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Bilateral Teleoperation of Robotic Systems with Predictive Control

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Abstract— This paper presents a new control approach with prediction to minimize the effects of time delays while ensuring stability and system performance. Two predictors at the slave and master sides are constructed assuming that the time delays in both transmission channels are measurable. Simulation and experimental results are compared with the scheme without prediction to show the effectiveness of this approach. The influence of data dropout to the proposed teleoperation system is studied in the experiment.

I. Introduction

As the name suggests, teleoperation is the remote operation of a robotic device or a system. Teleoperation is the art of controlling a mobile robot or a system over short or long distances through a communication medium in a structured or unstructured environment. The distance may vary from a few meters to thousands of kilometers. The communication medium is usually the internet, especially when the distance is large. The most commonly used areas of teleoperation are in hostile environments, explorations and in museums or exhibitions where the robot acts as a tour guide.

A typical teleoperation system consists of three subsystems: the master side, the slave side and the communication block. The master side usually consists of an operator and a master manipulator. The operator is basically a human being, who sends commands to the slave and oversees the activities on the slave side if required. The operator oversees the activities through visual feedback, force feedback, etc. The commands are sent with the help of a master manipulator. The master manipulator can be a joystick, data glove, some other haptic devices or even a robot. The slave side consists of a slave and an environment in which the slave navigates.

In the literature, a number of control methods have been proposed to maintain the stability and synchronization for a teleoperation system. The passivity approach was one among the first developed strategies to deal with the time delay uncertainties associated with a teleoperated system [1]. They are based on the concepts of power and energy and can be used to handle large uncertainties. In the wave variables approach, the stability of the system is maintained but performance of the system is not so good [2]. The performance of the system was much better when the time delays associated with the system was taken to be fixed. Later on the wave variables approach was extended to varying time delays [3]. Once again the stability was maintained but the performance degradation still remained a major issue. Though the wave variables approach is robust it works well only for passive systems. The major problem with passivity is that it makes the entire system too conservative.

The idea of neural networks for teleoperation was also implemented for the time delay problem in teleoperation [4]. This method provided a better transparency between the master and the slave side but plenty of off-line and on-line learning techniques limited their practical applications. Similarly the sliding mode approach also had some limitations when it came to practical implementation in the presence of varying time delays [5]. Model based systems were introduced to minimize the effects of delays in the system [6]. Model based systems is another possibility for the time delay problem in which the entire teleoperation model is depicted as a dynamic model of the entire process. The design of the model based approach becomes very complicated when the degrees of freedom (DOF) increases. In the literature, predictive control for teleoperation has shown satisfactory results even in the presence of varying time delays [4] [7].

In this paper, the predictive approach in [8] is extended to the case without knowing the human operator model, which reduces the order of the state space form of the master system. The proposed control structure includes two predictors in both master and slave sides. These predictors are applied to simultaneously estimate the master and the slave internal dynamics. The estimated dynamics, instead of transmitted delayed signals, are used in the construction of the controllers. As a consequence, the influence of the delay on the whole system can be minimized and performance can be improved. Both simulation and experimental results are demonstrated for the effectiveness of the proposed approach. The case with data dropout is also demonstrated in the experimental results which further shows the advantage of the proposed scheme.

II. Problem Formulation

The basic working principle [9] of a bilateral teleoperation system is shown in Figure 1. The human operator applies a force f_h to the master manipulator. The master

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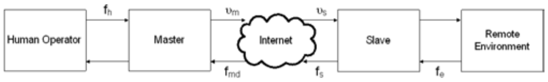

Fig. 1. Standard bilateral teleoperation system

manipulator as a result of the force exerted on it moves with a velocity υ_m. This velocity υ_m is transmitted to the slave manipulator through the internet which is the communication channel. In the remote environment, the slave manipulator will act according to the signal received from the master side. In bilateral teleoperation, the contact force from the remote environment f_e is transmitted back to the master side operator through the master manipulator as f_{md}.

