Passivity-Based Bilateral Tele-Driving System With Parametric Uncertainty and Communication Delays

Yimeng Dong and Nikhil Chopra

***Abstract*—In this letter, a new bilateral tele-driving control design is proposed to enable a human driver to tele-drive a car-like mobile robot with haptic feedback. In the presence of communication delays and dynamic parametric uncertainties, a passivity-based adaptive control algorithm is designed to achieve scaled coordination between a local and a remote robot. The efficacy of the proposed control scheme is verified through numerical simulations.**

***Index Terms*—Human-in-the-loop control, control over communications.**

I. Introduction

Bilateral teleoperation system can greatly extend the human capability to conduct a remote operation through communication networks. There are various applications of such system like handling hazardous materials [1], space exploration [2], and telesurgery [3]. Fig. 1 shows the structure of a typical bilateral teleoperation system. The state information of two coupling robotic manipulators, termed the local and remote robot, is exchanged through a communication network. By manipulating the local robot, the human operator can control the remote robot to complete a task in a remote environment with haptic feedback.

One major difference between a tele-driving system and a traditional bilateral teleoperation system such as Fig. 1 is the kinematic dissimilarity between the local and remote robot. A sketch for the proposed bilateral tele-driving system is shown in Fig. 2. In this system, a car-like remote robot is driven by a human driver using a two degree-of-freedom (DOF) local robot (joystick) through a communication network. This two DOF system can be analogously considered as a steering and gas pedal input.

Manuscript received July 31, 2018; revised October 6, 2018; accepted October 24, 2018. Date of publication November 8, 2018; date of current version November 19, 2018. This work was supported in part by the National Science Foundation under Grant ECCS1711554, and in part by the Naval Air Warfare Center Aircraft Division, Pax River, MD, USA, under Contract N00421132M022. Recommended by Senior Editor Z.-P. Jiang. *(Corresponding author: Yimeng Dong.)*

The authors are with the Department of Mechanical Engineering, University of Maryland, College Park, MD 20740 USA (e-mail: ymdong@umd.edu; nchopra@umd.edu).

Digital Object Identifier 10.1109/LCSYS.2018.2879952

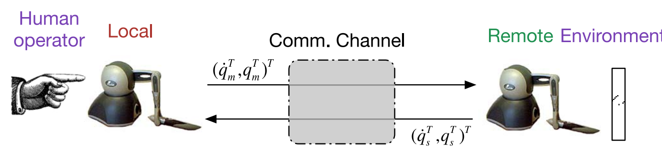

Fig. 1. An example of bilateral teleoperation system structure.

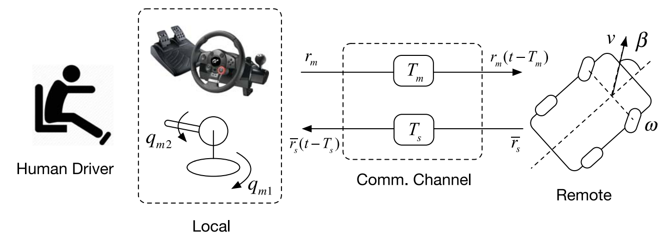

Fig. 2. The sketch for tele-driving scheme: q_{m1}, q_{m2} are two joint variables of the local joystick, β is the steering angle, ω is the angular velocity of the front wheel, v is the linear velocity of the front wheel, T_m, T_s are constant communication delays and $r_m, \bar{r}_s$ are the transmitted data defined later in Section IV.

Considering previous work in control of bilateral tele-driving systems, the notion of feedback r-passivity was proposed and utilized in [4] and [5] to study the bilateral tele-driving scheme for a two-wheeled mobile robot. An impedance control framework was proposed for bilateral teleoperation of a car-like rover in [6]. In [7], a wave-variable method was applied on a kinematic model called extended virtual-mass model for the car-like mobile robot teleoperation. In the previously described algorithms, one DOF of the local device was used to control the remote car's linear velocity. In [6] and [7], the haptic feedback on the environmental force was achieved for obstacle avoidance by defining a virtual environmental force based on the relative distance and speeds between rover and obstacle. To better emulate normal car driving, in this letter we utilize an additional DOF of the local robot as a gas pedal for controlling the remote car's acceleration, and to generate haptic feedback when the remote car is in hard contact with an obstacle in the environment.

In this letter, a tele-driving scheme with a new control mode is proposed, where (q_{m1}, β)-coordination and $(q_{m2}, \dot{\omega})$-coordination (see Fig. 2) is achieved. Here $(.,.)$ implies that these signals track each other asymptotically, and this is made precise in Section IV. Specifically, (q_{m1}, β)-coordination and $(q_{m2}, \dot{\omega})$-coordination imply that the local robot's link variables q_{m1}, q_{m2} are used to control the steering angle β and the angular acceleration $\dot{\omega}$, respectively. In the proposed setup, the $(q_{m2}, \dot{\omega})$-coordination is equivalent to a $(q_{m2}, \dot{v})$-coordination as $v = r_F\omega$, where r_F is the radius of the front wheel.

