Stability and Transparency Analysis of a Bilateral Teleoperation in Presence of Data Loss

A. Bakhshi, H.A. Talebi, A.A. Suratgar, and M. Abdeetedal

Abstract—This paper presents a novel approach for stability and transparency analysis for bilateral teleoperation in the presence of data loss in communication media. A new model for data loss is proposed based on a set of periodic continuous pulses and its finite series representation. The passivity of the overall system is shown using wave variable approach including the newly defined model for data loss. Simulation results are presented to show the effectiveness of the proposed approach.

I. INTRODUCTION

In a teleoperation system, the operator can perform a task in a remote environment via slave robot that commanded by the master robot. Tele-manipulation tasks are done by sending position, velocity, and/or force information remotely. The main applications are outer space explorations and controlling robots used for modelling.

Anderson and Spong used scattering transformation, network theory and the passivity to provide the stability of a teleoperation system in presence of constant time delay [4]. Niemeyer and Slotine introduced wave variables [5]. In this wave-based framework, the scattered wave variables are communicated via the delayed transmission lines instead of the typical power-conjugated variables such as force and velocity. The use of the wave scattering approach solved the destabilizing effects incurred in the transmission lines by passifying the communication channels independent of the amount of the delay. However, this approach is not readily applicable to time-varying delays. Moreover there is no guarantee in performance in the presence of even constant communication delay.

Since position information does not pass through the communication channels, system faces position drift and raising tracking error. Furthermore the time varying delay causes distorted velocity signal and results in tracking error. In order to compensate the effects of time varying delay, wave variables are sent along their integrations [6], [7] . In this method the main signal and its integral are received by the slave and the position is then calculable. Moreover in [7], pre mentioned approach is extended by sending power signal of the wave variable along side other signals. In [8], instability is avoided by defining new gains in communication channels. These gains result in stability of the system, although cause poor performance. In [9], delayed position signals are also used but this strategy causes tracking error as well. Similar approach has been used in [10] to converge the velocity error to zero. However, it failed to provide zero position tracking error.

In [11], a proper state feedback is designed and passive input/output system is defined such that it includes the position and velocity information. This approach result in good performance in presence of time delay. To avoid the adverse effects of wave distortion due to time varying delays and data losses, a novel solution based on the digital reconstruction of the wave variables is proposed in [12]. This approach introduces the use of buffering and interpolation scheme that preserves the passivity of the system which reduces the tracking error under time-varying delays and packet losses. In [13], the passivity of the system has been shown in the presence of data loss by considering zero value Wave in a discrete communication. As long as data loss causes poor performance, considering data reconstruction methods is mandatory. In [14], the effects of time delay and packet loss are compensated by estimating the received wave variables. This technique is based on Smith predictor and Kalman filter. Several researches have been done on compensating the effects of time delay in communication channels though most of which result in poor performance in the presence of data loss.

In network control system (NCS) literature, data loss often is modelled by using three main categories. In [15], data loss has been modelled as jump linear systems with Markov chains. In [16], modelling has been done using asynchronous dynamical system(ADS). In [17], random sample system has been used for modelling.

In this paper, a robust and high performance teleoperation system in the presence of data loss and different initial conditions is presented. A new model for data loss is proposed based on a set of periodic continuous pulses and its finite series representation and a state feedback control law for master and slave manipulators is designed. The presented control laws contains both position and velocity information. The new architecture, built within the passivity framework, provides good transparency which is measured in terms of position tracking abilities of the bilateral system. This configuration provides robust performance against network effects such as packet losses and reordering which shows the ability of the architecture to teleoperate over unreliable communication networks.
The structure of this paper is as follows. In Section II, our proposed model for data loss is presented. The data loss is presented as a set of periodic continuous pulses and its finite series representation. In Section III, the structure of the teleoperation system in presence of the data loss is proposed. In Section IV, the stability of the teleoperation system is shown by defining a Lyapunov function candidate and obtain conditions to have acceptable performance. In Section V, the validation of our control approach is investigated via simulations and conclusion is presented in Section VI.