The dynamics of a single degree of freedom (DOF) for a master and slave system are as follows [8] [7]:

$$M_m\dot{\upsilon}_m(t) = u_m(t) + f_h(t) \quad (1)$$

$$M_s\dot{\upsilon}_s(t) = u_s(t) - f_e(t) \quad (2)$$

where M_i are the masses, υ_i are the motor velocities, u_i is the input force and $i = m, s$ where subscripts m and s stands for master and slave respectively. f_h is the force exerted by the human operator and f_e is the force exerted on the slave by its environment. In this paper, the slave side considers the application of wheeled mobile robots, the contact friction force exerted on the slave by its environment is expressed as

$$f_e(t) = \sigma_1\upsilon_s(t) + f_n \arctan\left(\frac{\upsilon_s(t)}{\delta}\right) \quad (3)$$

where $\upsilon_s(t)$ is the wheel's rotational angular speed, σ_1,f_n and δ are constants.

The time delays can be measured as assumed in [7] and [8]. This assumption is very useful in the design of the controllers. The delays from the master to the slave side and vice versa can be estimated by calculating the local current time (t) from where the signal is sent and the delayed signal is received at the other side $(t - T(t))$, where $T(t)$ is denoted as the delay. For instance, consider x_m to be the signal sent from the master to the slave at time (t) through the communication channel. If the signal reaches the slave side after a delay of $T(t)$ then the signal can be expressed as $x_m(t-T(t))$ on the slave side. Hence we can also delay the signals artificially if required. The signal $\hat{x}_m(t-\hat{T}(t))$ is the estimated version of the signal $x_m(t)$ which was delayed artificially. The above mentioned assumptions are very useful because certain signals may not be available at the master and the slave sides at a particular instant. In those scenarios we will have to use only the estimated or delayed version of the signals. In order to use the delayed version of the signals we assume that the measurement of time delays are accurate, $\hat{T}(t) = T(t)$. As we proceed further in this chapter we will know the usefulness of the assumptions made in this section.

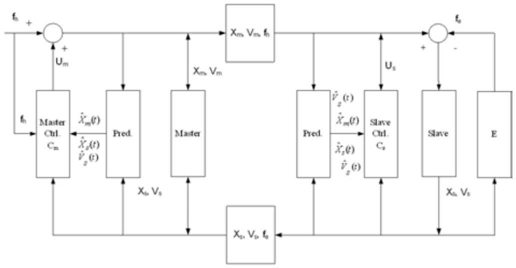

Fig. 2. A bilateral teleoperation system with the predictive control strategy

III. Controller Design

Figure 2 shows the schematic diagram for the proposed predictive control strategy. The human operator dynamics is not taken into account. The environmental model is considered to be non linear because of the friction caused by the rotational motion of the wheeled mobile robot. The objective of this article is to predict at the slave side the undelayed motion of the external contact force $\hat{f}_e(t)$ and at the slave side to predict the undelayed motion of the master $\hat{x}_m(t)$ and $\hat{\upsilon}_m(t)$. The controller on the master side is designed as follows [7],

$$\begin{aligned} u_m(t) &= -\alpha f_h(t) - B_m\upsilon_m(t) - K_m x_m(t) \\ &\quad +\beta\hat{f}_e(t) + \beta\{f_e(t-T(t)) - \hat{f}_e(t-\hat{T}(t))\}, \end{aligned}$$

where B_m, K_m,α and β are design constants. $\hat{T}(t)$ is the estimate of the time delay that can be measured as explained earlier and $\hat{f}_e(t) = \sigma_1\hat{\upsilon}_s(t) + f_n \arctan\left(\frac{\hat{\upsilon}_s(t)}{\delta}\right)$ where $\hat{f}_e(t-\hat{T}(t))$ and $\hat{x}_m(t-\hat{T}(t))$ are the estimated signals which are artificially delayed. $f_e(t-T(t))$, $\upsilon_m(t-T(t))$ and $x_m(t-T(t))$ are the signals f_e, υ_m and x_m respectively that have been sent through the communication channel from one side to another side. The controller on the slave side is designed as follows,

$$\begin{aligned} u_s(t) &= (1-k_f)f_e(t) - B_s\upsilon_s(t) - K_s x_s(t) + B_\omega\hat{\upsilon}_m(t) \\ &\quad +K_\omega\hat{x}_m(t) + B_\omega\{\upsilon_m(t-T(t)) \\ &\quad -\hat{\upsilon}_m(t-\hat{T}(t))\} + K_\omega\{x_m(t-T(t)) \\ &\quad -\hat{x}_m(t-\hat{T}(t))\}, \end{aligned}$$

