plus damping (nP+D) control scheme has been utilized to deal with joint-space synchronization problem of nonlinear teleoperation system subjected to time-varying delays and actuator saturation. In [20], an anti-windup approach is developed to analyze

Manuscript received: October 15, 2020; Revised: January 10, 2021; Accepted: February 11, 2021. This paper was recommended for publication by Editor Jee-Hwan Ryu upon evaluation of the Associate Editor and Reviewers' comments. This research was supported by the Canada Foundation for Innovation under Grant LOF 28241, by the Alberta Innovation and Advanced Education Ministry through Small Equipment under Grant RCP12-021, by the Natural Science and Engineering Research Council of Canada through the Collaborative Health Research Projects, and by the Quanser, Inc.

[1]A. Zakerimanesh, M. Sharifi, and M. Tavakoli are with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton T6G 1H9, Alberta, Canada. {amir.zakerimanesh, m.sharifi, mahdi.tavakoli}@ualberta.ca

[2]F. Hashemzadeh is with the Department of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran. {hashemzadeh}@tabrizu.ac.ir

Digital Object Identifier (DOI): see top of this page.

the effect of actuator saturation for the bilateral teleoperation system subjected to varying time delays. In [21], the prescribed performance synchronization control approach is developed based on adaptive neural network for teleoperation system and auxiliary system is designed to deal with the input saturation.

In this paper, a novel nP+D like controller is developed to deal with actuators saturation and time-varying delays. By Lyapunov stability theory, the asymptotic stability of the nonlinear bilateral teleoperation is proved and the stability conditions on the controller parameters are established. In free motion, it is shown that the proposed controller guarantees the joint position synchronization problem. The contributions of this paper and its advantages can be summarized as follows.

- In the previous nP+D [19] and similar controllers [16], [22], [23], the amplitude of the nonlinear function was capped by the condition that the sensitivity to change of the function value with respect to a change in position error should be less than one. However, with the proposed controller and its stability analysis, the mentioned condition is relaxed and unnecessary, though ensures the stability of the nonlinear bilateral teleoperation systems in the presence of time-varying delays and bounded actuation.
- Given certain steady-state tracking error and communication delays, the proposed control scheme is capable of applying higher actuator torques in physical interactions compared to the one proposed in [19], which is due to the relaxation of the above-mentioned condition.
- For small amplitudes of the nonlinear function, because of the capped joint-velocity component in our control strategy, much more room is offered to the contribution of the error signal. Consequently, the position synchronization is improved in comparison with the established nP+D controller [19]. Therefore, the proposed controller mitigates the trade-off between the robustness to larger time-varying delays and the tracking performance of the telerobotic system.

The rest of the paper is organized as follows. Section II gives the problem formulation while the proposed controller and its stability analysis are studied in sections III and V, respectively. In section IV, assumptions, definitions, lemmas and properties as the preliminary information are discussed. Finally, in sections VI, VII and VIII, the simulation results, the experimental results and conclusion are discussed, respectively.

II. Problem Formulation

Assuming that the manipulators in the teleoperation system are modeled by Lagrangian systems, driven by actuated revolute joints and their control signals are subjected to actuators saturation, then for $k{\in}\{m,s\}$, the dynamics of the leader (m) and follower (s) robots are given as

$$\mathbf{M}_k(\mathbf{q}_k)\ddot{\mathbf{q}}_k{+}\mathbf{C}_k(\mathbf{q}_k,\dot{\mathbf{q}}_k)\dot{\mathbf{q}}_k{+}\mathbf{g}_k(\mathbf{q}_k){=}\boldsymbol{\tau}_{e_k}{+}\mathbf{s}_k(\boldsymbol{\tau}_k) \quad (1)$$

where $\mathbf{q}_k,\dot{\mathbf{q}}_k,\ddot{\mathbf{q}}_k{\in}\mathbb{R}^{n\times1}$ are respectively the vectors of the joint positions, velocities and accelerations, and n denotes the number of joints. $\mathbf{M}_k(\mathbf{q}_k){\in}\mathbb{R}^{n\times n}$, $\mathbf{C}_k(\mathbf{q}_k,\dot{\mathbf{q}}_k){\in}\mathbb{R}^{n\times n}$ and $\mathbf{g}_k(\mathbf{q}_k){\in}\mathbb{R}^{n\times1}$ are the inertia matrix, the Coriolis/centrifugal matrix and the gravitational vector, respectively. Moreover, $\boldsymbol{\tau}_{e_k}{\in}\mathbb{R}^{n\times1}$ shows the exerted torques on the robots, and $\boldsymbol{\tau}_k{\in}\mathbb{R}^{n\times1}$ are robots' control signals. The saturation of the control signals are modeled by the vector function $\mathbf{s}_k(\boldsymbol{\tau}_k)$: $\mathbb{R}^{n\times1}{\to}\mathbb{R}^{n\times1}$ whose elements $s_{k_i}(\tau_{k_i}){:}\mathbb{R}{\to}\mathbb{R};i{=}1,\ldots,n,$ are defined as

$$s_{k_i}(\tau_{k_i}){=}\begin{cases} b_{k_i} & \text{if} \quad \tau_{k_i}{>}b_{k_i} \\ \tau_{k_i} & \text{if} \quad |\tau_{k_i}|{\le}b_{k_i} \\ -b_{k_i} & \text{if} \quad \tau_{k_i}{<}{-}b_{k_i} \end{cases} \quad (2)$$

where $b_{k_i}{\in}\mathbb{R}_{>0}$ is the saturation level of the corresponding actuator, and τ_{k_i} is the control signal applied on the i^{th} joint of the robot k. To characterize the fact that the actuators are capable of overcoming the gravity, it is required to have $0{<}\omega_{k_i}{<}b_{k_i}$ where $|g_{k_i}(\mathbf{q}_k)|{\le}\omega_{k_i}$ and $g_{k_i}(\mathbf{q}_k)$ is the i^{th} element of the gravity vector $\mathbf{g}_k(\mathbf{q}_k)$. The joint-space position errors and their derivatives are defined as (3) and (4), respectively:

$$\begin{aligned} \mathbf{e}_m&{=}\mathbf{q}_m{-}\mathbf{q}_s(t{-}d_s), \quad \mathbf{e}_m^0{=}\mathbf{q}_m{-}\mathbf{q}_s \\ \mathbf{e}_s&{=}\mathbf{q}_s{-}\mathbf{q}_m(t{-}d_m), \quad \mathbf{e}_s^0{=}\mathbf{q}_s{-}\mathbf{q}_m \end{aligned} \quad (3)$$

$$\begin{aligned} \dot{\mathbf{e}}_m&{=}\dot{\mathbf{q}}_m{-}\left(1{-}\dot{d}_s\right)\dot{\mathbf{q}}_s(t{-}d_s) \\ \dot{\mathbf{e}}_s&{=}\dot{\mathbf{q}}_s{-}\left(1{-}\dot{d}_m\right)\dot{\mathbf{q}}_m(t{-}d_m) \end{aligned} \quad (4)$$

where d_m and d_s are time-varying forward (from the leader robot to the follower robot) and backward (from the follower robot to the leader robot) delays, respectively. In the rest of the paper, the notations $\mathbf{M}_k$, $\mathbf{C}_k$ and $\mathbf{g}_k$ are used instead of $\mathbf{M}_k(\mathbf{q}_k)$, $\mathbf{C}_k(\mathbf{q}_k,\dot{\mathbf{q}}_k)$ and $\mathbf{g}_k(\mathbf{q}_k)$, respectively. In the next step, the proposed controller which is put forward to achieve $\mathbf{e}_k{\to}\bar{\mathbf{0}}$, is discussed.