It should be noted that many existing passivity-based methods for BTOS synchronization, for example [8]–[10] cannot be directly utilized for $(q_{m2}, \dot{\omega})$-coordination, as the pair $(q_{m2}, \dot{\omega})$ implies position-acceleration coordination. However, the aforementioned algorithms can only achieve coordination between the variables with the same physical unit (such as position-position coordination and velocity-velocity coordination). This is due to the fact that these algorithms relied on feedback passivation, where the dynamics of system were shaped using feedback so that the system dynamics were passive with respect to an appropriate output. Coordination of these outputs then guaranteed coordination of desired state variables [9].

In this letter, the proposed scheme for the $(q_{m2}, \dot{\omega})$-coordination is inspired by the control algorithm for the (q, v)-coordination in [4], where a new variable $r = \dot{q} + \lambda q$ is defined and transmitted to coordinate with v. In this letter, to achieve $(q_{m2}, \dot{\omega})$-coordination, a new variable $r_{m2} = \dot{q}_{m2} + \lambda_1 q_{m2} + \lambda_2 \int_0^t q_{m2}(s)ds$, $\lambda_1, \lambda_2 > 0$ is defined and transmitted to coordinate with ω. Then $(q_{m2}, \dot{\omega})$-coordination can be approximately achieved by coupling r_{m2} with ω when the magnitude of $\dot{q}_{m2}$ and $\ddot{q}_{m2}$ are relatively small.

On the other hand, the (q_{m1}, β)-coordination requires position-position coordination. A PD-based control was applied in [4], but its controller gain is time delay dependent as shown in equation (11) in [4]. In this letter, a control scheme similar to the state synchronization scheme in [9, Sec. 4.3.2] is proposed for the (q_{m1}, β)-coordination and the (r_{m2}, ω)-coordination, thereby avoiding delay dependent control gains.

Additionally, an adaptive control approach is utilized to address the uncertainties in the system dynamics. Furthermore, the synchronization algorithms discussed in [8]–[10] were developed under passivity assumptions on the human operator, which not always be the case in practice as discussed in [11]. In the proposed work, inspired by the scheme in [12], the passivity assumption is replaced with a boundedness condition on the human and environment input. The proposed control framework is different from [12] in two main respects: **(i)** The formulation is different. The scheme in [12] achieved the position tracking while the velocities are driven to zero and it cannot be applied here to achieve the new control mode for tele-driving. **(ii)** The system is different. Reference [12] studied a traditional teleoperation system, while a tele-driving system is considered here.

The contributions of this letter can be summarized as follows: a passivity-based adaptive bilateral tele-driving control scheme is proposed in the presence of communication delays and dynamic parametric uncertainties.

(i) Different from previous works [4]–[7], the proposed scheme can achieve a new control mode for tele-driving that is the position-acceleration $(q_{m2}, \dot{\omega})$ coordination.

(ii) Inspired by the formulation in [12], the proposed algorithm avoids the typically assumed passivity assumption on the human and the environment. It should be noted that the control algorithms in [8]–[10] can be analogously modified to make them more broadly applicable.

The rest of this letter is organized as follows. In Section II, the notations used throughout this letter are introduced. In Section III, the dynamics of the bilateral tele-driving system are presented. In Section IV, the details of the proposed tele-driving control algorithm are provided. The simulation results are discussed in Section V.

II. Notations

The following notations are adopted throughout this letter. Symbols $\mathbb{R}^n$, $\mathbb{R}^{n\times m}$, $\mathbb{R}_0^+$ and $\mathbb{R}^+$ denote n-dimensional real-valued vectors, n by m matrices with real-valued elements, sets of nonnegative real numbers, and sets of positive real numbers, respectively. For a matrix A, $\lambda_m(A)$ and $\lambda_M(A)$ denote the minimum and maximum eigenvalues of matrix A, A^T denotes its transpose, and if A is invertible then A^{-1} denotes its inverse. *diag* denotes the diagonal matrix. For a vector x, $|x|$ denotes the Euclidean norm of vector x. For any function $f : \mathbb{R}_0^+ \to \mathbb{R}^n$, the $\mathcal{L}_\infty$-norm is defined as $\|f\|_\infty = sup_{t\geq 0}|f(t)|$, and $\mathcal{L}_2$-norm is defined as $\|f\|_2 = (\int_0^\infty |f(t)|^2 dt)^{1/2}$. The $\mathcal{L}_\infty$ and $\mathcal{L}_2$ spaces are defined as the set $\{f : \|f\|_\infty < \infty\}$ and $\{f : \|f\|_2 < \infty\}$, respectively.

III. Preliminaries: System Dynamics

In this section, the dynamics of the proposed bilateral tele-driving system are described.

Following [13], the dynamics of a n-link robotic manipulator can be given as

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau \quad (1)$$

where $q \in \mathbb{R}^n$ represents the generalized coordinates, $M(q)$ is the inertial matrix, $C(q, \dot{q})$ is the centrifugal and Coriolis matrix, $g(q)$ is the gravitational torque and τ is the generalized force acting on the system. Due to the Lagrangian dynamics structure, (1) has the following properties [13] which are utilized later in this letter:

(P1) Under an appropriate definition of $C(q, \dot{q})$, the matrix $\dot{M}(q) - 2C(q, \dot{q})$ is skew symmetric.