where B_s, K_s, B_ω and K_ω are design constants. $\hat{x}_m(t)$ and $\hat{\upsilon}_m(t)$ are estimates of the signals $x_m(t)$ and $\upsilon_m(t)$ respectively. $\hat{\upsilon}_m(t-\hat{T}(t))$ and $\hat{x}_m(t-\hat{T}(t))$ are the estimated signals which are artificially delayed. $\upsilon_m(t-T(t))$ and $x_m(t-T(t))$ are the signals υ_m and x_m respectively that have been sent through the communication channel from one side to another side.

A. Predictor Design

For the predictor design, the state space form of the master and the slave controllers are derived as

$$\dot{\mathbf{z}}_m(t) = A_m\mathbf{z}_m(t) + \mathbf{b}_m u_{sm} + \mathbf{b}_{nm} f_{nm}(t) + \mathbf{b}_h f_h(t), \quad (4)$$

where A_m, $\mathbf{b}_m$, $\mathbf{b}_h$ and $\mathbf{b}_{nm}$ are matrices with stable eigenvalues. $y_m(t) = z_{m2}(t) = x_m(t)$.

$$A_m = \begin{bmatrix} 0 & 1 \\ -\frac{K_m}{M_m} & -\frac{B_m}{M_m} \end{bmatrix}, \mathbf{b}_h = \begin{bmatrix} 0 \\ \frac{(1-\alpha)}{M_m} \end{bmatrix},$$
$$\mathbf{b_m} = \begin{bmatrix} \frac{\beta\sigma_0}{M_m} \\ \frac{\beta\sigma_1}{M_m} \end{bmatrix}, \quad \mathbf{b}_{nm} = \begin{bmatrix} 0 \\ \frac{\beta f_n}{M_m} \end{bmatrix},$$

$$u_{sm}(t) = \hat{x}_s(t) + x_s(t - T(t)) - \hat{x}_s(t - \hat{T}(t)),$$
$$f_{nm}(t) = \arctan\left(\frac{\hat{\upsilon}_s(t)}{\delta}\right) + \arctan\left(\frac{\upsilon_s(t - T(t))}{\delta}\right) - \arctan\left(\frac{\hat{\upsilon}_s(t - \hat{T}(t))}{\delta}\right).$$

For the slave side,

$$\dot{\mathbf{z}}_s(t) = A_s\mathbf{z}_s(t) + \mathbf{b}_s u_{ss}(t) + \mathbf{b}_{ns} f_{ns}(t), \qquad (5)$$

where A_s, b_s and b_{ns} are matrices with stable eigenvalues. y_s=$z_{s2}(t)$=$x_s(t)$.

$$A_s = \begin{bmatrix} 0 & -\frac{k_s + k_f\sigma}{M_s} \\ 1 & -\frac{B_s + k_f\sigma_1}{M_s} \end{bmatrix}, \mathbf{b_s} = \begin{bmatrix} \frac{K_\omega}{M_s} \\ \frac{B_\omega}{M_s} \end{bmatrix}; \mathbf{b}_{ns} = \begin{bmatrix} 0 \\ \frac{-k_f f_n}{M_s} \end{bmatrix},$$

$$u_{ss}(t) = \hat{x}_m(t) + x_m(t - T(t)) - \hat{x}_m(t - \hat{T}(t)),$$
$$f_{ns}(t) = \arctan\left(\frac{\upsilon_s(t)}{\delta}\right).$$

Certain signals might not be available at particular instants. In that case we make use of the delayed versions of the signals as we can estimate the delayed versions of the signals. In the above predictor equations (8) and (10), only the delayed version of the transmit signals $u_{sm}(t)$ and $u_{ss}(t)$ are available. To overcome this, we duplicate the predictor equations at both sides.