III. The Proposed Controller

Considering (1), the control signal is designed as

$$\boldsymbol{\tau}_k{=}\underbrace{\mathbf{g}_k{-}\mathbf{p}(\mathbf{e}_k){-}\sigma_1\mathbf{p}(\dot{\mathbf{q}}_k)}_{\triangleq\boldsymbol{\delta}_k}{-}\sigma_2\mathbf{p}(\dot{\mathbf{q}}_k) \quad (5)$$

where $\sigma_1,\sigma_2{\in}\mathbb{R}{>}0$. Based on [19], $\mathbf{p}(\mathbf{e}_k){:}\mathbb{R}^{n\times1}{\to}\mathbb{R}^{n\times1}$ is a nonlinear vector function whose elements $p_i(e_{k_i}){:}\mathbb{R}{\to}\mathbb{R},i{=}1,\ldots,n$ are required to be strictly increasing, bounded, continuous, passing through the origin, concave for positive e_{k_i} and convex for negative e_{k_i} with continuous first derivative around the origin such that $p_i(-e_{k_i}){=}{-}p_i(e_{k_i})$, and $N_i{=}\sup\{p_i(e_{k_i})\}$. For instance, by choosing $p_i(e_{k_i}){=}a_i\tan^{-1}(e_{k_i})$ [16], [19], [23] (see Fig. 1) or $p_i(e_{k_i}){=}a_i sat(e_{k_i})$ [22], $a_i{>}0$, all the mentioned properties are satisfied, $\frac{\partial p_i(e_{k_i})}{\partial e_{k_i}}$ is positive and bounded, and $N_i{=}a_i\pi/2$ for $p_i(e_{k_i}){=}a_i\tan^{-1}(e_{k_i})$. However, in contrary to [16], [19], [22], [23], here the upper bound for a_i can be bigger than 1 as well (see condition 12b and Remark 2) by which, for instance, one can exert higher actuation torques in physical interactions having a certain steady-state tracking error (i.e., $\dot{\mathbf{q}}_k{\approx}0$).

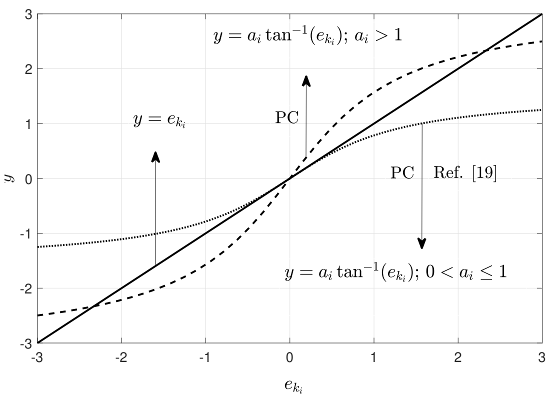

Fig. 1. The nonlinear function that can be utilized in the proposed controller (PC), and the one used in the Ref. [19].

IV. Preliminaries

Assumption 1. The time-varying delays in the communication channels are continuous.

Definition 1. The operators and the environment are passive, i.e., there exists positive constant $\vartheta_k<\infty$ such that

$$\vartheta_k+\int_0^t -\dot{q}_k^T(\mu)\tau_{e_k}(\mu)d\mu>0 \tag{6}$$

Lemma 1. The following inequalities hold [19]:

$$\dot{\mathbf{q}}_m^T\big(\mathbf{p}(\mathbf{e}_m^0)-\mathbf{p}(\mathbf{e}_m)\big)\leq 2|\dot{\mathbf{q}}_m|^T\int_{t-d_s}^t \mathbf{p}(|\dot{\mathbf{q}}_s(\mu)|)d\mu \tag{7}$$

$$\dot{\mathbf{q}}_s^T\big(\mathbf{p}(\mathbf{e}_s^0)-\mathbf{p}(\mathbf{e}_s)\big)\leq 2|\dot{\mathbf{q}}_s|^T\int_{t-d_m}^t \mathbf{p}(|\dot{\mathbf{q}}_m(\mu)|)d\mu \tag{8}$$

Lemma 2. The following inequalities hold [19]:

$$\begin{aligned}|\dot{\mathbf{q}}_m|^T\int_{t-d_s}^t \mathbf{p}(|\dot{\mathbf{q}}_s(\mu)|)d\mu-\int_{t-d_s}^t \dot{\mathbf{q}}_s^T(\mu)\mathbf{p}(|\dot{\mathbf{q}}_s(\mu)|)d\mu\\ \leq \bar{d}_s\dot{\mathbf{q}}_m^T\mathbf{p}(\dot{\mathbf{q}}_m)\end{aligned} \tag{9}$$

$$\begin{aligned}|\dot{\mathbf{q}}_s|^T\int_{t-d_m}^t \mathbf{p}(|\dot{\mathbf{q}}_m(\mu)|)d\mu-\int_{t-d_m}^t \dot{\mathbf{q}}_m^T(\mu)\mathbf{p}(|\dot{\mathbf{q}}_m(\mu)|)d\mu\\ \leq \bar{d}_m\dot{\mathbf{q}}_s^T\mathbf{p}(\dot{\mathbf{q}}_s)\end{aligned} \tag{10}$$

where $\bar{d}_m$ and $\bar{d}_s$ are the maximum of the forward and backward time-varying delays, respectively.

Important properties of the nonlinear dynamics (1) according to [24], [25] are as follows.

Property 1. The inertia matrix $\mathbf{M}_k\in\mathbb{R}^{n\times n}$ is symmetric positive-definite and has the following upper and lower bounds:

$$0<\lambda_{min}(\mathbf{M}_k)\mathbf{I}_n\leq\mathbf{M}_k\leq\lambda_{max}(\mathbf{M}_k)\mathbf{I}_n<\infty$$

Property 2. $\dot{\mathbf{M}}_k-2\mathbf{C}_k$ is a skew symmetric matrix.

Property 3. The time derivative of $\mathbf{C}_k$ is bounded if $\ddot{\mathbf{q}}_k$ and $\dot{\mathbf{q}}_k$ are bounded.

Property 4. The gravity vector $\mathbf{g}_k$ is bounded. There exist positive constants ω_{k_i} such that every elements of the gravity vector $g_{k_i}(\mathbf{q}_k)$ satisfies $|g_{k_i}(\mathbf{q}_k)|\leq\omega_{k_i}$.

Property 5. For a manipulator with revolute joints, there exists a positive φ bounding the Coriolis/centrifugal term as follows

$$\|\mathbf{C}_k(\mathbf{q}_k,\mathbf{x})\mathbf{y}\|_2\leq\varphi\|\mathbf{x}\|_2\|\mathbf{y}\|_2$$

V. Stability Analysis

Applying the controller (5) to the robots dynamics (1), the following closed-loop dynamics can be found.

$$\mathbf{M}_k\ddot{\mathbf{q}}_k+\mathbf{C}_k\dot{\mathbf{q}}_k+\mathbf{g}_k=\boldsymbol{\tau}_{e_k}+\mathbf{s}_k(\boldsymbol{\delta}_k-\sigma_2\mathbf{p}(\dot{\mathbf{q}}_k)) \tag{11}$$

Now, the time is ripe for studying the stability of system with taking account of interaction forces in which we will investigate by two cases including: 1) Theorem 1: The operator and environment are passive and 2) Theorem 2: The human operator applies a nonpassive force and the follower robot is in contact with the environment which is assumed to be passive.

Theorem 1. Given the closed-loop system (11), and assuming that the operator and the environment are passive, the signals including joint-space position errors (3), the joints velocities $\dot{\mathbf{q}}_k$, and the joints accelerations $\ddot{\mathbf{q}}_k$ are bounded, and converge to zero in free motion ($\boldsymbol{\tau}_{e_k}=0$) if

$$\sigma_1>2T_r \quad\text{and}\quad 0<\sigma_2\ll 1 \tag{12a}$$

$$0<N_i<\min_k\left\{\frac{b_{k_i}-\omega_{k_i}}{1+\sigma_1}\right\} \tag{12b}$$

are satisfied. T_r is maximum round-trip delay defined as $T_r\triangleq\bar{d}_m+\bar{d}_s$. Note that if $p(e_{k_i})=a_i\tan^{-1}(e_{k_i})$ then $N_i=a_i\pi/2$.