II. DATA LOSS MODELLING

In this paper, we propose a new continuous time model for data loss.

**Assumption 2.1:** Data loss occurs in periodic manner which can be written as a train of pulse as shown in Fig. 1.

Where \((.)^*\) indicates signals which passes through communication channel in which data loss occurs, \(\alpha\) is loss rate, \(\alpha < T\) and \(L(t)\) is a periodic function of time and.

**Assumption 2.2:** \(L(t)\) can be written as a finite Fourier series which is continuous and periodic where:

\[
L(t) = \sum_{n=1}^{N} a_n \cos(nw_0 t) + b_n \sin(nw_0 t)
\]

\[a_n = \frac{2}{T} \int L(t) \times \cos(nw_0 t) dt\]

\[b_n = \frac{2}{T} \int L(t) \times \sin(nw_0 t) dt\]

Substituting the loss rate \(\alpha\) and frequency of the train pulse signal \(W_0 = \frac{\alpha}{T}\) into (1), we obtain

\[a_n = \frac{1}{\pi n} \sin \left( \frac{2 \pi n \alpha t}{T} \right)\]

\[b_n = \frac{1}{\pi n} \left[ \cos \left( \frac{2 \pi n \alpha t}{T} \right) - (-1)^n \right]\]

\[L(t) = \sum_{n=1}^{N} a_n \cos(nw_0 t) + b_n \sin(nw_0 t).\] (2)

In fact, \(L(t)\) is a continuous function that describes data loss as a periodic phenomenon.

III. COORDINATION ARCHITECTURE FOR BILATERAL TELEOPERATION

The new presented model for data loss is implemented on the teleoperation structure in [11]. Master and slave dynamics are considered as follows:

\[M_m(q_m)\dot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + g_m(q_m) = J^T F_h + \tau_m\]

\[M_s(q_s)\dot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + g_s(q_s) = \tau_s - J^T F_e\] (3)

where \(q_m, q_s\) are \(n \times 1\) master and slave robots joint variables vectors, \(\dot{q}_m, \dot{q}_s\) are \(n \times 1\) joint velocity vectors, \(\tau_m, \tau_s\) are \(n \times 1\) applied torque vectors, \(M_s, M_m\) are positive definite inertial \(n \times n\) matrices, \(C_s, C_m\) are \(n \times n\) Coriolis matrices and \(g\) is \(n \times 1\) gravitational vectors.

It is worth mentioning that some properties of the robot structures are as follows

**Property 1:** The inertia matrix \(M\) is symmetric positive definite and there exist some positive constants \(m_1, m_2\) such that \(m_1 I < M < m_2 I\).

**Property 2:** Using the Christoffel symbols, the matrix \(M - 2C\) is skew-symmetric.

The master and slave control torques are given by

\[\tau_m = -M_m\lambda \dot{q}_m - C_m\lambda \dot{q}_m + \tau_m\]

\[\tau_s = -M_s\lambda \dot{q}_s - C_s\lambda \dot{q}_s + g_s + \tau_s\] (4)

Where \(\tau_m, \tau_s\) are master and slave actuators torques respectively. By substituting (4) in (3) the master and slave dynamic can be expressed

\[M_m\dot{r}_m + C_m\dot{r}_m = F_h + \bar{\tau}_m = \dot{r}'_m\]

\[M_s\dot{r}_s + C_s\dot{r}_s = -F_e + \bar{\tau}_s = \dot{r}'_s\] (5)

Where \(r_m, r_s\) are defined as in (6)

\[r_m = \dot{q}_m + \lambda \dot{q}_m\]

\[r_s = \dot{q}_s + \lambda \dot{q}_s.\] (6)

In fact, \(r_m, r_s\) are new outputs of the teleoperation system, where

\[\int_0^t \tau'_m T r_m = \int_0^t \tau'_s T r_s = 0.\] (7)

Hence according to (7) the new teleoperation system is lossless. where \((\tau'_m, r_m)\) and \((\tau'_s, r_s)\) indicate new input/output of the system. Since master and slave are passive based on new input/output definitions hence just the stability of channel should be proven. As in [11] the new structure of the teleoperation systems with respects to new definitions is illustrated in Fig. 2.