(P2) The Lagrangian dynamics are linearly parametrizable in the sense that

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = Y(q, \dot{q}, \ddot{q})\phi \quad (2)$$

where $Y(q, \dot{q}, \ddot{q}) \in \mathbb{R}^{n\times p}$ is called regressor which is a matrix of known functions of generalized coordinates and their derivatives, ϕ is called parameters vector which is a constant p-dimensional vector of the inertia parameters (such as mass, moment of inertia, etc.).

In the proposed tele-driving scheme in Fig. 2, the dynamics for the local manipulator are given as

$$M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + g_m(q_m) = \tau_m + f_h \quad (3)$$

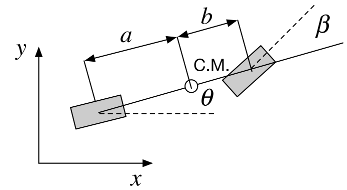

Fig. 3. The single track model of the car-like robot: β is the steering angle, θ is the angel between the world reference frame and the longitudinal axis of the robot, a, b are the distance from center of mass to each wheel.

where $q_m = [q_{m1}, q_{m2}]^T \in \mathbb{R}^2$ represents the angular positions of the local robot, M_m is the inertial matrix, C_m is the centrifugal and Coriolis matrix, g_m is the gravitational torque, τ_m is the local robot control input and f_h is the human input.

The dynamics of the remote car-like mobile robot are approximated by a single-track model shown in Fig. 3. Following [14], the dynamics are given as

$$M_s(q_s)\dot{\eta} + C_s(q_s, \dot{q}_s)\eta = \tau_s - f_e \tag{4}$$

where $\eta = [\dot{\beta}, \omega]^T \in \mathbb{R}^2$, $q_s = [\beta, \dot{\beta}]^T \in \mathbb{R}^2$, M_s is the inertial matrix, C_s is the centrifugal and Coriolis matrix, τ_s is the remote robot control input and f_e is the environment input.

To simplify the car-like robot model in [14], the following assumptions are made in this letter:

- The robot moves on a horizontal plane without slip.
- Each wheel is modeled as a rigid wheel and the tire mechanics are not considered.
- Friction is neglected in the model.

Following [14], the mathematical expression for each matrix of (4) is given as

$$M_s = \begin{bmatrix} J_{F,v} & r_F J_{F,v}\sin\beta/l \\ r_F J_{F,v}\sin\beta/l & m_{22} \end{bmatrix},$$
$$C_s = \begin{bmatrix} 0 & r_F J_{F,v}\cos\beta\dot{\beta}/l \\ 0 & c_{22} \end{bmatrix} \tag{5}$$

where

$$\begin{aligned} m_{22} &= r_F^2 J_B \sin^2\beta/l^2 + J_{F,h} + r_F^2[m_F + \cos^2\beta(m_R \\ &\quad + J_{R,h}/r_R^2)] + [(a^2 + l^2 + b(a+l)\cos 2\beta)m_B \\ &\quad + 2\sin^2\beta(J_{F,v} + J_{R,v})]/l^2 \\ c_{22} &= \sin 2\beta[(J_B + J_{R,v} + J_{F,v})r_R^2 - (J_{R,h} + m_R r_R^2)l^2 \\ &\quad - (a+l)bm_B r_R^2] r_F^2 \dot{\beta}/2l^2 r_R^2 \end{aligned}$$

In the above equations, besides the notations introduced in Fig. 3, $J_B, J_{R,v}, J_{R,h}, J_{F,v}, J_{F,h}$ are the moments of inertia of body, and the moments of inertia of rear wheel and front wheel along vertical and horizontal wheel axis, respectively; r_F, r_R are the radius of front and rear wheel, respectively; $l := a + b$ is the distance between front and rear wheel; m_B, m_F, m_R are the mass of body, front wheel and rear wheel, respectively.

Given the structure of M_s, C_s in (5) and the fact that the local joystick can be modeled as a manipulator with two revolute joints as (3), it can be verified that the properties **(P1)** and **(P2)** of Lagrangian dynamics also hold for the dynamics of the local and remote robot.

IV. Bilateral Tele-Driving Control Scheme

The proposed adaptive coordination control framework is detailed in this section. An adaptive control law is first used to render the local and remote robot dynamics passive with respect to the new defined outputs. Then a passive coordination control is applied to achieve the desired coordination between the local and remote robot.

