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Nonlinear Model-Mediated Teleoperation for Surgical Applications under Time Variant Communication Delay

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Abstract: Robot-assisted surgery is often carried out through master-slave teleoperation. With the progress of robotic technology and development of novel surgical procedures, new challenges emerge like need for haptic feedback and time delay in teleoperation communication channels, etc. Most existing bilateral teleoperation works in literature emphasize more on maintaining system stability at the cost of degraded transparency, with time variant communication delay further worsening the situation. In this paper, we present a nonlinear Hunt-Crossley model-mediated bilateral teleoperation scheme with targeted applications in robot-assisted surgery. The system stability is guaranteed by decoupling the master and slave sub-systems and the system transparency is enhanced with online environment parameter estimation using recursive least squares (RLS) technique. Simulation studies have been carried out for both constant and time varying interaction environments. The proposed teleoperation scheme is shown to be efficient in providing stable and transparent performance and robust against communication delay and environment parameter variance.

Keywords: Bilateral teleoperation, Hunt-Crossley model, communication delay, robotic surgery.

1. INTRODUCTION

Robotic technologies have found their way to the surgery area since long time, but only until recent two decades robot-assisted surgery has seen its revolutionary developments and wide applications in medical practice. Minimally invasive surgery (MIS), as the most recent revolution in manual surgery, has shown numerous advantages over traditional open surgery, such as less trauma, less pain, shortened hospital stay and reduced cost, etc. Robotic minimally invasive surgery (RMIS) has further sharpened the edge of MIS by providing more stable and more dexterous manipulation, new task-specific tools, reduced physical and mental burden for the surgeon and correspondingly improved safety and comfortability for the patient. Encouraged by the success of RMIS, with the representative example of the world-wide use of da Vinci[®] robotic surgery system, robot-assisted surgery has stepped towards single-port laparoscopy (SPL) and natural orifice transluminal endoscopic surgery (NOTES) attempting to further enhance the cosmetic benefits of minimally invasive surgery while minimizing the potential morbidity associated with multiple incisions.

In most robot-assisted surgeries, the surgeon is isolated from the operating site inside the patient body and his operation is executed by the robotic instrument(s) via a unilateral teleoperation manner, i.e. the robotic instrument purely executes the surgeon's commands without sending back any haptic information about the working environment and the operation consequence. The lack of

feedback information has been observed and evaluated by researchers in surgical robotics (Okamura (2009)), and numerous bilateral teleoperation approaches have been proposed in literature to address this problem (Dobbelsteen et al. (2012), Kuchenbecker et al. (2010), McMahhan et al. (2011)). For most of the developed bilateral telesurgery schemes, the communication delay has been ignored. It can be explained that in most RMIS the surgeon stays close to the patient and robotic surgery system such that delay in communication is negligible. However, for new robotic intervention methods as SPL and NOTES, all robotic instruments (including actuator, sensors, etc.) need to be miniaturized. The existence of communication cables/wires appear cumbersome and limit the maneuverability of operating tools, and in some cases even not feasible, e.g. in swallowable capsule robots for monitoring or diagnosis purposes. The most promising solution is to replace the wired communication by wireless communication, as has been implemented in miniaturized modular robots for endocavitary surgery (Tortora et al. (2014)). But as a downside, the wireless communication inevitably introduces considerable communication delay.

Different from general time-delayed system control which mainly considers system stability, the time-delayed bilateral teleoperation design should consider both *stability* and *transparency*, which are usually two conflicting objectives (Hokayem and Spong (2006)). Without time delay, it has been shown that perfect stability and transparency can be achieved (Lawrence (1993), Hashtrudi-Zaad and Salcudean (2001)). But with the presence of time delay, Anderson

and Spong showed that even small time delay in communication can destroy system stability based on scattering theory, and they proposed an active control method to alleviate this problem with constant time delay (Anderson and Spong (1989)). A conceptually similar wave variable formulation has been proposed by Niemeyer and Slotine in (Niemeyer and Slotine (1991)), which can guarantee system passivity against theoretically arbitrary time delay. Later on, many passivity-based schemes such as wave-variable transformation (Franken et al. (2011), Kawashima et al. (2009), Bate et al. (2011), Li and Kawashima (2014), Guo et al. (2015)) and time domain passivity approach (Hannaford and Ryu (2002), Ryu et al. (1994), Ryu (2007)), have been proposed in literature. However, all these passivity-based methods guarantee system stability at the cost of sacrificing transparency to certain extent.