Where variables in Fig. 2 are as follows:

\[u_m = \frac{1}{\sqrt{2b}} (F_{md} + br_{md})\]

\[V_m = \frac{1}{\sqrt{2b}} (F_{md} - br_{md})\]

\[u_s = \frac{1}{\sqrt{2b}} (F_{sd} + br_{sd})\]

\[V_s = \frac{1}{\sqrt{2b}} (F_{sd} - br_{sd}).\] (8)
where \( r_{md}, r_{sd} \) are the signals obtained from scattering transformation. Control signals \( F_{sd}(\bar{r}_s) \) and \( F_{md}(-\bar{r}_m) \) are obtained in (9).

\[
\begin{align*}
F_{sd} &= K_s(r_{sd} - r_s) \\
F_{md} &= K_m(r_{md} - r_m) \quad \text{(9)}
\end{align*}
\]

Where \( b, K_s \) and \( K_m \) are positive definite diagonal matrices which should be chosen properly. According to Fig. 1 Input signals of communication channel \( u_m, v_s \) and output signals \( u_s, v_m \) in presence of data loss are as in Fig. 3 and in (10):

\[
\begin{align*}
u_m^* &= u_m \sum_{n=1}^{N} a_n \cos(nw_0 t) + b_n \sin(nw_0 t) = u_s \\
v_s^* &= v_s \sum_{n=1}^{N} a_n \cos(nw_0 t) + b_n \sin(nw_0 t) = v_m
\end{align*}
\]

and similarly (13) is obtained.

In order to determine \( K_m \) and \( K_s \), using presented data loss modelling and substituting (10) into (8) result in (11) : 

\[
F_{md}^* + br_{md}^* = F_{sd} + br_{sd}^* \quad \text{(11)}
\]

and by substituting (9) in (11), (12) result in.

\[
(b + K_s) r_{sd}^* = (b - K_m) r_{md}^* + K_m r_s^* + K_s r_m \quad \text{(12)}
\]

and similarly (13) is obtained.

\[
(b + K_m) r_{md}^* = (b - K_s) r_{sd}^* + K_s r_s^* + K_m r_m \quad \text{(13)}
\]

In (12) and (13) according to the effects of \( r_{md}^* \) and \( r_{sd}^* \) on \( r_{md} \) and \( r_{sd} \) respectively and the wave reflecting phenomenon, \( K_m \) and, \( K_s \) are selected equal to \( b \), which simplifies (12), (13) to:

\[
\begin{align*}
K_m &= K_s = b \\
2r_{sd}^* &= r_m^* + r_s \\
2r_{md}^* &= r_s^* + r_m
\end{align*}
\]

**IV. STABILITY ANALYSIS**

In order to analyse stability of the system, first tracking errors are defined as follows:

\[
\begin{align*}
e_m &= q_m^* - q_s \\
e_s &= q_s^* - q_m
\end{align*}
\]

The main goal of the controller is that defined errors are converging to zero which result in highly improve transparency of the system.

**Assumption 4.1:** The environment and operator are assumed to be passive with inputs \( r_m, r_s \).

**Assumption 4.2:** The environment’s and operator’s forces are assumed to be bounded.

**Assumption 4.3:** \( r_{md}, r_{sd} \) are assumed to be zero for \( t < 0 \)

**Theorem 4.1:** A teleoperation system described as (5), (8) and (14) in presence of data loss described as (2) is stable and errors defined as (15) are bounded.