Proof. Let define $\mathbf{x}_t=\mathbf{x}_t(t+\wp)$ as the state of the system where $\mathbf{x}_t(t)\triangleq[\mathbf{q}_m,\mathbf{q}_s,\dot{\mathbf{q}}_m,\dot{\mathbf{q}}_s]$, $-d_{max}\leq\wp\leq 0$ and $d_{max}=\max\big(\bar{d}_m,\bar{d}_s\big)$. Therefore, for the stability analysis, Lyapunov-Krasovskii functional $v=v(\mathbf{x}_t)$ can be defined as

$$\begin{aligned}v=&\underbrace{\sum_k\frac{1}{2}\dot{\mathbf{q}}_k^T\mathbf{M}_k\dot{\mathbf{q}}_k}_{v_1}+\underbrace{\sum_k\int_0^t -\dot{\mathbf{q}}_k^T(\mu)\boldsymbol{\tau}_{e_k}(\mu)d\mu+\vartheta_k}_{v_2}\\ &\underbrace{+\sum_k\int_0^t\sum_{i=1}^n -\dot{q}_{k_i}(s_{k_i}(\delta_{k_i}-\sigma_2 p_i(\dot{q}_{k_i}))-\delta_{k_i})d\mu}_{v_3}\\ &\underbrace{+\sum_{i=1}^n\int_0^{q_{m_i}-q_{s_i}} p_i(\mu_i)d\mu_i}_{v_4}\\ &\underbrace{+2\sum_k\int_{-\bar{d}_k}^0\int_{t+\mu}^t \dot{\mathbf{q}}_k^T(\eta)\mathbf{p}(\dot{\mathbf{q}}_k(\eta))d\eta d\mu}_{v_5}\end{aligned} \tag{13}$$

such that $\delta_{k_i} \triangleq g_{k_i} - p_i(e_{k_i}) - \sigma_1 p_i(\dot{q}_{k_i})$. First, we need to show that v_3 is a positive function. To this end, considering (2), Property 4 and the condition (12b), it is straightforward to conclude that

$$|\delta_{k_i}| < b_{k_i}, \quad \delta_{k_i} = s_{k_i}(\delta_{k_i}) \tag{14}$$

and since the saturation function (2) is strictly increasing in the linear region, it warrants the following relations:

$$\begin{aligned} s_{k_i}(\delta_{k_i} - \sigma_2 p_i(\dot{q}_{k_i})) &\leq s_{k_i}(\delta_{k_i}) \quad \text{if} \quad \dot{q}_{k_i} \geq 0 \\ s_{k_i}(\delta_{k_i} - \sigma_2 p_i(\dot{q}_{k_i})) &> s_{k_i}(\delta_{k_i}) \quad \text{if} \quad \dot{q}_{k_i} < 0 \end{aligned} \tag{15}$$

and therefore

$$-\dot{q}_{k_i}(s_{k_i}(\delta_{k_i} - \sigma_2 p_i(\dot{q}_{k_i})) - \delta_{k_i}) \geq 0 \tag{16}$$

Note that under the assumption that the actuators are capable of overcoming the gravity, $b_{k_i} - \omega_{k_i} > 0$. Taking the time derivative of the $v(\mathbf{x}_t)$ by considering the closed-loop dynamics (11) and Property 2 leads to

$$\begin{aligned} \dot{v} \leq & \underbrace{\sum_k \dot{\mathbf{q}}_k^T(\boldsymbol{\tau}_{e_k} + \mathbf{s}_k(\boldsymbol{\tau}_k) - \mathbf{g}_k)}_{=\dot{v}_1} + \underbrace{\sum_k -\dot{\mathbf{q}}_k^T \boldsymbol{\tau}_{e_k}}_{=\dot{v}_2} \\ & + \underbrace{\sum_k -\dot{\mathbf{q}}_k^T(\mathbf{s}_k(\boldsymbol{\tau}_k) - \boldsymbol{\delta}_k)}_{=\dot{v}_3} + \underbrace{\sum_k \dot{\mathbf{q}}_k^T \mathbf{p}(\mathbf{e}_k^0)}_{=\dot{v}_4} \\ & + \underbrace{2\sum_k \left(\bar{d}_k \dot{\mathbf{q}}_k^T \mathbf{p}(\dot{\mathbf{q}}_k) - \int_{t-d_k}^t \dot{\mathbf{q}}_k^T(\mu) \mathbf{p}(\dot{\mathbf{q}}_k(\mu)) d\mu \right)}_{\geq \dot{v}_5} \end{aligned} \tag{17}$$

Now, we need to simplify the relation (17). To this end, we take the following steps. Please note that, for instance, for simplicity we use notation $\dot{v}_{123}$ for $\dot{v}_1 + \dot{v}_2 + \dot{v}_3$.

$$\dot{v}_{123} = \dot{\mathbf{q}}_k^T(\boldsymbol{\delta}_k - \mathbf{g}_k) = -\sum_k \dot{\mathbf{q}}_k^T(\mathbf{p}(\mathbf{e}_k) + \sigma_1 \mathbf{p}(\dot{\mathbf{q}}_k)) \tag{18}$$

Adding $\dot{v}_4$ to (18) and using Lemma 1 we get

$$\begin{aligned} \dot{v}_{1234} \leq & 2|\dot{\mathbf{q}}_m|^T \int_{t-d_s}^t \mathbf{p}(|\dot{\mathbf{q}}_s(\mu)|) d\mu \\ & + 2|\dot{\mathbf{q}}_s|^T \int_{t-d_m}^t \mathbf{p}(|\dot{\mathbf{q}}_m(\mu)|) d\mu - \sum_k \sigma_1 \dot{\mathbf{q}}_k^T \mathbf{p}(\dot{\mathbf{q}}_k) \end{aligned} \tag{19}$$

Adding $\dot{v}_5$ to (19), using Lemma 2, and defining $T_r \triangleq \bar{d}_m + \bar{d}_s$ as the round-trip delay results in

$$\begin{aligned} \dot{v} = \dot{v}_{12345} \leq & 2T_r \dot{\mathbf{q}}_m^T \mathbf{p}(\dot{\mathbf{q}}_m) + 2T_r \dot{\mathbf{q}}_s^T \mathbf{p}(\dot{\mathbf{q}}_s) \\ & - \sigma_1 \dot{\mathbf{q}}_m^T \mathbf{p}(\dot{\mathbf{q}}_m) - \sigma_1 \dot{\mathbf{q}}_s^T \mathbf{p}(\dot{\mathbf{q}}_s) \end{aligned} \tag{20}$$

Therefore, in order to have $\dot{v} \leq 0$, the following relation should be satisfied.

$$\sigma_1 > 2T_r \tag{21}$$

Considering (15), σ_2 suffices to be a 'small' positive scalar, or to be exact, we need $0 < \sigma_2 \ll 1$. In conclusion, we would have $\dot{v}(\mathbf{x}_t) \leq 0$ which means that all terms in $v(\mathbf{x}_t)$ are bounded. Therefore, $\dot{\mathbf{q}}_k, \mathbf{e}_k^0 \in L_\infty$. For instance, considering v_5 in (13), since the nonlinear function $\mathbf{p}(\dot{\mathbf{q}}_k(\eta))$ is bounded we can get the boundedness of $\dot{\mathbf{q}}_k$. Also, from v_4 in (13), since the nonlinear function is bounded, then the upper limit of the integration should be bounded as well, so $\mathbf{e}_k^0 \in L_\infty$. Consequently since $\mathbf{e}_m = \mathbf{e}_m^0 + \int_{t-d_s}^t \dot{\mathbf{q}}_s(\tau) d\tau$ and $\mathbf{e}_s = \mathbf{e}_s^0 + \int_{t-d_m}^t \dot{\mathbf{q}}_m(\tau) d\tau$, so $\mathbf{e}_k \in L_\infty$. Considering (1), using Properties 1, 4 and 5, and given the boundedness of $\mathbf{s}_k(\boldsymbol{\tau}_k)$, it is possible to see that $\ddot{\mathbf{q}}_k \in L_\infty$. Therefore, the first part of Theorem 1 is proved.