$$\dot{\hat{\mathbf{z}}}_m(t) = A_m\hat{\mathbf{z}}_m(t) + \mathbf{b}_m u_{sm}(t) + \mathbf{b}_{nm} f_{nm}(t) + \mathbf{b}_h f_h(t)$$
$$\dot{\hat{\mathbf{z}}}_s(t) = A_s\hat{\mathbf{z}}_s(t) + \mathbf{b}_s u_{ss}(t) + \mathbf{b}_{ns}\hat{f}_{ns}(t)$$

where $\hat{f}_{ns}(t) = \arctan\left(\frac{\hat{\upsilon}_s(t)}{\delta}\right)$. Both $f_{nm}(t)$ and $\hat{f}_{ns}(t)$ has the signal $\hat{\upsilon}_s(t)$ which is calculated from $\hat{\upsilon}_s(t) = \dot{\hat{\mathbf{z}}}_{s2}$. The slave side controller $u_s(t)$ also has the signal $\hat{\upsilon}_m(t)$ which can be calculated from $\hat{\upsilon}_m(t) = \dot{\hat{\mathbf{z}}}_{m2}$.

B. Stability Analysis

Stability along with the performance of a system are important factors that cannot be neglected. In this section, emphasis on the error dynamics, convergence of the predictor and close-loop stability based on Lyapunov stability analysis are discussed. The error dynamics for the master and the slave side are as follows

$$\tilde{\mathbf{z}}_i(t) = \hat{\mathbf{z}}_i(t) - \mathbf{z}_i(t).$$

Hence,

$$\dot{\tilde{\mathbf{z}}}_m(t) = A_m\tilde{\mathbf{z}}_m(t) + \mathbf{b}_h\left(f_h(t - T(t)) - f_h(t)\right),$$
$$\dot{\tilde{\mathbf{z}}}_s(t) = A_s\tilde{\mathbf{z}}_s(t) + \mathbf{b}_{ns}\left(\hat{f}_{ns}(t) - f_{ns}(t)\right).$$

For simplicity, we define $d_m(t) = f_h(t - T(t)) - f_h(t)$ and $d_s(t) = \hat{f}_{ns}(t) - f_{ns}(t)$. $|d_m(t)| = |f_h(t - T(t)) - f_h(t)| \leq T^*\rho f$, where T^* is the upper bound of the delay $T(t)$ and ρf is a constant. What it implies is that $d_m(t)\epsilon L_\infty[0, \infty]$ and $d_s(t)\epsilon L_\infty[0, \infty]$,i.e., $|d_s(t)| \leq k_c = const$ as $d_s(t)$ is bounded and is actually an $atan(\cdot)$.

C. Convergence

The stable matrices A_m and A_s are considered for our analysis. For details, it is similar as the analysis in [7] and hence it is omitted here.

Master Side: Consider the matrix A_m, $P\epsilon R^{2\times 2}, P = P^T > 0, \gamma_1 > 0$ satisfying,

$$\begin{pmatrix} A_m^T P + PA_m + I & P\mathbf{b}_h \\ \mathbf{b}_h^T P & -\gamma_1^2 I \end{pmatrix} < 0 \qquad (6)$$

then, $||\tilde{\mathbf{z}}_\mathbf{m}(t)||$ - the estimation error normalization, tends, in finite time, to a function B_{r1} defined as $B_{r1} = (\tilde{\mathbf{z}}_m(t) : ||\tilde{\mathbf{z}}_m(t)|| \leq \gamma_1 T^*\rho f = r)$.

Slave Side: Consider the matrix A_s, $Q\epsilon R^{2\times 2}, Q = Q^T > 0, \gamma_2 > 0$ satisfying,

$$\begin{pmatrix} A_s^T Q + QA_s + I & Q\mathbf{b}_{ns} \\ \mathbf{b}_{ns}^T Q & -\gamma_2^2 I \end{pmatrix} < 0 \qquad (7)$$

then, $||\tilde{\mathbf{z}}_s(t)||$ - the estimation error normalization, tends, in finite time, to a function B_{r2} which was defined earlier as well $B_{r2} = (\tilde{\mathbf{z}}_s(t) : ||\tilde{\mathbf{z}}_s(t)|| \leq \gamma_2 k_c = r)$.