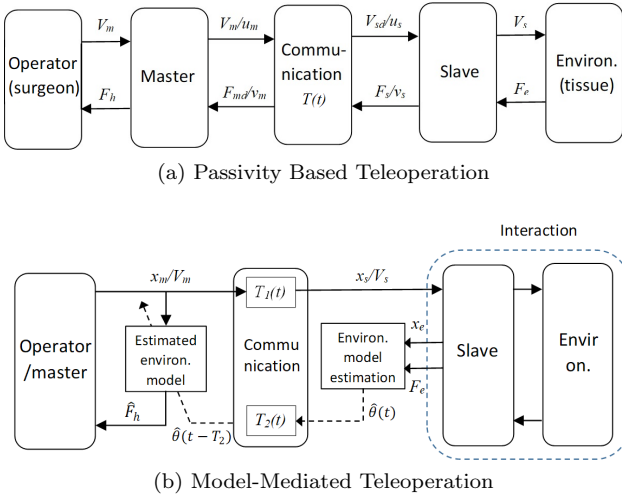


Fig. 1. General diagrams of bilateral teleoperation systems

In (Hannaford (1989)), an online environment estimation scheme was proposed for teleoperation system with time delay. In this approach, non-delayed force feedback signal is provided to the operator directly using an online estimated environment model and hence presents an alternative type of information exchange between the master and slave. This kind of teleoperation design concept is referred to as model-based, model predictive/prediction based, or model-mediated teleoperation (MMT). Different from the conventional teleoperation architecture wherein the force signals or wave variables are transmitted in the backward channel (Fig. 1a), MMT systems send the estimated model parameters to the master instead (Fig. 1b). The main interesting properties of MMT system lie in that: first of all, the overall system is separated into two decoupled sub-system (master loop and slave loop) and therefore system stability can be studied separately on the master side and slave side, which is obviously much more convenient than conventional passivity based teleoperation system design; secondly, given a fast and accurate environment modelling method, the haptic force rendered to the human operator well mimics the real interaction on the slave side and presents trivial time delay if the environment properties change slowly or in a predictable way, and therefore high operation transparency can be achieved; also, MMT reduces transmission data complexity thanks to its increased level of abstraction and therefore allows relatively lower system update rate (more robustness to time delay) since

environment model parameters are transmitted instead of high bandwidth force signals (Mitra and Niemeyer (2008)). Many MMT methods have been proposed in literature including Smith-predictor based methods (Love and Book (2004), Tzafestas and Velanas (2013), Yoon et al. (2004), Smith and Hashtrudi-Zaad (2005), Sheng and Spong (2004), Willaert et al. (2012), Smisek et al. (2015), Li et al. (2016)).

For our targeted surgical application where miniaturized robotic instruments are controlled wirelessly, MMT presents a very promising solution due to its robustness to relatively large and time variant communication delay and intrinsic advantage to tolerate limited bandwidth communication constrained by wireless transmission protocols, such as ZigBee (Guo et al. (2014)). The major challenge for this MMT implementation is to choose a suitable environment model for human living tissue, which should be both accurate in interaction description and efficient for real-time calculation. Recent result in (Guo et al. (2017)) employs linear Kelvin-Boltzmann model for teleoperated robotic palpation. In (Achhammer et al. (2010)), a physically more accurate nonlinear Hunt-Crossley model has been used for bilateral teleoperation, but the time delay in communication is not considered. Non-parametric neural network (NN) modelling has also been used in (Smith and Hashtrudi-Zaad (2005b), Li et al. (2016b)), but such kind of NN-based methods suffer problems such as the reciprocal relationships among the computational complexity, estimation accuracy and convergence rate and therefore is not suitable for surgical applications. In this paper, as to the authors' knowledge, we propose the first nonlinear Hunt-Crossley model based bilateral teleoperation scheme taking into account time variant communication delay. Efficient parameter estimation can be realized using log linearization technique and recursive least squares (RSL) method for real-time calculation purpose. The system stability is investigated by analysing the dissipation energy and the system transparency is evaluated through simulation studies under different conditions. The system analyses and simulation studies are carried out considering real surgical practice and requirements towards solving the targeted surgical application.