As shown in Fig. 2, define the two coordination signals r_m and $\bar{r}_s$ as

$$r_m = \begin{bmatrix} r_{m1} \\ r_{m2} \end{bmatrix} = \begin{bmatrix} \dot{q}_{m1} + \lambda q_{m1} \\ \dot{q}_{m2} + \lambda_1 q_{m2} + \lambda_2 \int_0^t q_{m2}(s)ds \end{bmatrix} \tag{6}$$
$$\bar{r}_s = \begin{bmatrix} \bar{r}_{s1} \\ \bar{r}_{s2} \end{bmatrix} = K r_s = K\begin{bmatrix} \dot{\beta} + \lambda\beta \\ \omega \end{bmatrix} \tag{7}$$

where β is the steering angle, ω is the angular velocity of the front wheel as shown in Fig. 2, and $\lambda, \lambda_1, \lambda_2 > 0$ are constant coefficients. It is natural to consider a scaling factor between r_m and r_s due to the kinematic dissimilarity between the local and remote robot. Hence, a constant diagonal positive definite scaling factor matrix K is considered here. Consequently, in the ideal no delay case, the coordination control would guarantee that Kr_s tracks r_m, where $K = diag([k_1, k_2]), k_1, k_2 > 0$.

Assume there exists constant time delays T_m and T_s between the local and remote robot in the network as shown in Fig. 2. Then, the coordination error signals can be defined as

$$e_{rm} = r_m - \bar{r}_s(t - T_s), \quad e_{rs} = \bar{r}_s - r_m(t - T_m) \tag{8}$$

Definition 1: In this letter, the coordination is said to be achieved by the proposed tele-driving system if

$$\begin{aligned} \lim_{t\to\infty}(q_{m1}(t - T_m) - k_1\beta) &= \lim_{t\to\infty}(q_{m1} - k_1\beta(t - T_s)) = 0 \\ \lim_{t\to\infty}(\dot{q}_{m1}(t - T_m) - k_1\dot{\beta}) &= \lim_{t\to\infty}(\dot{q}_{m1} - k_1\dot{\beta}(t - T_s)) = 0 \\ \lim_{t\to\infty}(r_{m2}(t - T_m) - k_2\omega) &= \lim_{t\to\infty}(r_{m2} - k_2\omega(t - T_s)) = 0 \end{aligned} \tag{9}$$

Assuming that the dynamics of the local and remote robots are uncertain, their control inputs τ_m and τ_s are then chosen as

$$\begin{aligned} \tau_m &= u_m - \hat{M}_m(\begin{bmatrix} \lambda\dot{q}_{m1} \\ \lambda_1\dot{q}_{m2} + \lambda_2 q_{m2} \end{bmatrix} - \dot{\bar{r}}_s(t - T_s)) \\ &\quad - \hat{C}_m(\begin{bmatrix} \lambda q_{m1} \\ \lambda_1 q_{m2} + \lambda_2\int_0^t q_{m2}(s)ds \end{bmatrix} - \bar{r}_s(t - T_s)) + \hat{g}_m \end{aligned} \tag{10}$$

$$\begin{aligned} \tau_s &= u_s - \hat{M}_s(\begin{bmatrix} \lambda\dot{\beta}, \\ 0 \end{bmatrix} - K^{-1}\dot{r}_m(t - T_m)) \\ &\quad - \hat{C}_s(\begin{bmatrix} \lambda\beta \\ 0 \end{bmatrix} - K^{-1}r_m(t - T_m)) \end{aligned} \tag{11}$$

where $\hat{M}_i$, $\hat{C}_i$ $(i = m, s)$ and $\hat{g}_m$ are the estimates of the model matrices, and u_m, u_s are the coordination control inputs to be designed.

Using property **(P2)**, the above control inputs can be rewritten as

$$\begin{aligned} \tau_m &= u_m + Y_m(q_m, \dot{q}_m, \bar{r}_s(t - T_s), \dot{\bar{r}}_s(t - T_s))\hat{\phi}_m \\ &= u_m + Y_m\phi_m + Y_m\tilde{\phi}_m, \end{aligned} \tag{12}$$

$$\tau_s = u_s + Y_s(\beta, \dot{\beta}, r_m(t-T_m), \dot{r}_m(t-T_m))\hat{\phi}_s = u_s + Y_s\phi_s + Y_s\tilde{\phi}_s \quad (13)$$

where $\hat{\phi}_m, \hat{\phi}_s$ are the time-varying estimates of the robots model parameters given by ϕ_m, ϕ_s respectively and $\tilde{\phi}_m := \hat{\phi}_m - \phi_m, \tilde{\phi}_s := \hat{\phi}_s - \phi_s$ are the parameters estimation errors.

Then substituting (12) and (13) into (3) and (4) gives

$$M_m\dot{e}_{rm} + C_m e_{rm} = u_m + Y_m\tilde{\phi}_m + f_h \quad (14)$$

$$\bar{M}_s\dot{e}_{rs} + \bar{C}_s e_{rs} = u_s + Y_s\tilde{\phi}_s - f_e \quad (15)$$

where $\bar{M}_s = M_s K^{-1}, \bar{C}_s = C_s K^{-1}$.

The update laws for the uncertain parameters estimates are given as

$$\dot{\hat{\phi}}_m = -\Gamma_m^{-1} Y_m^T e_{rm}, \quad \dot{\hat{\phi}}_s = -\Gamma_s^{-1} Y_s^T e_{rs} \quad (16)$$

where Γ_m and Γ_s are constant positive definite matrices.