From part 1, we know $\mathbf{e}_k^0, \mathbf{e}_k, \dot{\mathbf{q}}_k, \ddot{\mathbf{q}}_k, \mathbf{p}(\dot{\mathbf{q}}_k) \in L_\infty$ and given that $\partial \mathbf{p}(\dot{\mathbf{q}}_k) / \partial \dot{\mathbf{q}}_k$ is bounded, then $d/dt(\mathbf{p}(\dot{\mathbf{q}}_k)) \in L_\infty$. Now, integrating both sides of (20) from 0 to t, regarding Fig. 1, and defining $\psi \triangleq \sigma_1 - 2T_r$, one can conclude that

$$v(t) - v(0) \leq \begin{cases} -\sum_k \psi \|\mathbf{p}(\dot{\mathbf{q}}_k)\|_2^2 & \text{if } 0 < a_i \leq 1 \\ -\sum_k \psi \|\dot{\mathbf{q}}_k\|_2^2 & \text{if } a_i > 1 \ \& \ |\mathbf{p}(\dot{\mathbf{q}}_k)| > |\dot{\mathbf{q}}_k| \\ -\sum_k \psi \|\mathbf{p}(\dot{\mathbf{q}}_k)\|_2^2 & \text{if } a_i > 1 \ \& \ |\mathbf{p}(\dot{\mathbf{q}}_k)| \leq |\dot{\mathbf{q}}_k| \end{cases} \tag{22}$$

From (22), we have $\dot{\mathbf{q}}_k \in L_2$ or $\mathbf{p}(\dot{\mathbf{q}}_k) \in L_2$. Thus, having $\dot{\mathbf{q}}_k, \mathbf{p}(\dot{\mathbf{q}}_k) \in L_2$ and $\ddot{\mathbf{q}}_k, d/dt(\mathbf{p}(\dot{\mathbf{q}}_k)) \in L_\infty$, and using Barbalat's lemma [26] results in $\dot{\mathbf{q}}_k \to 0$ or $\mathbf{p}(\dot{\mathbf{q}}_k) \to 0$. Noting that the nonlinear function $p_i(.)$ passes through the origin, $\mathbf{p}(\dot{\mathbf{q}}_k) \to 0$ gives $\dot{\mathbf{q}}_k \to 0$ as well. Exploring (1) in free motion yields

$$\ddot{\mathbf{q}}_k = \mathbf{M}_k^{-1}(-\mathbf{C}_k \dot{\mathbf{q}}_k - \mathbf{g}_k + \mathbf{s}_k(\boldsymbol{\delta}_k - \sigma_2 \mathbf{p}(\dot{\mathbf{q}}_k))) \tag{23}$$

and taking the time derivative from both sides of Eq. (23) we get

$$\begin{aligned} \dddot{\mathbf{q}}_k = & \frac{d}{dt}(\mathbf{M}_k^{-1})(-\mathbf{C}_k \dot{\mathbf{q}}_k - \mathbf{g}_k + \mathbf{s}_k(\boldsymbol{\delta}_k - \sigma_2 \mathbf{p}(\dot{\mathbf{q}}_k))) \\ & + \mathbf{M}_k^{-1} \frac{d}{dt}(-\mathbf{C}_k \dot{\mathbf{q}}_k - \mathbf{g}_k + \mathbf{s}_k(\boldsymbol{\delta}_k - \sigma_2 \mathbf{p}(\dot{\mathbf{q}}_k))) \\ = & \frac{d}{dt}(\mathbf{M}_k^{-1})(-\mathbf{C}_k \dot{\mathbf{q}}_k - \mathbf{g}_k + \mathbf{s}_k(\boldsymbol{\delta}_k - \sigma_2 \mathbf{p}(\dot{\mathbf{q}}_k))) \\ & + \mathbf{M}_k^{-1} \frac{d}{dt}(-\mathbf{C}_k \dot{\mathbf{q}}_k - \mathbf{g}_k) + \mathbf{M}_k^{-1} \dot{\mathbf{g}}_k \dot{\mathbf{s}}_k(\boldsymbol{\delta}_k - \sigma_2 \mathbf{p}(\dot{\mathbf{q}}_k)) \\ & - \mathbf{M}_k^{-1} \frac{d}{dt}(\mathbf{p}(\mathbf{e}_k) + \sigma_1 \mathbf{p}(\dot{\mathbf{q}}_k)) \dot{\mathbf{s}}_k(\boldsymbol{\delta}_k - \sigma_2 \mathbf{p}(\dot{\mathbf{q}}_k)) \end{aligned} \tag{24}$$

where

$$\frac{d}{dt}(\mathbf{M}_k^{-1}) = -\mathbf{M}_k^{-1}(\mathbf{C}_k + \mathbf{C}_k^T)\mathbf{M}_k$$

is bounded due to $\dot{\mathbf{q}}_k \in L_\infty$ and the Properties 1 and 5. Given (4), $\dot{\mathbf{q}}_k \to 0$, $\dot{\mathbf{q}}_k \in L_\infty$ and Assumption 1 yields $\dot{\mathbf{e}}_k \in L_\infty$ and so $d/dt(\mathbf{p}(\mathbf{e}_k)) \in L_\infty$. Now, 1) if $|\delta_{k_i} - \sigma_2 p_i(\dot{q}_{k_i})| \leq b_{k_i}$, then by considering (2) it is obvious that $\dot{s}_{k_i}(\delta_{k_i} - \sigma_2 p_i(\dot{q}_{k_i})) = 1$. Having $\dot{\mathbf{q}}_k \in L_\infty$ gives $\dot{\mathbf{g}}_k \in L_\infty$, and considering the Properties 1, 3, 4 and 5, one can readily get $\dddot{\mathbf{q}}_k \in L_\infty$ and 2) if $|\delta_{k_i} - \sigma_2 p_i(\dot{q}_{k_i})| > b_{k_i}$, then $\dot{s}_{k_i}(\delta_{k_i} - \sigma_2 p_i(\dot{q}_{k_i})) = 0$ and from (24) again one can conclude that $\dddot{\mathbf{q}}_k \in L_\infty$. Therefore, having $\dddot{\mathbf{q}}_k \in L_\infty$ and $\dot{\mathbf{q}}_k \to 0$, using the Barbalat's lemma [26] we get $\ddot{\mathbf{q}}_k \to 0$. Now, applying $\dot{\mathbf{q}}_k, \ddot{\mathbf{q}}_k \to 0$ into the closed-loop dynamics (11), in free motion, we get

$$\mathbf{s}_k(\mathbf{g}_k - \mathbf{p}(\mathbf{e}_k)) \to \mathbf{g}_k \tag{25}$$

and noting that the condition (12b) implies also $0 < a_i \leq \min_k\{b_{k_i} - \omega_{k_i}\}$, then $|g_{k_i} - p_i(e_{k_i})| \leq b_{k_i}$ and so $\mathbf{s}(\mathbf{g}_k - \mathbf{p}(\mathbf{e}_k)) = \mathbf{g}_k - \mathbf{p}(\mathbf{e}_k)$. Thus, from (25), we get $\mathbf{p}(\mathbf{e}_k) \to 0$ and considering that the nonlinear function $p_i(.)$ passes through the origin, then $\mathbf{e}_k \to 0$. Therefore, the proof of Theorem 1 has been completed. $\square$