2. ROBOT-TISSUE INTERACTION MODEL SELECTION

A realistic and accurate robot-tissue interaction model is essential to achieve a model-mediated bilateral teleoperation which can provide the surgeon with high operation transparency (true operation feeling).

2.1 Model Selection

Several models have been developed in literature to describe the viscoelastic behaviour of soft tissues (Kobayashi et al. (2012)). The most complete study on viscoelastic tissue model is addressed in (Fung (1993)). Although accurate for off-line analysis, this model is complex and difficult to be used for applications with real time requirement. One simple and intuitive way to describe the interaction between robotic tools and soft tissues is to analytically build the force-displacement (or stress-strain) relationship. Analytical models are usually presented as combinations

of springs and dampers (Fung (1993)), and are defined by the following components: the exerted force by the tissue, $F_e(t)$, when a strain is applied; the indentation (or penetration), $x(t)$, computed as the amount of displacement of the tissue from the rest position; the velocity of the deformation $\dot{x}(t)$; the elastic and damping coefficients K and b respectively.

Following this modelling method, several linear models have been developed:

- Elastic model:

$$F_e(t) = Kx(t). \quad (1)$$

- Maxwell model:

$$F_e(t) = b\dot{x}(t) - \alpha\dot{F}_e(t) \quad (2)$$

where $\dot{F}_e(t)$ is the derivative of the exerted force and $\alpha = \frac{b}{K}$.

- Kelvin-Voigt model:

$$F_e(t) = Kx(t) + b\dot{x}(t). \quad (3)$$

- Kelvin-Boltzmann:

$$F_e(t) = Kx(t) + \eta\dot{x}(t) - \gamma\dot{F}_e(t) \quad (4)$$

where $K = \frac{k_1 k_2}{k_1 + k_2}$, $\eta = \frac{b k_2}{k_1 + k_2}$, $\gamma = \frac{b}{k_1 + k_2}$ with k_1 , k_2 and b denoting the elastic and damping coefficients respectively.

The above linear models may apply to contacts with objects of linear and homogeneous properties, but physical limitations can be observed when contact with soft tissue is considered. Combining the loading and unloading behaviours, a hysteresis loop should be observed as the force-displacement relationship for soft tissue during the contact. However, linear models predict a discontinuous sudden jump force during the switch between these two modes. Also, by analysing the power flow during contact as calculated by $P(t) = F_e(t)\dot{x}(t)$, it is found that during the unloading phase linear viscoelastic models indicate the existence of a positive energy meaning that power still flows from the end-effector to the tissue after separation, which is physically impossible (Diolati et al. (2005)).

To address the aforementioned problems with linear viscoelastic models, a nonlinear Hunt-Crossley (HC) model has been proposed by replacing the spring/damper linear combination in (3) with a nonlinear one (Hunt and Crossley (1975)):

$$F(t) = \begin{cases} Kx^\beta(t) + \lambda x^\beta \dot{x}(t), & x \geq 0 \\ 0 & x < 0 \end{cases} \quad (5)$$

where β is a positive scalar and normally ranges from 1.1 to 1.3 for soft tissues. The main characteristic of HC model is the effect of deformation depth on the damping term. With the HC model, the contact force evolves from zero reaching the maximum value during the loading phase and returns to zero during the unloading phase. Accordingly, a physically correct power flow can be obtained. Therefore, in this work this more realistic model will be employed to serve as the estimator of robot-tissue (environment) interaction.

2.2 Real-Time Model Parameter Identification

Since the Hunt-Crossley model is nonlinear, it is not straightforward to online identify the model parameters.

The model equation (5) can be further written for positive deformation x as:

$$F_e(t) = Kx^\beta(t)(1 + \frac{\lambda}{K}\dot{x}(t)) = Kx^\beta(t)(1 + \delta\dot{x}(t)) \quad (6)$$

where $\delta = \frac{\lambda}{K}$.