D. Closed Loop Stability:

The master and slave controller with state variables are represented as

$$u_m^r(t) = -\alpha f_h^r(t) - B_m\upsilon_m^r(t) - K_m x_m^r(t) + \beta f_e^r(t).$$
$$u_s^r(t) = (1 - k_f)f_e^r(t) - B_s\upsilon_s^r(t) - K_s x_s^r(t) + B_\omega\upsilon_m^r(t) + K_\omega x_m^r(t).$$

where x_m^r, υ_m^r, x_s^r and υ_m^r are state variables. This is the case without time delay. Then the state space representation of the master and the slave becomes

$$\dot{\mathbf{z}}_m^r(t) = A_m\mathbf{z}_m^r(t) + \mathbf{b}_m\mathbf{z}_{s2}^r(t) + \mathbf{b}_{nm} f_{ns}^r(t) + \mathbf{b}_h f_h(t)$$
$$\dot{\mathbf{z}}_s^r(t) = A_m\mathbf{z}_s^r(t) + \mathbf{b}_s\mathbf{z}_{m2}^r(t) + \mathbf{b}_{ns} f_{ns}^r(t)$$

where $f_{ns}^r(t) = \arctan\left(\frac{\upsilon_s^r(t)}{\delta}\right)$. The tracking error is obtained as

$$\dot{\mathbf{e}}_m(t) = A_m\mathbf{e}_m(t) + \mathbf{b}_m\mathbf{e}_{s2}(t) + \mathbf{b}_m\zeta_{m1}(t) + \mathbf{b}_{nm}\zeta_f(t) + \mathbf{b}_{nm}\zeta_{m2}(t)$$
$$\dot{\mathbf{e}}_s(t) = A_s\mathbf{e}_s(t) + \mathbf{b}_s\mathbf{e}_{m4}(t) + \mathbf{b}_s\zeta_s(t) + \mathbf{b}_{ns}\zeta_f(t)$$

where $\mathbf{e}_i(t) = \mathbf{z}_i(t) - \mathbf{z}_i^r(t)$ and $i = (m, s)$,

$$\begin{aligned}
\zeta_{m1}(t) &= \tilde{\mathbf{z}}_{s2}(t) - \tilde{\mathbf{z}}_{s2}(t - T(t)), \\
\zeta_f(t) &= \arctan\left(\frac{\upsilon_s}{\delta}\right) - \arctan\left(\frac{\upsilon_s^r}{\delta}\right), \\
\zeta_{m2}(t) &= \arctan\left(\frac{\hat{\upsilon}_s(t)}{\delta}\right) - \arctan\left(\frac{\upsilon_s(t)}{\delta}\right) \\
&\quad + \arctan\left(\frac{\upsilon_s(t - T(t))}{\delta}\right) \\
&\quad - \arctan\left(\frac{\hat{\upsilon}_s(t - T(t))}{\delta}\right), \\
\zeta_s(t) &= \tilde{\mathbf{z}}_{m4}(t) - \tilde{\mathbf{z}}_{m4}(t - T(t)).
\end{aligned}$$

In the error equations, there are two uncertain terms in $\zeta_{m2}(t)$ and $\zeta_f(t)$. Assume that $\zeta_{m2}(t)$ and $\zeta_f(t)$ $\epsilon L_\infty[0, \infty]$, $|\zeta_{m2}(t)| \leq 2k_c$ and $|\zeta_f(t)| \leq k_c$. Then the error dynamics can be written as

$$\dot{\mathbf{e}} = A\mathbf{e}(t) + B\zeta(t) \tag{8}$$

$$\begin{aligned}
A &= \begin{bmatrix} A_m & 0 \\ 0 & A_s \end{bmatrix}, \mathbf{e}(\mathbf{t}) = \begin{bmatrix} \mathbf{e}_m(t) \\ \mathbf{e}_s(t) \end{bmatrix}, \\
B &= \begin{bmatrix} \mathbf{b}_m & \mathbf{b}_{nm} & 0 & 0 \\ 0 & 0 & \mathbf{b}_s & \mathbf{b}_{ns} \end{bmatrix}, \zeta(t) = \begin{bmatrix} \zeta_f(t) \\ \zeta_{m1}(t) \\ \zeta_{m2}(t) \\ \zeta_s(t) \end{bmatrix}.
\end{aligned}$$