We next establish passivity properties of the local and remote systems, in the absence of external inputs f_h and f_e.

Lemma 1: Consider $f_h = 0$ in (14), system (14) is passive with (u_m, e_{rm}) as the input-output pair with respect to the storage function $S_m = \frac{1}{2}e_{rm}^T M_m e_{rm} + \frac{1}{2}\tilde{\phi}_m^T \Gamma_m \tilde{\phi}_m$.

Proof: Using the property **(P1)**, the derivative of S_m along the trajectory of (14) (16) is computed as

$$\dot{S}_m = e_{rm}^T(-C_m e_{rm} + u_m + Y_m\tilde{\phi}_m) + \frac{1}{2}e_{rm}^T\dot{M}_m e_{rm} - \tilde{\phi}_m^T Y_m^T e_{rm} = e_{rm}^T u_m$$

Following the definition of passivity from [9], the system (14) is passive with (u_m, e_{rm}) as the input-output pair with respect to the storage function S_m. ■

Similarly, when $f_e = 0$, system (15) is passive with (u_s, e_{rs}) as the input-output pair with respect to the storage function $S_s = \frac{1}{2}e_{rs}^T\bar{M}_s e_{rs} + \frac{1}{2}\tilde{\phi}_s^T\Gamma_s\tilde{\phi}_s$.

Utilizing the aforementioned passivity properties, the coordination control inputs u_m and u_s are designed as

$$u_m = -K_u e_{rm}, \quad u_s = -K_u e_{rs} \quad (17)$$

where K_u is a constant diagonal positive definite control gain matrix.

Theorem 1: Consider the tele-driving system described by (3)-(17). Then,

(a) if $f_h, f_e \in \mathcal{L}_2 \cap \mathcal{L}_\infty$, then the signal $e_{rm}, e_{rs}, \tilde{\phi}_m, \tilde{\phi}_s$ are bounded and the state coordination is achieved for the tele-driving system in the sense of *Definition 1*;

(b) if the tele-driven car is in hard contact with the environment assuming steady state $(\dot{q}_m, \ddot{q}_m, \dot{\beta}, \ddot{\beta}, \omega, \dot{\omega} \to 0)$, then the driver can perceive the environment contact force as $f_h \to f_e + K_u\begin{bmatrix} 0 \\ \lambda_2\int_{t-T_m}^t q_{m2}(s)ds\end{bmatrix} - Y_m\tilde{\phi}_m - Y_s\tilde{\phi}_s + (M_m + \bar{M}_s)\begin{bmatrix} 0 \\ \lambda_2 q_{m2}\end{bmatrix}$.

Proof:

(a) A positive semidefinite storage functional V is considered for the tele-driving system as

$$V = \frac{1}{2}e_{rm}^T M_m e_{rm} + \frac{1}{2}\tilde{\phi}_m^T\Gamma_m\tilde{\phi}_m + \frac{1}{2}e_{rs}^T\bar{M}_s e_{rs} + \frac{1}{2}\tilde{\phi}_s^T\Gamma_s\tilde{\phi}_s \quad (18)$$

With the help of the property **(P1)**, the derivative of V along the trajectories of system (14), (15) and (16) can be computed as

$$\begin{aligned}\dot{V} &= e_{rm}^T(-C_m e_{rm} + u_m + Y_m\tilde{\phi}_m + f_h) + \frac{1}{2}e_{rm}^T\dot{M}_m e_{rm} \\ &\quad - \tilde{\phi}_m^T Y_m^T e_{rm} + e_{rs}^T(-\bar{C}_s e_{rs} + u_s + Y_s\tilde{\phi}_s - f_e) \\ &\quad + \frac{1}{2}e_{rs}\dot{\bar{M}}_s e_{rs} - \tilde{\phi}_s^T Y_s^T e_{rs} \\ &= e_{rm}^T u_m + e_{rs}^T u_s + e_{rm}^T f_h - e_{rs}^T f_e\end{aligned}$$

Substituting u_m, u_s in (17) into above equation gives

$$\begin{aligned}\dot{V} &= -e_{rm}^T K_u e_{rm} - e_{rs}^T K_u e_{rs} + e_{rm}^T f_h - e_{rs}^T f_e \\ &\le -\lambda_K|e_{rm}|^2 - \lambda_K|e_{rs}|^2 + |e_{rm}||f_h| + |e_{rs}||f_e|\end{aligned}$$

where $\lambda_K = \lambda_m(K_u) > 0$.