Now, we would like to investigate the stability of the closed-loop system (11) when the human operator exerts a nonpassive force. Assume that $\mathbf{x}_k\in\mathbb{R}^{z\times 1}$ presents the positions of the robots in the task-space and let z be the dimension of the task-space. Also, we have the established relation $\dot{\mathbf{x}}_k=\mathbf{J}_k\dot{\mathbf{q}}_k$ where $\mathbf{J}_k\in\mathbb{R}^{z\times n}$ is the Jacobian matrix of the robot k. Suppose that the follower robot is in contact with the environment which is assumed to be passive with respect to $\dot{\mathbf{x}}_s$ and let the exerted forces be as [27]

$$\begin{aligned}\mathbf{f}_{e_m}&=\mathbf{r}_m-\alpha_m\dot{\mathbf{x}}_m\\ \mathbf{f}_{e_s}&=-\alpha_s\dot{\mathbf{x}}_s\end{aligned}\tag{26}$$

where $\mathbf{r}_m\in\mathbb{R}^{z\times 1}$ is a positive bounded vector, and $\alpha_k\in\mathbb{R}$ is a bounded nonnegative constant. Given (26), the closed dynamics (11) can be represented as

$$\mathbf{M}_k\ddot{\mathbf{q}}_k+\mathbf{C}_k\dot{\mathbf{q}}_k+\mathbf{g}_k=\mathbf{J}_k^T\mathbf{f}_{e_k}+\mathbf{s}_k(\boldsymbol{\delta}_k-\sigma_2\mathbf{p}(\dot{\mathbf{q}}_k))\tag{27}$$

Theorem 2. Consider the closed-loop dynamics (27) with the proposed controller (5) and the exerted forces (26). All signals in the system's state are bounded provided that the conditions (12a) and (12b) hold true.

Proof. Given (13), consider Lyapunov-Krasovskii functional as $v=v_1+v_3+v_4+v_5$. Now, using a similar approach utilized in the proof of Theorem 1, $\dot{v}$ culminates in

$$\begin{aligned}\dot{v}\leq&-(\sigma_1-2T_r)\dot{\mathbf{q}}_m^T\mathbf{p}(\dot{\mathbf{q}}_m)-(\sigma_1-2T_r)\dot{\mathbf{q}}_s^T\mathbf{p}(\dot{\mathbf{q}}_s)\\ &+\dot{\mathbf{q}}_m^T\mathbf{J}_m^T\mathbf{f}_{e_m}+\dot{\mathbf{q}}_s^T\mathbf{J}_s^T\mathbf{f}_{e_s}\\ \leq&-(\sigma_1-2T_r)\dot{\mathbf{q}}_m^T\mathbf{p}(\dot{\mathbf{q}}_m)-(\sigma_1-2T_r)\dot{\mathbf{q}}_s^T\mathbf{p}(\dot{\mathbf{q}}_s)\\ &+\dot{\mathbf{x}}_m^T\mathbf{r}_m-\alpha_m\dot{\mathbf{x}}_m^T\dot{\mathbf{x}}_m-\alpha_s\dot{\mathbf{x}}_s^T\dot{\mathbf{x}}_s\\ \leq&-(\sigma_1-2T_r)\dot{\mathbf{q}}_m^T\mathbf{p}(\dot{\mathbf{q}}_m)-(\sigma_1-2T_r)\dot{\mathbf{q}}_s^T\mathbf{p}(\dot{\mathbf{q}}_s)\\ &-\alpha_m\|\dot{\mathbf{x}}_m\|_2^2-\alpha_s\|\dot{\mathbf{x}}_s\|_2^2+\frac{1}{2}\|\mathbf{r}_m\|_2^2+\frac{1}{2}\|\dot{\mathbf{x}}_m\|_2^2\end{aligned}\tag{28}$$

Therefore, $\sigma_1\geq 2T_r$ is a sufficient condition for

$$\dot{v}(\mathbf{x}_t)\leq 0,\ \forall\ \alpha_m\|\dot{\mathbf{x}}_m\|_2^2+\alpha_s\|\dot{\mathbf{x}}_s\|_2^2\geq\frac{1}{2}\|\mathbf{r}_m\|_2^2+\frac{1}{2}\|\dot{\mathbf{x}}_m\|_2^2\tag{29}$$

which in turn keeps all terms in $v(\mathbf{x}_t)$ bounded. In other words, $\dot{\mathbf{q}}_k,\mathbf{e}_k^0,\mathbf{e}_k\in L_\infty$. Now, consider if we have $\alpha_m\|\dot{\mathbf{x}}_m\|_2^2+\alpha_s\|\dot{\mathbf{x}}_s\|_2^2<\frac{1}{2}\|\mathbf{r}_m\|_2^2+\frac{1}{2}\|\dot{\mathbf{x}}_m\|_2^2$. Regarding (26) and knowing that $\|\mathbf{r}_m\|_2$ and $\|\mathbf{f}_{e_m}\|_2$ are bounded, results in boundedness of $\|\dot{\mathbf{x}}_m\|_2$ and so $\|\dot{\mathbf{x}}_s\|_2$ is bounded. Therefore, we can conclude that $\|\dot{\mathbf{x}}_k\|_2$ is bounded and so $\dot{\mathbf{x}}_k\in L_\infty$. Since $\|\dot{\mathbf{x}}_k\|_\infty\leq\|\mathbf{J}_k\|_\infty\|\dot{\mathbf{q}}_k\|_\infty$, and $\|\mathbf{J}_k\|_\infty$ is bounded for the revolute joint robots then it is possible to see that $\dot{\mathbf{q}}_k\in L_\infty$, and so $\mathbf{e}_k^0,\mathbf{e}_k\in L_\infty$. Given $\dot{\mathbf{q}}_k\in L_\infty$, the closed-loop dynamics (11), relations (2) and (26), and using Properties 1, 4 and 5 result in $\ddot{\mathbf{q}}_k\in L_\infty$. Hereby, the proof of Theorem 2 is completed. □

Remark 1. In teleoperation systems, the leader robot's operator needs to have a level of perception of the interaction force between the follower robot and the environment. Thus we investigate this necessity in the proposed control structure. Let the follower robot be in a quasi-static hard contact with the environment and meanwhile the operator keeps exerting force on the end-effector of the leader robot. Therefore, $\dot{\mathbf{q}}_k,\ddot{\mathbf{q}}_k\approx 0$ and substituting it into the closed-loop dynamics (11) yields $\boldsymbol{\tau}_{e_k}\approx\mathbf{p}(\mathbf{e}_k)$ and since $p_i(e_{k_i})$ is an odd function, one can readily conclude that $\boldsymbol{\tau}_{e_m}+\boldsymbol{\tau}_{e_s}\approx 0$ by exploring which it is straightforward to infer that

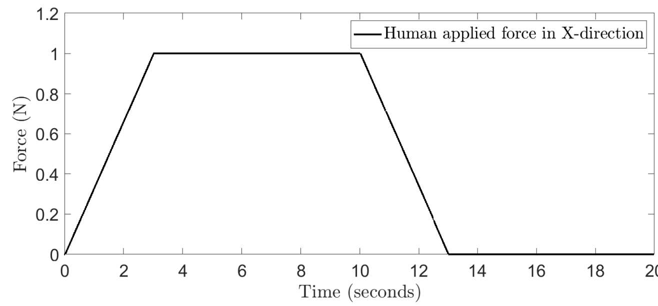

Fig. 2. The applied force on the end-effector of the leader.

$$\mathbf{f}_{e_m}\approx-\mathfrak{S}_m^{+}\mathbf{J}_s^T\mathbf{f}_{e_s}\tag{30}$$

where $\mathfrak{S}_m^{+}\triangleq\left(\mathbf{J}_m\mathbf{J}_m^T\right)^{-1}\mathbf{J}_m$ is the pseudo-inverse of $\mathbf{J}_m^T$. Given that $\boldsymbol{\tau}_{e_k}\approx\mathbf{p}(\mathbf{e}_k)$ is bounded and so relation (30) is bounded, then the static force reflection error is guaranteed to be bounded.