Then by taking natural logarithm of both sides, it has

$$\ln(F_e(t)) = \ln(K) + \beta\ln(x(t)) + \ln(1 + \delta\dot{x}(t)). \quad (7)$$

For soft tissue, generally the elastic coefficient K is much higher than the damping coefficient resulting in a small δ . Also, in robotic surgery, the surgeon moves the instruments slowly which leads to low interaction velocity $\dot{x}(t)$ especially considering that the unit of velocity is in m/s . Therefore, in most cases, it has

$$\ln(1 + \delta\dot{x}(t)) \simeq \delta\dot{x}(t) \quad (8)$$

so that

$$\begin{aligned} \ln(F_e(t)) &\simeq \ln(K) + \beta\ln(x(t)) + \delta\dot{x}(t) \\ &= [1, \ln(x(t)), \dot{x}(t)] \cdot [\ln(K), \beta, \delta]^T \end{aligned} \quad (9)$$

which presents the following form

$$y = \Phi^T \theta \quad (10)$$

with $y = \ln(F_e(t))$ measurable with the force sensor equipped on the robotic tool, $\Phi^T = [1 \ \ln(x(t)) \ \dot{x}(t)]$ measurable from the robot actuator encoders, and $\theta = [\ln(K) \ \beta \ \delta]^T$ being the model parameters to be online identified and fed to the estimated interaction model on the master side.

Therefore, various signal processing algorithms could be applied to solve this parameter estimation problem, such as exponentially weighted recursive least squares (RLS), self-perturbing RLS, etc. In this work, a standard recursive least squares method is used because of its easy implementation and efficient calculation in real time. The performance of this online estimation is shown in Section 4.

Remark 1: Regarding the persistent excitation condition for parameter estimation convergence, it is known that for identification of n parameters at least $n/2$ non-zero frequencies are required (Ioannou and Fidan (2006)). Considering the small number of Hunt-Crossley model parameters to be estimated and the complex movement trajectory involved in surgical operations, the persistent excitation condition could be easily met for estimation of constant or slowly time varying Hunt-Crossley model parameters.

Remark 2: Sudden and significant changes in model parameters and the contact model itself may cause sudden and significant changes in the estimated model parameters, which consequently leads to a sudden change to the force rendered to the human operator. This phenomenon is called model-jump effect (Willaert et al. (2012b)). Although such kind of parameter change rarely happens in surgical operations, smooth transition and safety switch/threshold should be considered in the parameter updating.

3. NONLINEAR MODEL-MEDIATED TELEOPERATION DESIGN

Based on the selected nonlinear robot-environment interaction model, a Hunt-Crossley model-mediated teleoper-

ation under communication delay can be synthesized as in Fig. 2.

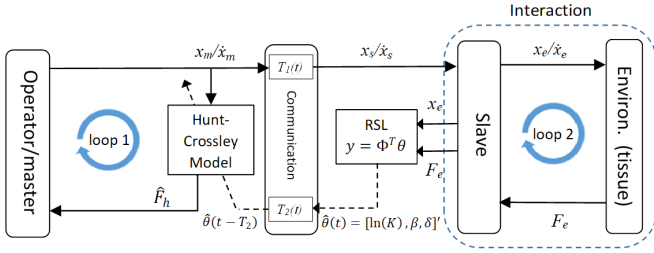


Fig. 2. Nonlinear model-mediated teleoperation with time delay

As seen from the system diagram, the human operator's motion command in position (x_m) or velocity (\dot{x}_m) is sent to the slave robot through the communication channel. Instead of sending back directly the high bandwidth signal of environment force (F_e) or wave variable (v_s), only estimated environment parameters from an online RLS estimator are fed back to the master side. This is particularly interesting for wireless telesurgery applications where wireless communication boards with limited data transmission bandwidth are used. As model parameter information is higher in terms of abstraction level compared to environment force information, it is possible to update them at a lower rate as long as the environment model is not changing fiercely, which is hardly possible during surgical operations.