Using Young's inequality, we have

$$|e_{rm}||f_h| \le \frac{|f_h|^2}{2\lambda_K} + \frac{\lambda_K|e_{rm}|^2}{2}, \quad |e_{rs}||f_e| \le \frac{|f_e|^2}{2\lambda_K} + \frac{\lambda_K|e_{rs}|^2}{2},$$

Thus,

$$\dot{V} \le -\frac{\lambda_K}{2}|e_{rm}|^2 - \frac{\lambda_K}{2}|e_{rs}|^2 + \frac{1}{2\lambda_K}|f_h|^2 + \frac{1}{2\lambda_K}|f_e|^2$$

Integrating $\dot{V}$ from 0 to t gives

$$\begin{aligned}&V(t) + \frac{\lambda_K}{2}\int_0^t |e_{rm}|^2 ds + \frac{\lambda_K}{2}\int_0^t |e_{rs}|^2 ds \\ &\le \frac{1}{2\lambda_K}\int_0^t |f_h|^2 ds + \frac{1}{2\lambda_K}\int_0^t |f_e|^2 ds + V(0)\end{aligned}$$

Letting $t \to \infty$, and using the assumption that $f_h, f_e \in \mathcal{L}_2$, we have $e_{rm}, e_{rs} \in \mathcal{L}_2$ and V is bounded. Hence, from (18) the signals $e_{rm}, e_{rs}, \tilde{\phi}_m, \tilde{\phi}_s$ are bounded.

From (14) and (15), and using the assumption that $f_h, f_e \in \mathcal{L}_\infty$, $\dot{e}_{rm}, \dot{e}_{rs}$ are also bounded. Using Barbalat's Lemma [15] gives $\lim_{t\to\infty} e_{rm}(t) = \lim_{t\to\infty} e_{rs}(t) = 0$, which means

$$\lim_{t\to\infty}(\bar{r}_{s1}(t-T_s) - r_{m1}) = \lim_{t\to\infty}(r_{m1}(t-T_m) - \bar{r}_{s1}) = 0 \quad (19)$$

$$\lim_{t\to\infty}(\bar{r}_{s2}(t-T_s) - r_{m2}) = \lim_{t\to\infty}(r_{m2}(t-T_m) - \bar{r}_{s2}) = 0 \quad (20)$$

Using (7), (20) is equivalent to

$$\lim_{t\to\infty}(r_{m2}(t-T_m) - k_2\omega) = \lim_{t\to\infty}(r_{m2} - k_2\omega(t-T_s)) = 0 \quad (21)$$

The signal $\bar{r}_{s1}(t-T_s) - r_{m1}$ can be rewritten as

$$\bar{r}_{s1}(t-T_s) - r_{m1} = \dot{e}_\beta + \lambda e_\beta \quad (22)$$

where $e_\beta := k_1\beta(t-T_s) - q_{m1}$.

As (22) is an exponentially stable linear system with input $\bar{r}_{s1}(t-T_s) - r_{m1}$ and state e_β, by (19) and [9, Th. A.4], if $\bar{r}_{s1}(t-T_s) - r_{m1} \in \mathcal{L}_2$ and asymptotically converges to zero, then

$$\lim_{t\to\infty} e_\beta = \lim_{t\to\infty}\dot{e}_\beta = 0 \quad (23)$$

Similarly, if $r_{m1}(t-T_m) - \bar{r}_{s1}$ is rewritten as

$$r_{m1}(t-T_m) - \bar{r}_{s1} = \dot{e}_{q_{m1}} + \lambda e_{q_{m1}} \quad (24)$$

where $e_{q_{m1}} := q_{m1}(t-T_m) - k_1\beta$, it can be shown that

$$\lim_{t\to\infty} e_{q_{m1}} = \lim_{t\to\infty}\dot{e}_{q_{m1}} = 0 \quad (25)$$

Hence, the proof of the part (a) is complete.

(b) Now assuming $\dot{q}_m, \ddot{q}_m, \dot{\beta}, \ddot{\beta}, \omega, \dot{\omega} \to 0$, then we have $C_m(q_m, \dot{q}_m) \to 0$ as $\dot{q}_m \to 0$ and $\dot{e}_{rm} \to [0, \lambda_2 q_{m2}]^T$ in (14), thus

$$\begin{aligned} f_h &\to -u_m - Y_m\tilde{\phi}_m + M_m\begin{bmatrix} 0 \\ \lambda_2 q_{m2} \end{bmatrix} \qquad (26) \\ &= K_u\begin{bmatrix} -k_1\lambda\beta(t-T_s) + \lambda q_{m1} \\ \lambda_1 q_{m2} + \lambda_2 \int_0^t q_{m2}(s)ds \end{bmatrix} - Y_m\tilde{\phi}_m \\ &\quad + M_m\begin{bmatrix} 0 \\ \lambda_2 q_{m2} \end{bmatrix} \end{aligned}$$

In (15), $\dot{\bar{r}}_s \to 0$ and $\bar{C}_s(q_s, \dot{q}_s) \to 0$ due to the structure of C_s in (5). Hence,

$$\begin{aligned} f_e &\to u_s + Y_s\tilde{\phi}_s - \bar{M}_s\begin{bmatrix} 0 \\ \lambda_2 q_{m2}(t-T_m) \end{bmatrix} \\ &= K_u\begin{bmatrix} -k_1\lambda\beta + \lambda q_{m1}(t-T_m) \\ \lambda_1 q_{m2}(t-T_m) + \lambda_2 \int_0^{t-T_m} q_{m2}(s)ds \end{bmatrix} + Y_s\tilde{\phi}_s \\ &\quad - \bar{M}_s\begin{bmatrix} 0 \\ \lambda_2 q_{m2}(t-T_m) \end{bmatrix} \qquad (27) \end{aligned}$$