Remark 2. Using the proposed controller of [19]:

$$\boldsymbol{\tau}_k=\mathbf{g}_k-\mathbf{p}(\mathbf{e}_k)-\sigma_1\dot{\mathbf{q}}_k\tag{31}$$

and its adopted corresponding stability analysis, the stability condition mentioned in [19] can be rearranged as

$$\sigma_1>2T_r\quad\&\quad a_i\leq\min\left\{\frac{2(b_{k_i}-\omega_{k_i})}{\pi(1+\sigma_1)},1\right\}$$

comparing which with the stability condition of this work obtained (through its corresponding stability analysis) as

$$\sigma_1>2T_r\quad\&\quad a_i\leq\min\left\{\frac{2(b_{k_i}-\omega_{k_i})}{\pi(1+\sigma_1)}\right\},$$

we can see that using the capped joint-velocity in the proposed controller and advising an appropriate stability analysis, the nonlinear function's limitation that the sensitivity to change of the function value with respect to a change in position error should be less than one, is no longer necessary.

Remark 3. The condition (12b) guarantees relations in (14), and by setting $0<\sigma_2\ll 1$, it can be ensured that the control torque efforts will not undergo saturation. Therefore, regarding condition (12a), larger time delays do not impose any limitation on the applicability of the proposed controller. That said, considering (12b), the larger the time-delays, the less the amplitude a_i can be set to meet the stability conditions.

VI. Simulation Studies

In this section, the simulation results are presented to verify the theoretical findings. The leader and follower robots are considered to be 3-DOF planar revolute-joint robots, each with identical links such that $M_m=0.35\ kg$ and $L_m=0.3\ m$ are chosen for the mass and length parameters of the leader robot, and $M_s=0.49\ kg$ and $L_s=0.42\ m$ for the follower robot, respectively. Initial conditions $\mathbf{q}_m(0)=\left[\frac{\pi}{6},\frac{\pi}{6},\frac{\pi}{6}\right]^T$, $\mathbf{q}_s(0)=\left[\frac{\pi}{4},\frac{\pi}{4},\frac{\pi}{4}\right]^T$

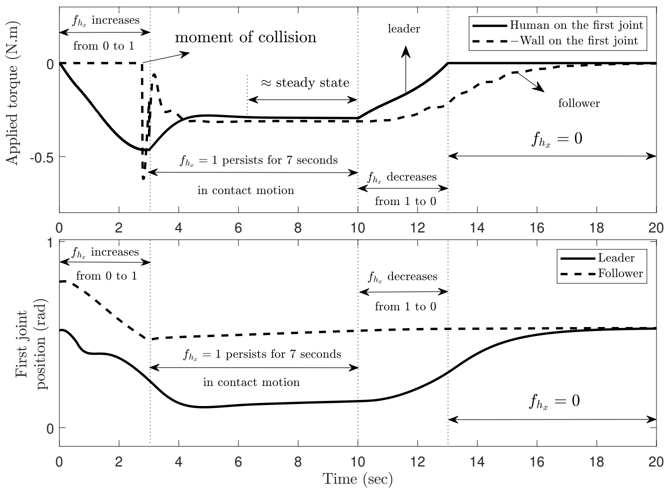

Fig. 3. The first joint positions and the torques applied on, using the proposed controller.

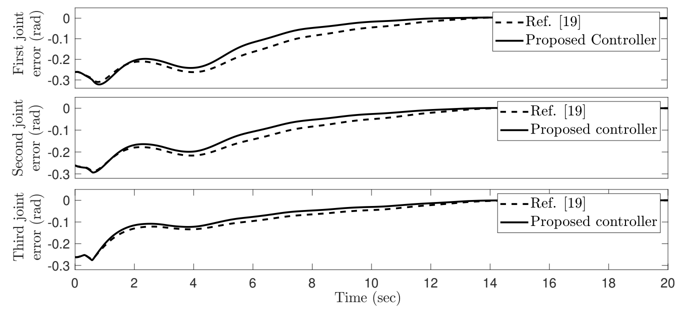

Fig. 4. Comparison of the joint position errors between the leader and follower robots, using the proposed controller and the controller of [19].

are chosen for the joint positions, and $\dot{\mathbf{q}}_k(0)=\ddot{\mathbf{q}}_k(0)=0$ for the initial joint velocities and accelerations, respectively. The control signals of the leader and follower robots are subject to the actuators saturation at levels ± 10 $N.m$ and ± 20 $N.m$, respectively, i.e., $b_{m_i}=10$ $N.m$ and $b_{s_i}=20$ $N.m$. Forward and backward time-varying delays are assumed respectively as $d_m(t)=0.2+0.03\sin(7t)+0.08\sin(4t)+0.05\sin(7t)$ and $d_s(t)=0.3+0.04\sin(4t)+0.2\sin(3t)+0.05\sin(3t)$ so that $\bar{d}_m=0.36$, $\bar{d}_s=0.59$ and thus $T_r=0.95$. We assume that $\omega_{m_i}=6.18$ N and $\omega_{s_i}=12.11$ N for $i=1,2,3$, so using stability condition (12b), we get $a_1=a_2=0.83$. Therefore, the controllers have been set to

$$\boldsymbol{\tau}_k=\mathbf{g}_k-0.83\tan^{-1}(\mathbf{e}_k)-1.59\tan^{-1}(\dot{\mathbf{q}}_k) \tag{32}$$

We assume that the human operator applies his/her force on the end-effector of the leader robot only in X-direction according to Fig. 2, and there is a stiff wall at $X=0.65$ m at the follower site. The wall is supposed to behave like a spring-damper with a spring stiffness equal to 100 N/m and damping coefficient equal to $6N.s/m$. Therefore, when the end-effector of the follower robot reaches the wall and tries to move further in positive X-direction, the feedback force in the negative X-direction will be $f_{w_x}=100(X-0.65)+6\dot{X}$ N for $X\geq 0.65$ m, and in Y-direction will be $f_{w_y}=0$. Therefore, the reflected force will impede the advance of the follower robot's end-effector through an equivalent torque of $\mathbf{J}_s^T[f_{w_x}\,0]^T$ on the joints of the follower robot. Fig. 3 shows the operator and wall exerted torques on the first joints of the robots, and also trajectories of the first joints during free-space motion and contact motion. As it can be seen from Fig. 3 and according to Remark 1, in steady state, the applied torques converge. For the sake of brevity, only the results of the first joints were shown and discussed, and similar outputs for the rest can be inferred.

Now, we tend to make a comparison between the performance of the proposed controller and the controller used in [19] as our benchmark controller. Given the applied force in Fig. 2, and the controller (32), the simulation results are shown in Fig. 4 for the space-free motion error between the joint positions, i.e., $\mathbf{e}(t)=\mathbf{q}_m(t)-\mathbf{q}_s(t)$. As we can see, the proposed controller outperforms the benchmark controller in terms of settling time and transient error so that the synchronisation has been improved. It would be also useful to compare the performance of the proposed controller with the controller of [19] in terms of the amount of the control effort applied on the joints. Fig. 5 shows the control torques applied on the joints of the leader and follower robots using the proposed controller (PC) and adopting the controller of [19]. Considering Figs. 4 and 5, it is obvious that though the amount of the control efforts exerted on the leader robot through the both methods are practically the same, but using the proposed controller, the resultant control effort on the follower robot is larger which results in better synchronization performance. In other words, since the control inputs do not exceed the allowable actuation limits (saturation limits), having a better synchronization warrants exerting an admissible larger actuation effort.