Moreover, since this teleoperation scheme is not passivity based and does not resort to wave transformation, position movement command can be sent directly to the slave instead of velocity and therefore avoids the common problem of position drift due to velocity integration as in most conventional passivity-based bilateral teleoperation approaches.

3.1 System Stability

As shown in Fig. 2, the overall teleoperation system constitutes two decoupled sub-systems (sub-loops) on the master and slave side, denoted by "loop 1" and "loop 2" respectively. There exists no force/motion feedback from the slave to the master but only estimated contact model parameter information. Therefore, instead of considering the overall system closed over the communication channel, system stability can be analysed separately based on the two sub-systems. As long as the stability of the two sub-loops can be guaranteed, the overall teleoperation system is ensured to be stable.

The master sub-system (loop 1) can be considered as a cascade connection of human operator, master device and the Hunt-Crossley model approximator. The human operator and master device are considered to possess passive mechanical impedances (Hashtrudi-Zaad and Salcudean (2001)). So if the Hunt-Crossley model approximator with updated model parameters is passive, the master sub-system is passive as well.

The passivity of the Hunt-Crossley interaction model can be evaluated by investigating its dissipation energy using equation (6) as

$$\begin{aligned} \int_0^t F_e \cdot \dot{x} dt &= \int_0^t K x^\beta (1 + \delta \dot{x}) \dot{x} dt \\ &= \int_0^t (K x^\beta \dot{x} + \delta x^\beta \dot{x}^2) dt \\ &= \int_0^t K x^\beta \dot{x} dt + \int_0^t \delta x^\beta \dot{x}^2 dt \\ &= \int_{x(0)}^{x(t)} K x^\beta dx + \int_0^t \delta x^\beta \dot{x}^2 dt \\ &= K(x^\beta(t) - x^\beta(0)) + \int_0^t \delta x^\beta \dot{x}^2 dt \quad (11) \end{aligned}$$

It is noted that above analysis stands only when the robot is in contact with the soft tissue, i.e. $x > 0$, otherwise the robot is in free motion and correspondingly works in another mode. Hence if $\delta > 0$ it has

$$\int_0^t \delta x^\beta \dot{x}^2 dt \geq a \int_0^t \delta \dot{x}^2 dt \geq 0 \quad (12)$$

where a represents the minimum value of $x^\beta(t)$ over whole time duration $[0, t]$, which is clearly non-negative.

By substituting inequality (12) into (11), it has

$$\int_0^t F_e \cdot \dot{x} dt \geq K(x^\beta(t) - x^\beta(0)) \geq -Kx^\beta(0) \quad (13)$$

for non-negative K and thus shows that the Hunt-Crossley interaction is passive.

In fact, K , β and $\delta = \frac{\lambda}{K}$ are all positive model parameters with physical meanings in reality, and their positive-ness guarantees the passivity of Hunt-Crossley interaction. Therefore, if the estimated model parameters \hat{K} , $\hat{\beta}$, $\hat{\delta}$ converge to their true values or lower bounded by a positive threshold during updating, the master side Hunt-Crossley model estimator is also passive. In consequence, the master sub-system (loop 1) is stable.

For the slave sub-system (loop 2), no matter the received master command is in motion (position/velocity) or in force, various control methods have been proposed in literature for stable interaction between robot and soft working environment (Moreira et al. (2012), Golovin et al. (2014)). With both master and slave sub-systems stable, the proposed Hunt-Crossley model-mediated teleoperation system is guaranteed to be stable.

3.2 System Transparency

Ideal system transparency is defined as a perfect match between master and slave position and force signals (Yokokohji and Yoshikawa (1994)), or a match between the environment impedance and the perceived impedance by the operator (Lawrence (1993)).

For model-mediated bilateral teleoperation, the system transparency essentially depends on the preciseness of environment description model and efficiency of model parameter identification. The nonlinear Hunt-Crossley model has been proved to be accurate in soft tissue modelling and efficient in model-based force control (Pappalardo et al. (2016)). As commented in *Remark 1*, the model parameters can be identified accurately if the excitation signals are rich enough in frequency. If the environment

model remains constant during operation, the operator can perceive exactly the same environment dynamics as if there exists no communication delay after the convergence time of model parameter estimation plus one backward communication delay (time variant or not). If the environment model parameters are changing at a relatively lower rate compared with the communication delay, the operator can still be rendered with almost ideal transparency of the environment dynamics. The system transparency of our proposed teleoperation scheme is evaluated in different situations as shown in next section.