**Proof:** Let us define a Lyapunov function candidate as :

\[
V = \frac{1}{2}r_r^T T M_r r_r + \frac{1}{2}r_s^T T M_s r_s + \frac{1}{2}e^T K_1 e + e_s^T K_2 e_s + \frac{1}{2}e_m^T K_2 e_m
\]

Hence just should be shown that :

\[
V = \int_0^t F_{md}^T r_{md} - F_{sd}^T r_{sd} dt > 0
\]

From (8) can be shown :

\[
F_{md} = \sqrt{\frac{b}{2}} (u_m + v_m) , \quad F_{sd} = \sqrt{\frac{b}{2}} (u_s + v_s) \quad \text{(17)}
\]

\[
r_{md} = \frac{1}{\sqrt{2b}} (u_m - v_m) , \quad r_{sd} = \frac{1}{\sqrt{2b}} (u_s - v_s) \quad \text{(18)}
\]

Using (17) and (18) :

\[
V_1 = \int_0^t \frac{1}{2} (u_m^2 - v_m^2) - \int_0^t \frac{1}{2} (u_s^2 - v_s^2) dt \quad \text{(19)}
\]

And substituting (10) and (19) :

\[
V_1 = \int_0^t \frac{1}{2} (u_m^2 - v_m^2) dt - \int_0^t \frac{1}{2} (u_s^2 - v_s^2) dt + \int_0^t \frac{1}{2} (v_s^2 - v_m^2) dt \quad \text{(20)}
\]

According to data loss model in Fig. 1, it is clear that \( u_m^2 - (u_m^*)^2 > 0 , \quad v_s^2 - (v_s^*)^2 > 0 \) and therefore the candidate Lyapunov function is positive definite.

The time derivative of \( V \) is :
\[ \dot{V} = r_m^T M_m \dot{r}_m + \frac{1}{2} r_s^T M_s \dot{r}_s + r_s^T e_1 \]
\[ + \frac{1}{2} r_s^T M_s r_s + e_1^T K_1 e_1 + e_s^T K_2 e_s \]
\[ + F_e^T r_s - F_H^T r_m + F_m^T r_m'^d - F_s^T r_s'd. \]
\[ = r_m^T (-C_m r_m + F_h - F_m^d) + \frac{1}{2} r_s^T M_s r_s \]
\[ + r_s^T (-C_s r_s + F_e - F_s) + \frac{1}{2} r_s^T M_s r_s + e^T M e \]
\[ + e^T K_2 e_s + F_e^T r_s - F_H^T r_m + F_m^T r_m'^d - F_s^T r_s'd \]
\[ = r_m^T (F_h - F_m^d) + r_s^T (-F_e - F_s) + e^T K_1 e_m \]
\[ + e^T K_2 e_s + F_e^T r_s - F_H^T r_m + F_m^T r_m'^d - F_s^T r_s'd \]
\[ = - (r_m'^d - r_m)T b(r_m'^d - r_m) - (r_s - r_s'd)T b(r_s - r_s'd) \]
\[ + e^T K_1 e_m + e^T K_2 e_s \]

Using (14) and (15) :
\[ r_m = \dot{q}_m + \lambda q_m - \dot{q}_m - \lambda q_m = \dot{e}_s + \lambda e_s \quad (21) \]
\[ r_s = \dot{q}_s + \lambda q_s - q_m + \lambda q_m = \dot{e}_s + \lambda e_s \]
\[ \dot{V} = -\frac{1}{4} (r_m - r_m)T b(r_m - r_m) - \frac{1}{4} (r_s - r_s)T b(r_s - r_s) \]
\[ + e^T K_1 e_m + e^T K_2 e_s \]
\[ = -\frac{1}{4}(\dot{e}_s + \lambda e_s)T b(\dot{e}_s + \lambda e_s) \]
\[ - \frac{1}{4}(e_s^T b \dot{e}_s + e_s^T \dot{b} \lambda e_s + e^T b \lambda \dot{e}_s) + e^T K_2 e_s \]
\[ = -\frac{1}{4}(e_s^T \dot{b} \lambda e_s + \dot{e}_s^T b \lambda e_s + e^T b \lambda \dot{e}_s) + e^T K_2 e_s \]
\[ = -\frac{1}{4}(e_s^T \dot{b} \lambda e_s + \dot{e}_s^T b \lambda e_s + e^T b \lambda \dot{e}_s) + e^T K_1 e_m + e^T K_2 e_s \]