The matrix A is stable as both A_m and A_s have stable values and $S \epsilon R^{2\times 2}$, $S = S^T > 0, \gamma_3 > 0$, then,

$$\begin{pmatrix} A^T S + SA + I & SB \\ B^T S & -\gamma_3^2 I \end{pmatrix} < 0. \tag{9}$$

If (9) holds for $S = S^T > 0$ and $\gamma_3 > 0$ and where $S \epsilon R^{2\times 2}$ is a positive definite symmetric matrix, then the tracking error normalization of the closed loop tends, in finite time, to the function B_{r3} defined as $B_{r3} = (\tilde{\mathbf{z}}_m(t) : ||\tilde{\mathbf{z}}_m(t)|| \leq \gamma_3 T^* \rho f = r)$ which means that the error is bounded and since A is a stable matrix, (9) is always satisfied.

Remark: The convergence error at the master side B_{r1}, the convergence error at the slave side B_{r2} and the tracking error B_{r3} are all bounded and the associated matrices A_m, A_s and A respectively are always stable.

IV. Simulation Results

The main objective of the simulation is to monitor the tracking performance of the proposed predictive control method for different time delays. The performance of the proposed method can be judged by comparing its results with the results of the desired and the conventional model. In the simulations, the models are tested for different time delays. The master signal x_m, slave signal x_s and the error signals or tracking error (e_{xm} and e_{xs}) of all the three models are plotted and compared. The error signal as the name suggests, is the difference in a particular signal of the system with the predictor or without the predictor to the corresponding signal in the desired model. For instance, the error signal of the

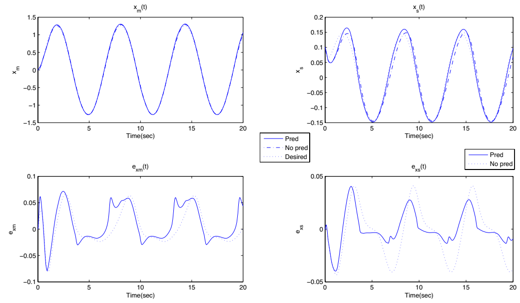

Fig. 3. Comparison of signals when the time delay is $0.2+0.2\sin(t)$ seconds for the whole system. (a) Master side signals; (b) Slave side signals; (c) Error signals at master side; (d) Error signals at slave side.

predictor at the slave side is calculated by finding out the difference in the slave signal of the predictor to the slave signal of the desired model. Ideally the error signal should be close to zero which implies that the system has better tracking which means that the system has better impedance match.

In the simulation, the parameters are selected as $M_m = 1kg.m^2, B_m = 5Nms, K_m = 2Nm, \alpha = 0.5, M_s = 1kg.m^2, B_s = 1.5Nms, K_s = 5Nm, k_f = 5, B_\omega = 2Nms, K_\omega = 5, f_n = 0.3, \beta = 1, \sigma_1 = 0.4$ and $\delta = 0.1$. The force exerted $f_h = 5\sin(t)$. The initial conditions of the system in state space form are $x_m(0) = 0.5rad, \upsilon_m(0) = 0rad/sec, x_s(0) = 0.1rad$ and $\upsilon_s(0) = 0rad/sec$. The values are chosen according to the user specification while preserving the passive close-loop properties. This passivity property is equivalent to the condition $\lambda_{min} G(j\omega) + [G(j\omega)]^* \geq 0$, where $\lambda_{min}(\cdot)$ denotes the minimum eigenvalue with respect to the corresponding argument and $[G(j\omega)]^* = [G(-j\omega)]^T$ denotes the conjugate of the transfer function $G(j\omega)$ [8].

Figure 3 shows the signals at the master and the slave sides for all three simulation models and also the error signals at the master and the slave side for a time delay of $0.2 + 0.2\sin(t)$. From Figure 3(b), it is evident that system performance of the predictive control model is better than the system without prediction as the slave signal $x_s(t)$ of the predictive control model closely tracks the slave signal of the desired model. The error signals at both the master and the slave sides of the predictive control model are smaller when compared to the respective error signals of the conventional model. The simulations were carried out for various time delays and in all scenarios the predictive control model had better tracking and smaller error signals than the conventional model. Hence from the results it is evident that the performance of the predictive control model is much better than the conventional scheme. The proposed scheme works well for time delay uncertainties which underlines the fact that the system is robust.