4. PERFORMANCE EVALUATION BY SIMULATION STUDIES

In this section, simulation studies are carried out to evaluate the performance of the proposed Hunt-Crossley model-mediated bilateral teleoperation scheme under variant time delay, mimicking an robotic telesurgery with wireless communication. For clearer presentation and without loss of generality when extended to multiple degrees of freedom (DOF) (Anderson and Spong (1989)), teleoperation system of one DOF is used in the simulation study. Two different situations are considered: interaction with environment of constant but unknown parameters, and with environment of time variant parameters. As shown in (Guo et al. (2014)), the round trip communication delay for wireless ZigBee transmission is at the scale of few hundreds of milliseconds (ms). In the simulation, for both cases, the time variant communication delays are defined in *ms* as:

$$T_{com}(t) = \begin{cases} T_1(t) = 200 + 55\sin(2\pi t), & \text{forward} \\ T_2(t) = 300 + 35\sin(2\pi t + \pi/2), & \text{backward} \end{cases}$$

Here, sinusoidal functions are used to simulate communication time variance. Theoretically the designed system can work with more complex (even arbitrary) time variances. The system transparency is evaluated by comparing the ratios between position and force signals of master and slave sides as $\frac{F_m}{x_m}$ v.s. $\frac{F_s}{x_s}$ (Yokokohji and Yoshikawa (1994)).

4.1 Constant Environment

In this study, the environment used as ground-truth is described by a constant model:

$$F_e(t) = Kx^\beta(t)(1 + \delta\dot{x}(t)) = 2000x^{1.23}(1 + 0.1\dot{x}) \quad (14)$$

The model parameters are roughly set based on the soft material estimation in (Diolati et al. (2005)). The slave robot is assumed to start from the zero-contact position of the environment surface ($x(0) = 0$). For both the master side approximation model and the slave side RLS estimator, the initial values of unknown environment parameters are approximated as $\hat{K} = 665$, $\hat{\beta} = 1$ and $\hat{\delta} = 0$. And to avoid the violent parameter changes during the transition (convergence) period, the master model will wait for 1 second before starting to receive the updating model parameters from the RLS estimator.

From Fig. 3, it is shown that the three estimated model parameters by RLS converge to their true values quickly, where $\ln(K) = \ln(2000) = 7.6$. Consequently, it is seen in Fig. 4 that the master force follows exactly the same environment force after the 1 second transition period

if the back-trip communication delay is compensated for comparison purpose. In the end, the environment dynamics ($\frac{F_m}{x_m}$) rendered to the human operator on the master side is faithful to the real one except a lead in phase as shown in Fig. 5, which reveals the predictive nature of model-mediated teleoperation approach.