VII. Experimental Evaluations

The functionality of the proposed bilateral nP+D control strategy is evaluated experimentally using a tele-robotic system including a Phantom Premium 1.5A robot (Geomagic Inc., Wilmington, USA) and a Quanser Robot (Quanser Consulting Inc., Markham, Canada) as the leader and follower, as demonstrated in Fig. 6. The first revolute joint of the Phantom Premium robot is locked in order to work with next two ones and have the same kinematics as Quanser robot with serial 2-DOF RR mechanism. The kinematics and dynamics of these robots were described in [28] and [29], respectively. The Quanser Robot is equipped with the Axia80-ZC22 F/T sensor (ATI Industrial Automation, Apex, NC, USA) to measure environment forces exerted on its end-effector. The QUARC (Quanser Real-Time Control) system is utilized as the software environment to effectuate the bilateral controller with the sampling rate of 1 kHz. In this experiment, the operator moves the leader (Phantom) robot to conduct a peg-in-hole task remotely by the follower (Quanser) robot.

In the teleoperation task, the maximum time delay of 200 ms is considered between the leader and follower for $\bar{d}_m$ and $\bar{d}_s$. In this case, the proposed controller's gains are adjusted

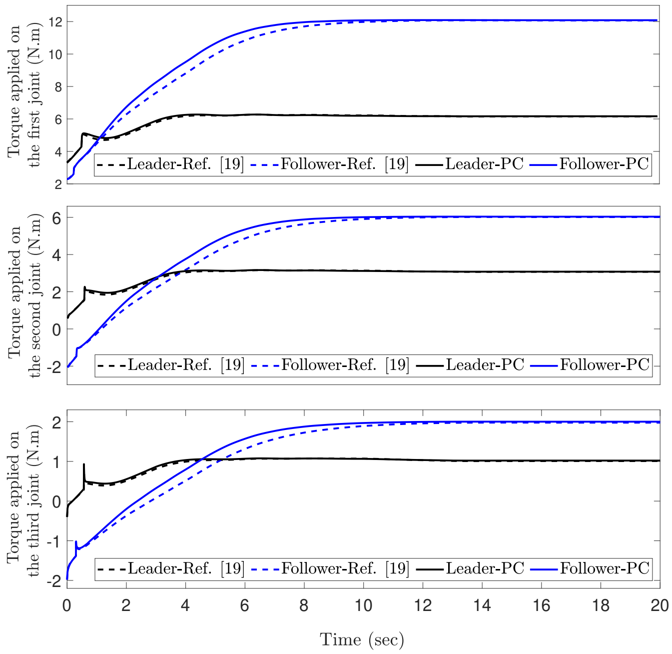

Fig. 5. Comparison between the control torque efforts exerted on the joints using using the proposed controller (PC) and the controller of [19].

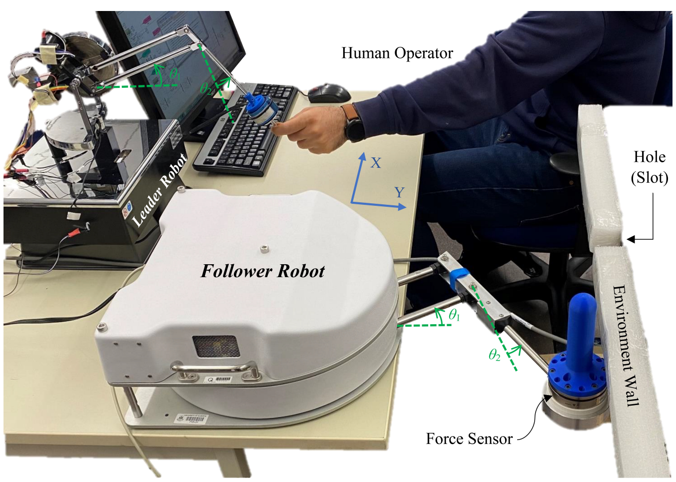

Fig. 6. Telerobotic experimental system: Phantom Premium robot (top-left) is the leader and Quanser robot (down-right) is as the follower, for performing a peg-in-hole task.

based on (12a) and (12b) to make the teleoperation system robust against this time delay such that we set σ_1=0.85, and considering b_{m_i}=2.4 $N.m$ and b_{s_i}=10 $N.m$, N_i and a_i are obtained as 1.30 and 0.83. The trajectory tracking performance of this leader-follower system in the joint space is shown in Fig. 7 before and after having physical interaction with the environment during the free motion and the insertion in the hole. As can be seen, the follower robot could track the leader's trajectory for each joint with less than 0.03 rad error that occurred during the interaction with the environment before insertion of the peg into the hole at t=10.75 sec.

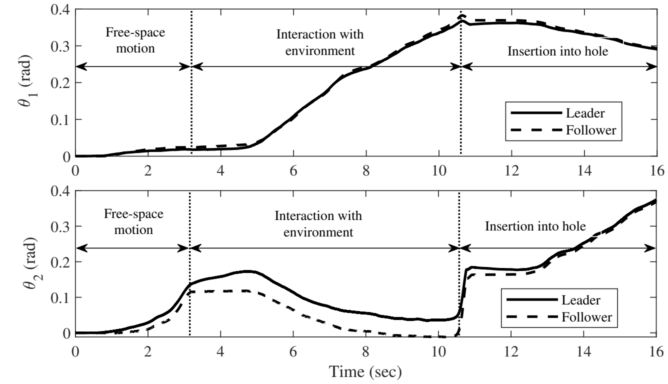

Fig. 7. Joint positions of the leader and follower robots using the proposed controller with adjusted gains and the maximum communication delay of 200 ms.

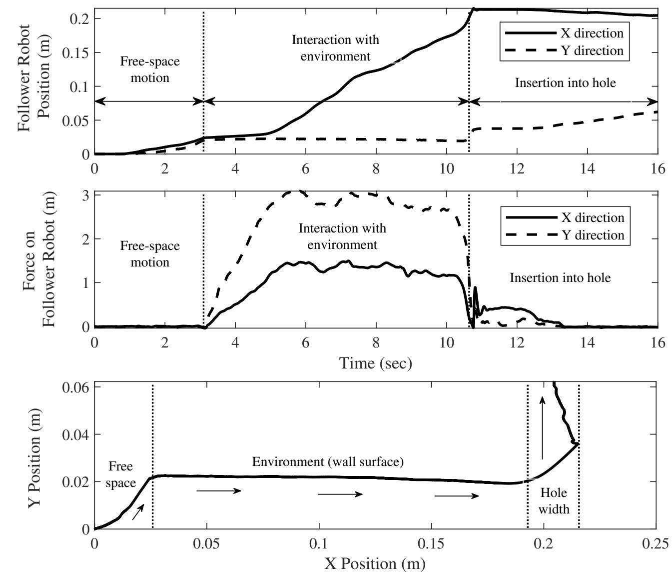

Fig. 8. X, Y and 2D trajectories of the follower robot and the corresponding environment forces exerted on it during the peg-in-hole task.

The X and Y trajectories and forces of the follower's end-effector with respect to the time and its motion in the 2D space are illustrated in Fig. 8. As seen, the end-effector is moved toward the environment surface placed at Y=0.021 m, and then the operator applies a palpation force and slides along the X direction to reach out the hole (slot) placed between X=0.195 m and X=0.215 m. This insertion into the hole is occurred at t=10.75 sec, when a sudden shift in Y direction is observed. After this moment, the follower's end-effector is moved mostly along Y axis (through the slot) and the external environment force decreased considerably to zero, as shown in Fig. 8.