For a signal $x(t)$ and $i = m, s$, $x(t) \to x(t-T_i)$ as $\lim_{t\to\infty} \dot{x}(t) = 0$, thus when $\dot{q}_m, \ddot{q}_m, \dot{\beta}, \ddot{\beta}, \omega, \dot{\omega} \to 0$, $f_h \to$

$$\begin{aligned} &K_u\begin{bmatrix} -k_1\lambda\beta(t) + \lambda q_{m1} \\ \lambda_1 q_{m2} + \lambda_2 \int_0^t q_{m2}(s)ds \end{bmatrix} - Y_m\tilde{\phi}_m + M_m\begin{bmatrix} 0 \\ \lambda_2 q_{m2} \end{bmatrix} \\ &= f_e + K_u\begin{bmatrix} 0 \\ \lambda_2 \int_{t-T_m}^t q_{m2}(s)ds \end{bmatrix} - Y_m\tilde{\phi}_m - Y_s\tilde{\phi}_s \\ &\quad + (M_m + \bar{M}_s)\begin{bmatrix} 0 \\ \lambda_2 q_{m2} \end{bmatrix} \qquad (28) \end{aligned}$$

which completes the proof of the part (b). ■

Remark 1: Compared with the state synchronization control scheme for the traditional bilateral teleoperation system in [8]–[10], the proposed scheme formulates a passive system as (14) and (15) with the new defined outputs e_{rm} and e_{rs} as (8). Additionally, the passivity assumption on the human and environment in [8]–[10] can be avoided as has been accomplished in part (a) of *Theorem 1*. It should be noted that the bilateral teleoperation algorithms and results developed in [8]–[10] can be made less conservative by avoiding the passivity assumption on the human operator and environment, as has been done in the proposed work.

Remark 2: From part (b) of *Theorem 1*, the force reflection from the environment can be perceived by the human driver when the car is in hard contact with the environment and in steady state. For example, when the car's tire hits an obstacle like the curb on the road, the environment force information can be provided to the local driver by (28), and hence the driver's situational awareness can be improved. In (28), the first and second row reflect the force feedback on the steering direction and the forward driving direction, respectively. Observing the final expression of (28), the effect of time delay on the force reflection is represented by the second term, the effect of model parameters estimation errors on the force reflection is represented by the third and fourth term, and the coupling between two directions is represented by the last term.

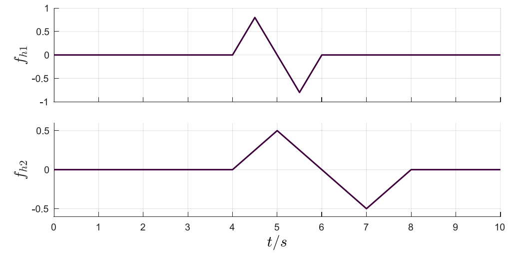

Fig. 4. The human input $f_h = [f_{h1}, f_{h2}]$ in simulation.

V. Simulations

The proposed tele-driving control scheme was simulated in Simulink. To simplify the presentation, it was assumed that the local robot dynamics are known and the remote robot dynamics are uncertain. The local robot consisted of two decoupled individual single link planar manipulators, and hence the dynamics can be written as

$$M_m\ddot{q}_m = \tau_m + f_h, \quad q_m \in \mathbb{R}^2 \qquad (29)$$

where $M_m = diag([J_{m1}, J_{m2}])$.

For the remote robot, following (4) (5), it can be shown that

$$\begin{aligned} &-M_s(\begin{bmatrix} \lambda\dot{\beta}, \\ 0 \end{bmatrix} - K^{-1}\dot{r}_m(t-T_m)) - C_s(\begin{bmatrix} \lambda\beta \\ 0 \end{bmatrix} \\ &-K^{-1}r_m(t-T_m)) = Y_s\phi_s, \qquad (30) \end{aligned}$$

and it can be verified that the parameters vector $\phi_s \in \mathbb{R}^7$ and the regressor matrix $Y_s(\beta, \dot{\beta}, r_m(t-T_m), \dot{r}_m(t-T_m)) \in \mathbb{R}^{2\times 7}$.