Since \( b \) and \( \lambda \) are positive definite diagonal matrices, Then
\[ \dot{V} = -\frac{1}{4}(e_s^T \dot{b} \lambda e_s + \dot{e}_s^T b \lambda e_s + e^T b \lambda \dot{e}_s) + e^T K_2 e_s \]
\[ = -\frac{1}{4}(e_s^T \dot{b} \lambda e_s + \dot{e}_s^T b \lambda e_s + e^T b \lambda \dot{e}_s) + e^T K_1 e_m + e^T K_2 e_s \]

by choosing \( K_1 = K_2 = \frac{\lambda b}{2} \), extra terms are omitted and \( \dot{V} \) is simplified to
\[ \dot{V} = -\frac{1}{4}(e_s^T \dot{b} \lambda e_s + \dot{e}_s^T b \lambda e_s + e^T b \lambda \dot{e}_s) + e^T K_2 e_s \]

As \( V \) is positive definite and \( \dot{V} \) is negative semi definite so the system is stable and the errors are bounded. Using property\[ r_m \] and \( r_s \) remain bounded.
\[ r_m = \dot{q}_m + \lambda q_m \Rightarrow q_m = \frac{r_m}{s + \lambda} \]
\[ r_s = \dot{q}_s + \lambda q_s \Rightarrow q_s = \frac{r_s}{s + \lambda} \quad (23) \]

According to (23) and boundedness of \( r_m \) and \( r_s \), boundedness of \( q_m, q_s, r_m, r_s, \dot{q}_m, \dot{q}_s \) is concluded. Hence
\[ q_m, q_s, r_m, r_s, \dot{q}_m, \dot{q}_s \] is bounded. (24)
In order to investigate the boundedness of $\dot{e}_m, \ddot{e}_s$ thus

$$
e_m = q_m^* - q_s = L(t)q_m - q_s$$

$$
\dot{e}_m = \dot{q}_m^* - \dot{q}_s = \dot{L}(t)q_m + L(t)\dot{q}_m - \dot{q}_s
$$

$$
\ddot{e}_m = \ddot{q}_m^* - \ddot{q}_s = \ddot{L}(t)q_m + 2\dot{L}(t)\dot{q}_m + L(t)\ddot{q}_m - \ddot{q}_s
$$

With using the boundedness of $q_m, L(t), \dot{L}(t), \ddot{L}(t), \dot{q}_m, \ddot{q}_m$ and $\dot{q}_m$ the boundedness of $\dot{L}(t)$ should be shown hence:

$$
L = \sum_{n=1}^{N} \frac{-1}{\pi n} \sin \left(\frac{2\pi n\alpha}{T}\right) \cos \left(\frac{2n\pi}{T} t\right)
+ \frac{1}{\pi n} \left[\cos \left(\frac{2\pi n\alpha}{T}\right) - (-1)^n \sin \left(\frac{2n\pi}{T} t\right)\right]
\dot{L} = \sum_{n=1}^{N} \frac{2}{T} \sin \left(\frac{2\pi n\alpha}{T}\right) \sin \left(\frac{2n\pi}{T} t\right)
+ \frac{2}{T} \cos \left(\frac{2\pi n\alpha}{T}\right) \cos \left(\frac{2n\pi}{T} t\right)
\ddot{L} = \sum_{n=1}^{N} \frac{2}{T} \frac{2n\pi}{T} \sin \left(\frac{2\pi n\alpha}{T}\right) \cos \left(\frac{2n\pi}{T} t\right)
- \frac{2}{T} \frac{2n\pi}{T} \sin \left(\frac{2\pi n\alpha}{T}\right) \sin \left(\frac{2n\pi}{T} t\right)