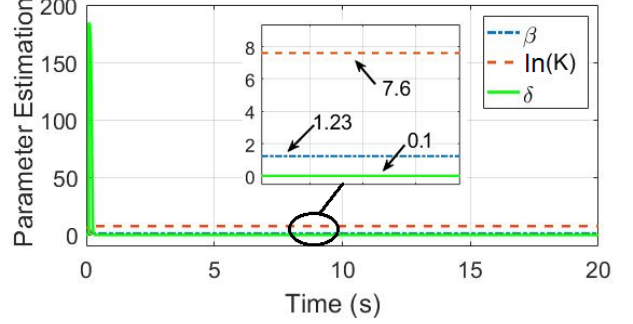


Fig. 3. RLS online estimation of environment parameters

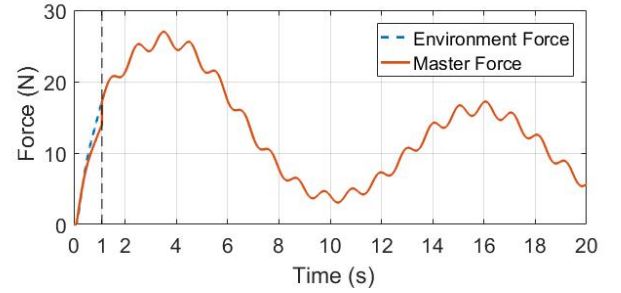


Fig. 4. Master force v.s. delay-compensated environ. force

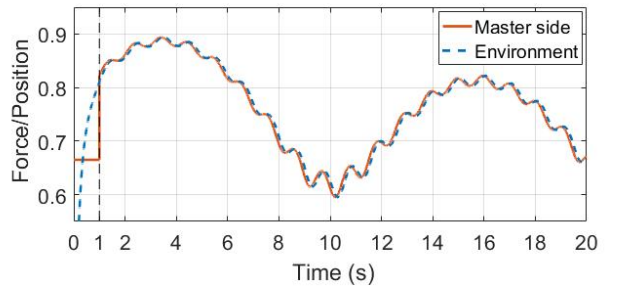


Fig. 5. Environment dynamics on master and slave side

4.2 Time Variant Environment

In this study, the parameters of ground-truth environment is time variant and defined as $\ln(K) = 7.6 + 0.1\sin(\frac{\pi}{4}t)$, $\beta = 1.23 + 0.01\sin(\frac{\pi}{2}t)$, $\delta = 0.1 + 0.01\sin(\frac{\pi}{8}t)$. Note that the value of K varies in the range of $[1808, 2208]$ correspondingly.

Since the environment parameters are time variant, the estimated model parameters do not converge to the true parameters accurately in real time. However, the force rendering and environment dynamics matching still perform well as shown in Fig. 6 and 7. Slight performance degradation are observed as compared to the first simulation

study. This can be explained by the parameter mismatch between master side estimator and slave environment due to non-convergent online parameter estimation, and hence again emphasizes the importance of model accuracy in this kind of model-mediated teleoperation.

The simulation studies verify the efficiency of the proposed bilateral teleoperation scheme in providing stable and transparent performance and robustness against communication delay and environment parameter variance.

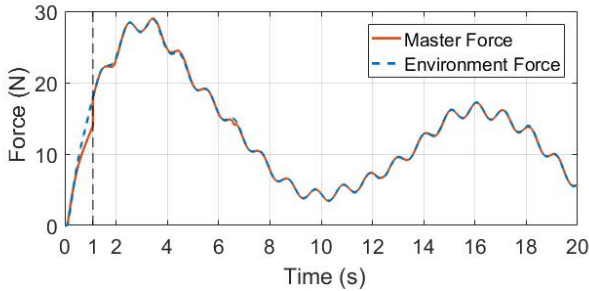


Fig. 6. Master force *v.s.* delay-compensated environ. force

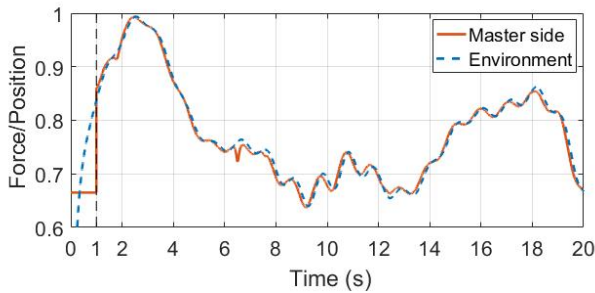


Fig. 7. Environment dynamics on master and slave side

5. CONCLUSION

A nonlinear model based bilateral teleoperation scheme has been developed in the work to address surgical applications where the working environment is soft tissue and the communication contains time variant delays due to the wireless communication protocol used (e.g. ZigBee), package loss, etc. The nonlinear Hunt-Crossley model has been chosen to describe the soft tissue environment which has been proved in literature to be more realistic and accurate than linear viscoelastic models. By resorting to online parameter identification technique, in this work recursive least square (RLS), the environment model parameters are estimated online and transmitted to the master side model which serves as a predictor and renders haptic force feedback to the human operator without delay. The overall system is guaranteed to be stable through passivity analysis. Simulation studies with both constant and varying contact environments show that the proposed teleoperation scheme can provide faithful interaction force to the operator and provide quite accurate matching between perceived and real environment dynamics.

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