The parameters in the control scheme were taken as following: $\lambda = 3, \lambda_1 = 2, \lambda_2 = 2, k_1 = 2, k_2 = 3$ and the control gain matrix $K_u = diag([4, 10])$. The simulation parameters were taken as following: simulation time $t = 12s$, time step $0.005s$, time delay $T_s = 0.1s, T_m = 0.15s$, the initial condition for system states $(q_{m1}, q_{m2}, \dot{q}_{m1}, \dot{q}_{m2}, \beta, \dot{\beta}, \omega)$ is $(-0.1, 0, 0, 0, 0.2, 0, 0)$, the nominal value of ϕ_s in (30) was chosen as $(1, 0.2, 4.04, 8.12, 1.24, 5.04, -0.5808)$. The human input on the local robot $f_h = [f_{h1}, f_{h2}]$ is shown in the Fig. 4. In (10) and (11), the derivative of $\bar{r}_s(t-T_s)$ and $r_m(t-T_m)$ were computed and used, and in the simulation, a low-pass filter was applied to $\bar{r}_s(t-T_s)$ and $r_m(t-T_m)$ before the derivatives were computed to get rid of the noise issue in the derivative computation. In the simulation, the nominal value of ϕ_s was unknown, and a perturbation was added on the nominal value of ϕ_s to generate an initial condition of $\hat{\phi}_s$ in the adaptation law (16) for the remote robot. To show the coordination performance of the proposed control scheme, a zoomed-in plot of the simulation results for $t \in [3s, 9s]$ is shown in Fig. 5. In each subplot, the coordination error between the two signals is denoted by the dashed line, where the error signal was generated by first time-shifting one of the two state trajectories based on the network delay and then subtracting two signals. As can be observed from the plots, good coordination performance under the human input was achieved in the presence of communication delays and uncertain dynamics. In the fourth subplot of Fig. 5, it is also verified the new control mode (position-acceleration $(q_{m2}, \dot{\omega})$ coordination) was achieved by the proposed control scheme.

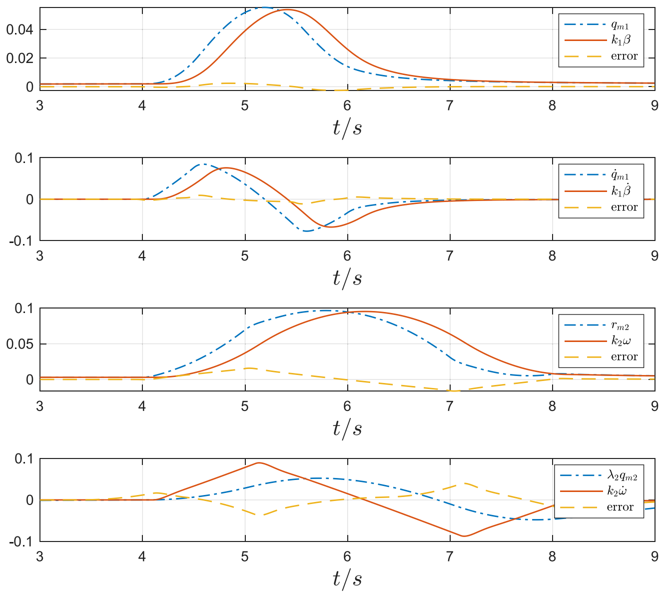

Fig. 5. The coordination performance for $t \in [3s, 9s]$.

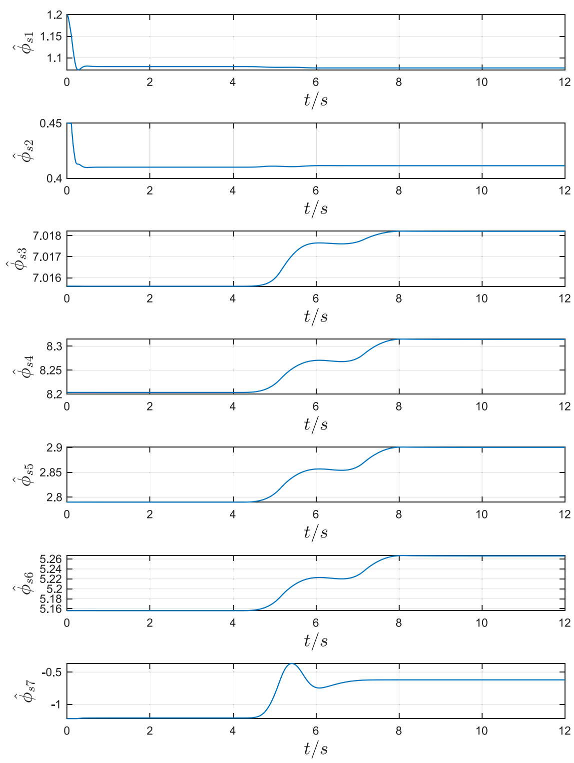

Fig. 6. The trajectories of the parameters vector $\hat{\phi}_S$ for the remote robot.

Fig. 6 displays the trajectories of the parameter vector $\hat{\phi}_s$, and as demonstrated in part (a) of *Theorem 1*, the parameter estimation errors are bounded.

VI. Summary

In this letter, a passivity-based adaptive coordination control scheme is proposed for a new bilateral tele-driving system in the presence of communication delays and dynamic parametric uncertainties. The proposed tele-driving scheme can achieve a new control mode and haptic feedback to better emulate normal car driving compared with the existing schemes in the mobile robot teleoperation such as [4]–[7]. Unlike the synchronization control scheme in [8]–[10] for traditional bilateral teleoperation system, the passivity assumption on the human and environment is replaced with a boundedness condition. Through simulations, it is verified that a good coordination performance under the human input can be achieved with the proposed control framework.

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