According to variation of $L(t)$ at $t = \alpha$ it is sufficient to investigate the boundedness neighbourhood of this point.

$$
\dot{L}_{t=\alpha} = \sum_{n=1}^{N} \frac{2}{T} \frac{2n\pi}{T} \sin \left(\frac{2\pi n\alpha}{T}\right) \cos \left(\frac{2n\pi}{T} \alpha\right)
- \frac{2}{T} \frac{2n\pi}{T} \cos \left(\frac{2\pi n\alpha}{T}\right) \cos \left(\frac{2n\pi}{T} \alpha\right)
\ddot{L}_t = \sum_{n=1}^{N} \frac{2}{T} \frac{2n\pi}{T} \sin \left(\frac{2\pi n\alpha}{T}\right) \cos \left(\frac{2n\pi}{T} t\right)
\dddot{L}_t = \sum_{n=1}^{N} \frac{2}{T} \frac{2n\pi}{T} \sin \left(\frac{2\pi n\alpha}{T}\right) \cos \left(\frac{2n\pi}{T} t\right)
$$

results in converging of this series to zero as $\alpha$ converges to zero. Hence, $\dot{L}$ remains bounded. Using [27] and [28], $V$ remains bounded. Hence $V$ is uniformly continuous, consequently

$$
V \to 0 \ as \ t \to \infty
$$

V. SIMULATION RESULTS

In this section we simulate our proposed teleoperation system on a single degree of freedom system with following dynamics:

$$M_m \ddot{q}_m = F_h + \tau_m$$

$$M_s \ddot{q}_s = \tau_s - F_c$$

With using [3] the dynamics can be simplified as follow

$$M_m \ddot{q}_m = \dot{F}_h - \dot{F}_{md}$$

$$M_s \ddot{q}_s = F_{sd} - F_c$$

The environment is set to be mass, spring and damper. The operator moves the master by inserting force $F_h$.

$$M_m = M_s = 1, \ b = 1.2$$

In the first step we investigate the stability of the system. In order to investigate the dissipation of the channel, we apply a pulse signal to the master in a limited time as depicted in Fig. 4. All signals converge to zero hence the channel is passive and stable See Fig. 5. In second step in order to investigate the performance of the system in the presence of different initial conditions we consider channel with no data loss ($F = 0$) and there is just initial condition between master and slave, see Fig. 6. The performance remains acceptable in presence of different initial conditions between master and slave position. Finally to investigate the performance of the system in the presence of data loss in communication media. Wave variable signals were lost in channel with period $T = 10(s)$ see Fig. 7 and Fig. 8. We assume loss rate $\frac{F}{T} = 0.02, 0.05$ and different initial conditions between master and slave see Fig. 9 and Fig. 10. The resulting performance is acceptable. Obviously, increasing loss rate results in poor transparency although the proposed teleoperation system remains stable with tolerable performance (even in in the presence of data loss and different initial conditions).

VI. CONCLUSIONS

In this paper we investigated the passivity based traditional architecture to cover position tracking in the presence of data loss and offset of initial conditions and proposed a new data loss model as a set of periodic continues pulses and use a coordination architecture which uses state feedback to define a passive output for a teleoperation system. This feedback is
containing both position and velocity information and simulation results verified the usefulness of mentioned architecture. Next approach would be investigating this architecture for a general model of data loss as a stochastic phenomenon and also improving force tracking in the presence of data loss.