Regarding the obtained results in this experimental study, the presented nonlinear bilateral control method was capable of facilitating a perfect position synchronization between leader and follower robots in free-space motions. Furthermore, a suitable teleoperation performance is obtained with bounded tracking error between robots during the physical interaction of the follower with the environment (in the presence of external forces). By appropriate adjustment of the controller's gains, the multi-DOF telerobotic system was made robust against high levels of communication delay.

VIII. Conclusion

A new nonlinear bilateral delay-robust controller was developed for the synchronization of multi-DOF telerobotic systems. The leader and follower robots were subjected to bounded actuation and time-varying delays in their signal communication. The proposed controller attenuated the compromise between the tracking performance and robustness against large time-varying delays due to its special design, resulted in facilitating both simultaneously. A limitation on the amplitude of a nonlinear function in the control law was relaxed compared to similar previous control designs. The proposed control strategy was assessed through simulation studies and experiments in free-space motions and physical interactions, having multi-DOF robots (such as Phantom Premium and Quanser) and a real-time control system. Appropriate tracking performance and robustness features were achieved due to the suitable adjustment of the controller gains. It is worth mentioning that the packet loss in communication channels and low sampling rates for implementation of the bilateral controller can occur as practical challenges, which will be taken into account in our future studies.

References

[1] M. Tavakoli, R. V. Patel, and M. Moallem, "A force reflective master-slave system for minimally invasive surgery," in *IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2003, pp. 3077–3082.

[2] M. Sharifi, H. Salarieh, S. Behzadipour, and M. Tavakoli, "Beating-heart robotic surgery using bilateral impedance control: Theory and experiments," *Biomed. Signal Process. and Control*, vol. 45, pp. 256 – 266, 2018.

[3] M. V. Jakuba, C. R. German, A. D. Bowen, L. L. Whitcomb, K. Hand, A. Branch, S. Chien, and C. McFarland, "Teleoperation and robotics under ice: Implications for planetary exploration," in *IEEE Aerosp. Conf.*, 2018, pp. 1–14.

[4] A. Zakerimanesh, F. Hashemzadeh, A. Torabi, and M. Tavakoli, "A cooperative paradigm for task-space control of multilateral nonlinear teleoperation with bounded inputs and time-varying delays," *Mechatronics*, vol. 62, p. 102255, 2019.

[5] S. N. Housley, K. Fitzgerald, and A. J. Butler, "Telerehabilitation robotics: Overview of approaches and clinical outcomes," in *Rehabil. Robot.* Elsevier, 2018, pp. 333–346.

[6] T. Imaida, Y. Yokokohji, T. Doi, M. Oda, and T. Yoshikawa, "Ground-space bilateral teleoperation of ets-vii robot arm by direct bilateral coupling under 7-s time delay condition," *IEEE Trans. Robot. Automat.*, vol. 20, no. 3, pp. 499–511, 2004.

[7] K. Gu, J. Chen, and V. L. Kharitonov, *Stability of time-delay systems*. Springer Science & Business Media, 2003.

[8] N. Chopra, M. W. Spong, and R. Lozano, "Synchronization of bilateral teleoperators with time delay," *Automatica*, vol. 44, no. 8, pp. 2142–2148, 2008.

[9] P. Arcara and C. Melchiorri, "Control schemes for teleoperation with time delay: A comparative study," *Robot. and Auton. Syst.*, vol. 38, no. 1, pp. 49–64, 2002.

[10] A. Aziminejad, M. Tavakoli, R. Patel, and M. Moallem, "Stability and performance in delayed bilateral teleoperation: Theory and experiments," *Control Eng. Pract.*, vol. 16, no. 11, pp. 1329–1343, 2008.

[11] M. Sharifi, "Impedance control of non-linear multi-dof teleoperation systems with time delay: absolute stability," *IET Control Theory & Appl.*, vol. 12, pp. 1722–1729, 2018.

[12] H. Gao, T. Chen, and J. Lam, "A new delay system approach to network-based control," *Automatica*, vol. 44, no. 1, pp. 39–52, 2008.

[13] C. C. Hua and X. P. Liu, "Delay-dependent stability criteria of teleoperation systems with asymmetric time-varying delays," *IEEE Trans. Robot.*, vol. 26, no. 5, pp. 925–932, 2010.

[14] D. H. Zhai and Y. Xia, "Adaptive finite-time control for nonlinear teleoperation systems with asymmetric time-varying delays," *Int. J. Robust Nonlinear Control*, vol. 26, no. 12, pp. 2586–2607, 2016.

[15] H. Yang, L. Liu, and Y. Wang, "Observer-based sliding mode control for bilateral teleoperation with time-varying delays," *Control Eng. Pract.*, vol. 91, p. 104097, 2019.

[16] A. Zakerimanesh, F. Hashemzadeh, A. Torabi, and M. Tavakoli, "Controlled synchronization of nonlinear teleoperation in task-space with time-varying delays," *International Journal of Control, Automation and Systems*, vol. 17, no. 8, pp. 1875–1883, 2019.

[17] A. Zakerimanesh, F. Hashemzadeh, and M. Tavakoli, "Task-space synchronisation of nonlinear teleoperation with time-varying delays and actuator saturation," *International Journal of Control*, vol. 93, no. 6, pp. 1328–1344, 2020.

[18] M. V. Kothare, P. J. Campo, M. Morari, and C. N. Nett, "A unified framework for the study of anti-windup designs," *Automatica*, vol. 30, no. 12, pp. 1869–1883, 1994.

[19] F. Hashemzadeh, I. Hassanzadeh, and M. Tavakoli, "Teleoperation in the presence of varying time delays and sandwich linearity in actuators," *Automatica*, vol. 49, no. 9, pp. 2813–2821, 2013.

[20] D. H. Zhai and Y. Xia, "Finite-time control of teleoperation systems with input saturation and varying time delays," *IEEE Trans. Syst. Man Cybern.*, vol. 47, no. 7, pp. 1522–1534, 2016.

[21] Y. Yang, C. Ge, H. Wang, X. Li, and C. Hua, "Adaptive neural network based prescribed performance control for teleoperation system under input saturation," *J. Franklin Inst.*, vol. 352, no. 5, pp. 1850–1866, 2015.

[22] D. H. Zhai and Y. Xia, "Robust saturation-based control of bilateral teleoperation without velocity measurements," *International Journal of Robust and Nonlinear Control*, vol. 25, no. 15, pp. 2582–2607, 2015.

[23] S. Ganjefar, S. Rezaei, and F. Hashemzadeh, "Position and force tracking in nonlinear teleoperation systems with sandwich linearity in actuators and time-varying delay," *Mechanical Systems and Signal Processing*, vol. 86, pp. 308–324, 2017.

[24] M. W. Spong, S. Hutchinson, M. Vidyasagar *et al.*, *Robot modeling and control*, 2006.

[25] R. Kelly, V. S. Davila, and J. A. L. Perez, *Control of robot manipulators in joint space*. Springer Science & Business Media, 2006.

[26] H. K. Khalil and J. W. Grizzle, *Nonlinear systems*. Prentice hall Upper Saddle River, NJ, 2002, vol. 3.

[27] Y. C. Liu and N. Chopra, "Control of semi-autonomous teleoperation system with time delays," *Automatica*, vol. 49, no. 6, pp. 1553–1565, 2013.

[28] M. C. Çavuşoğlu, D. Feygin, and F. Tendick, "A critical study of the mechanical and electrical properties of the phantom haptic interface and improvements for high performance control," *Presence*, vol. 11, no. 6, pp. 555–568, 2002.

[29] M. Dyck and M. Tavakoli, "Measuring the dynamic impedance of the human arm without a force sensor," in *IEEE 13th Int. Conf. Rehabil. Robot.*, 2013, pp. 1–8.