Figure 4 shows the results when there are some

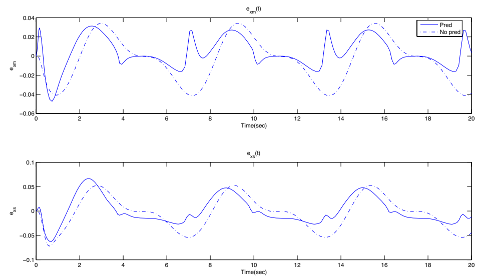

Fig. 4. Comparison of error signals at the slave side when the environment has some uncertainties: (a) $\Delta f_e(t) = 0.2\sin(t)$; (b) $\Delta f_e(t) = 0.5\sin(t)$

TABLE I

The error bound on the slave signals $\| e_{xs} \|$ after reaching the steady state($t \geq 5$ seconds) ((A) With Predictor; (B) Without Predictor)

Case	(A)	(B)
T(t): 0.2 sec	0.022	0.032
T(t): 0.2+0.2sin(t) sec	0.025	0.045
T(t): 0.4+0.3sin(t) sec	0.022	0.052
$\Delta f_e(t)$: 0.2sin(t) sec	0.023	0.038
$\Delta f_e(t)$: 0.5sin(t) sec	0.048	0.052

model uncertainties. In this case we assume that the environmental impedance model has some inaccuracies i.e., $f_e(t)$ is not accurate. Figure 4(a) and Figure 4(b) are assumed to have an environmental uncertainty of $\Delta f_e(t) = 0.2\sin(t)$ and $\Delta f_e(t) = 0.5\sin(t)$ respectively. The error signal is more in the case of Figure 4(b) as it has a greater uncertainty. Even though the tracking error is large the system still remains stable and better when compared to the conventional scheme.

Table I shows the error bounds. These values are obtained from the simulation results for different cases with different time delays. For various time delays and environmental uncertainty, the error signal of the predicted system is less when compared to the system without prediction. Hence the performance of the predicted system is better.

A. Experimental Setup

The simulation results show that the proposed predictive control method works well for different time delays. To guarantee the Quality of Service (QoS), the teleoperation models should be tested in a real environment. So the next step is to monitor the performance of the proposed predictive control strategy in a real environment with live data packets. In the experimental setup, packet loss and time delays are introduced between the master and the slave, and this is accomplished with the help of a package called NIST Net.

NIST stands for National Institute of Standards and Technology. NIST Net is a network emulation package that runs on Linux operating system and is used for testing a wide variety of network conditions, such as packet loss, packet duplication, time delays, bandwidth limitation and delay jitter on live data packets. NIST Net acts as a router to perform our required choice of tests on network conditions. It allows monitoring of two or more network clients. These network clients can be specified by NIST net using their IP addresses. The other advantage is that the network clients can be in two different subnets. In this article, there are only two clients - the master and the slave. Figure 5 gives a pictorial description of NIST Net setup. UDP is the protocol used for data transfer between the master and the slave sides.

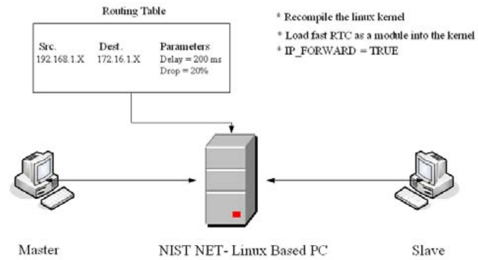

Fig. 5. NIST Net setup

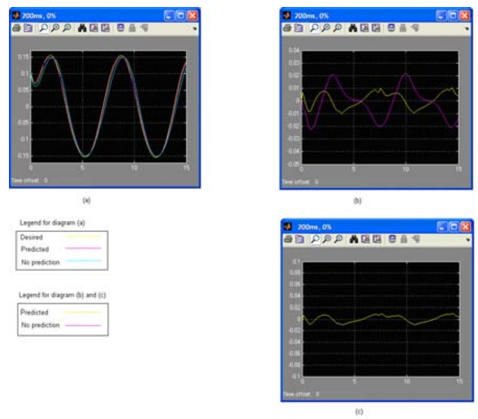

Fig. 6. Experimental results for a time delay of 200 ms and 0 percent packet loss. (a) Comparison of slave signals (b) Comparison of error signals (c) Error signal of proposed method.