REFERENCES

[1] L. F. Penn, K. Matsumoto, and S. Wakabayashi, "Force reflection for time-delayed teleoperation of space robots" in Proc. IEEE Int. Conf. Robot. Autom, San Francisco, CA, pp.3120-3125 April 2000

[2] K.A. Manocha, N. Fenlacone, and R.V. Dubey, "Variable position mapping based assistance in teleoperation for nuclear clean up" in Proc. IEEE Int Conf. Robot. Autom., Seoul, Korea, pp. 374379, April 2001

[3] Hongbin Liu, Jichun Li, Xiaojing Song, Seneviratne, L.D.; Althofer, K. ” Rolling Indentation Probe for Tissue Abnormality Identification During Minimally Invasive Surgery ” 2011

[4] R. J. Anderson and M. W. Spong, "Bilateral control of teleoperators with time delay" Automatic Control, IEEE Transactions on, vol. 34, no. 5, pp. 494501 1989.

[5] G. Niemeyer and J. J. E. Slotine, "Stable adaptive teleoperation," in IEEE J. Ocean, Eng. January 1991

[6] G. Niemeyer and J-J. E. Slotine. "Using wave variables for system analysis and robot control." In Proceedings of the IEEE International Conference on Robotics and Automation, vol. 3, pp. 16191625, Albuquerque, NMUSA, April 1997.

[7] G. Niemeyer and J-J. E. Slotine. "Towards force-reflecting teleoperation over the internet." In Proceedings of the IEEE International Conference on Robotics and Automation, vol. 3, pp. 19091915, May 1998.

[8] R. Lozano, N. Chopra, and M.W. Spong. "Passivation of force reflecting bilateral teleoperators with time varying delay." In Mechatronics 02. Enschede Netherlands, June 2002.

[9] N. Chopra, M. W. Spong, R. Ortega, and N. E. Barabanov. "On position tracking in bilateral teleoperation." In Proceedings of the IEEE American Control Conference, Boston, MA June 2004.

[10] N. Chopra, M. W. Spong, S. Hirche, and M. Buss. "Bilateral teleoperation over the internet: the time varying delay problem." In Proceedings of the IEEE American Control Conference, vol.1, pp. 15160June 2003.

[11] N. Chopra, M. W. Spong, and R. Lozano, "Adaptive coordination control of bilateral teleoperators with time delay" in Proc. IEEE Conf. Decis. Control, Paradise Island, The Bahamas, pp. 45404547. December. 2004

[12] P. Berestesky, N. Chopra, and M.W. Spong, "Discrete time passivity in bilateral teleoperation over the Internet" in Proc. IEEE Int. Conf. Robot. Autom. New Orleans, LA, pp. 45574564. April. 2004

[13] S. Hirche and M. Buss, "Packet loss effects in passive telepresence systems," in Proc. IEEE Conf. Decis. Control December 2004

[14] S. Munir and W. J. Book, "Variable position mapping based assistance in teleoperation for nuclear clean up" in Proc. IEEE Int Conf. Robot. Autom., Seoul, Korea, pp. 374379, April 2001

[15] G. Niemeyer and J-J. E. Slotine. "Using wave variables for system analysis and robot control." In Proceedings of the IEEE International Conference on Robotics and Automation, vol. 3, pp. 16191625, Albuquerque, NMUSA, April 1997.

[16] R. Krtolica, U. Ozguner, H. Chan, H. Gotkas, J. Winkleman, and M. Liubakka, "Stability of linear feedback systems with random communication delays via a discrete-time jump system approach" in Proc. Amer Control Conf. pp. 21992204 June 2000

[17] R. Krtolica, U. Ozguner, H. Chan, H. Gotkas, J. Winkleman, and M. Liubakka, "Stability of linear feedback systems with random communication delays" Int. J.Control, vol. 59, no. 4, pp. 925953.1994

[18] "Stability Analysis of Networked Sampled-Data Linear Systems With Markovian Packet Losses" Li Xie and Lihua Xie. IEEE Transaction on automatic control, vol. 54, NO. 6 June 2009

[19] Khalil, H.K. "Nonlinear System", Prentice Hall, 2002.