B. Experimental Results

The desired, conventional and proposed predictive control teleoperation models are now tested in a real time environment for various time delays and packet loss. Figure 6, shows the results for a time delay of 200 ms and no packet drops. The time delay is 200 ms in each direction. So the total delay in the system is 400 ms. In the Figure 6(a), it is clear that the tracking of the

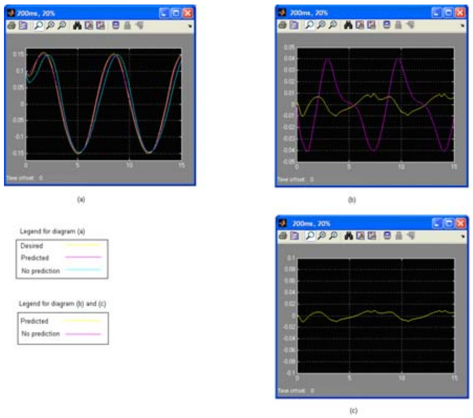

Fig. 7. Experimental results for a time delay of 200 ms and 20 percent packet loss. (a) Comparison of slave signals (b) Comparison of error signals (c) Error signal of proposed method.

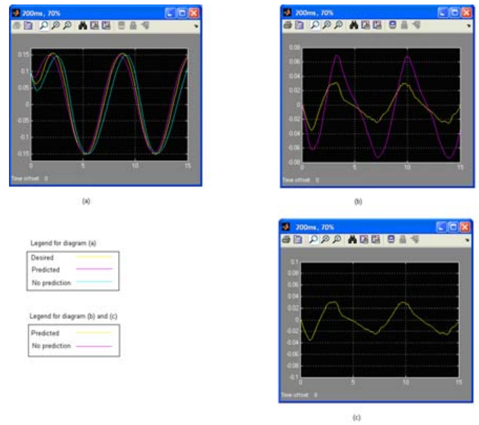

Fig. 8. Experimental results for a time delay of 200 ms and 70 percent packet loss. (a) Comparison of slave signals (b) Comparison of error signals (c) Error signal of proposed method.

proposed controller is much better than the tracking of conventional scheme i.e., the slave signal of the proposed controller is closer to the desired signal. Figure 6(b) shows that error signal for the proposed scheme to be smaller than the conventional scheme. Figure 6(c) shows the error signal of the proposed controller alone. This figure shows the variation of the proposed controller with respect to the zero axis. The experiments were carried on with the same time delay of 200 ms but the packet drops were varied. The results for a time delay of 200 ms and packet loss of 20 percent is shown in Figure 7. When compared to Figure 6, the results of the proposed controller show a very small increase in the tracking error. But the conventional scheme drifts further away from the desired signal and the tracking error for the conventional scheme has increased. In fact the tracking error for the conventional scheme has doubled for a packet loss increase of just 20 percent. For a packet loss of 20 percent, the system performance of the proposed controller is almost the same as 0 percent packet loss but in the conventional method the changes are appreciable.

Figure 8 shows the results for a packet loss of 70 percent. As expected for such a high packet loss the system won't be able to track the desired signal effectively. Now in Figure 8(a) the gaps between the signals are appreciable. Hence the tracking error of the proposed controller is large but on comparison with the conventional method the proposed controller still performs better.

V. Conclusions

A predictive control strategy is applied for a teleoperation system. This approach is compared with the scheme without prediction; the simulation results prove that the system performance of the model with predictor to be better than the system without the predictor. From the results, the proposed strategy works well for time varying delays and in unknown environmental model, which shows that the controller is robust. This performance of this strategy was tested experimentally when there are both time delays and packet loss.

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