Stability and Perception in Time-Delay Teleoperation

Matteo Franchini[‡] Carlo Benedetti[‡]
[‡]Dipartimento di Informatica
Universitá di Verona
37134 Verona, Italy

Paolo Fiorini[†,‡]
[†,‡]Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

Abstract: *This paper describes a new method for the control of force-feedback teleoperation in the presence of communication time-delay. The proposed scheme satisfies better than current approaches the two conflicting requirements of robust system stability and good operator perception. The paper first summarizes two of the main approaches for stable and transparent force feedback teleoperation, and then proposes a simple lead-leg scheme for teleoperation control. This scheme ensures stability in the presence of communication time delay without affecting position and force feedback to the operator. We analyse this approach by computing transmission matrix and system stability, and we show system performance by computer simulation.*

1 Introduction and Past Work

Force reflection is the feature of teleoperation systems that allows operators to feel the dynamic interaction between the remote slave robot and its surrounding environment by means of a local master device. In force reflection teleoperation systems, the main control loop is closed through the operator, who acts as the system controller, and whose dynamics affects the performance of the complete system. When the operator is far away from the slave robot data communication between the master device and the slave robot adds a delay to the control loop affecting the stability and perception in forcefeedback teleoperation. Time delay causes the reduction of stability margins and the possible insurgence of instability. Furthermore, time delay implicitly reduces the operator perception of a remote environment because control schemes used to compensate time delay slow down the operator's motion and change the perceived properties of the remote environment.

Compensation methods for time delay can be divided approximately in three main groups: predictive displays, teleprogramming and direct compensation. Predictive, graphic and/or haptic, displays rely on some knowledge of the manipulator and of the remote environment to display in real time the expected response of the remote robot [4], but contact with the environment may be difficult to control because of unknown surface properties. To overcome this problem, the approach proposed in [6] continuously updates the remote site model using feedback data. The approach works well when the environment can be modeled accurately, as in [13], but may requires command backtracking to retrace the operator actions in case of errors.

Direct compensation of communication time delay has been proposed by a number of authors, most notably [2] and [10]. In [1] the authors use passivity theory to develop a control scheme that guarantees stability for all time delays. In [2] this approach is extended to show the asymptotic stability of the teleoperator. However, in [3] the authors point out that stability is guaranteed at the expenses of reducing system performance, requiring higher levels of operator's force. In [8] a new algorithm is proposed in which force and velocities can be freely scaled, thus overcoming some of the earlier limitations of the passivity approach. In [11] the authors use the concept of wave variable to ensure passivity, and therefore stability, to a teleoperation architecture in the presence of time delay. In [12] the wave variable approach is extended to the case of variable time delay showing that the proposed architecture is stable under all time delay conditions. In [5] an architecture based on lead-lag filters is proposed to stabilize a teleoperator when high force gain or long time delays are required.

Similarly, teleoperation performance analysis has been the subject of extensive research. In [15] the authors give a definition of *distance* from the ideal teleoperation performance, using a linear approximation of the teleoperation system based on two-port models [7]. In [14] the new architecture is analyzed and its stability is verified. In [16] the ideal system response is defined and a new architecture satisfying the definition is proposed. In [9] the general definition of *transparent* system is proposed as an extension of the impedance concept.

In spite of the emphasis given to stability and perception, these two research areas have been mostly addressed independently of each other. In particular, the architecture presented in [1] is robust to all time delays, but perception of remote environment degrades rapidly with increasing communication time delay. Similarly, the transparent architecture described in [14] not robust to the presence of transmission time delay. This paper presents a simple control scheme that achieves a compromise between the above two needs by compensating communication time delay with a filter satisfying stability and transparency constraints.

The paper is organized as follows. Section 2 reviews the passivity approach for stable teleoperation control. Section 3 reviews the theory and definitions of transparent teleoperation. Section 4 shows the limitations of the approaches presented in Section 2 and Section 3. In Section 5 we introduce the control scheme satisfying stability and perception requirements, and in Section 6 we show a few significant simulation results. Finally Section 7 concludes the paper.

2 Stable Time Delay Teleoperation

A teleoperation system can be modeled with a linear approximation consisting of a series of two-port circuits each representing one of the elements in the system, as shown in Figure 1. Each two-port circuit has a math-

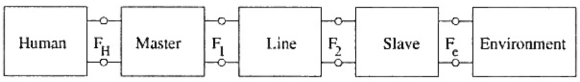

Figure 1: Two-port representation of a teleoperator.

ematical representation derived from electrical circuit theory using flow variables, i.e. velocities and currents, and effort variables, i.e. forces and voltages. The relations among input and output variables in a two-port circuit can be written using hybrid matrices as:

$$\begin{cases} F_1 = h_{11}v_1 + h_{12}F_2 \\ -v_2 = h_{21}v_1 + h_{22}F_2 \end{cases} \quad (1)$$

where h_{11} represents the impedance of the free slave; h_{12} is the force gain between master and slave when the master is blocked ($v_1 = 0$); h_{21} represents the velocity gain when the slave can move freely; h_{22} is the slave admittance when the master is blocked ($v_1 = 0$). The model can be simplified by reducing the teleoperator to a single two-port circuit and by representing operator and environment by two impedances Z_1 and Z_2.

The presence of a time delay between controller and process due to the communication channel may make the complete system unstable. To overcome this problem, Anderson and Spong [2, 1] developed a control architecture based on passivity theory, representing a teleoperation system with the following set of equations:

$$M_m\dot{v}_m = F_h + \tau_m \quad (2)$$

$$M_s\dot{v}_s = -F_e + \tau_s \quad (3)$$

The control law used in [1] is as follows:

$$\tau_m = -B_m v_m - F_{md} \quad (4)$$

$$\tau_s = -B_{s2}v_s + F_s - \alpha_f F_e \quad (5)$$

where F_s is the *coordination torque* given by:

$$F_s = K_s \int (v_{sd} - v_s)dt + B_{sl}(v_{sd} - v_s) \quad (6)$$

Using scattering theory, in [2] the authors show that the proposed configuration is passive, and therefore stable, for all time delays. Furthermore, the teleoperator is also lossless. The transmission line is lossless for any value of the time delay T. When $T = 0$ the control law yields $F_{md}(T) = F_s(t)$ and $v_{sd} = v_m$. Since the control law requires the sum of forces and velocities, a scaling factor is introduced in the equations, thus yielding is [1]:

$$F_{md}(t) = F_s(t-T) + n^2(-v_{sd}(t-T) + v_m(t)) \quad (7)$$

$$v_{sd}(t) = v_m(t-T) + \frac{1}{n^2}(-F_s(t) + F_{md}(t-T)) \quad (8)$$

3 Transparent Teleoperation

The two-port circuits *master, slave and* Line of Figure 1 can be grouped into a single element that can be modeled by:

$$\begin{bmatrix} F_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} v_1 \\ F_2 \end{bmatrix} = H \begin{bmatrix} v_1 \\ F_2 \end{bmatrix} \quad (9)$$

where v_1 is the velocity commanded by the operator, F_1 is the force reflected to the operator, v_2 is the slave velocity and F_2 is the force applied by the slave to the environment, and the matrix elements are:

$$h_{11} = \left[\frac{\partial F_1}{\partial v_1}\right]\Bigg|_{F_2=0} \quad h_{12} = \left[\frac{\partial F_1}{\partial F_2}\right]\Bigg|_{v_1=0} \quad (10)$$

$$h_{21} = \left[\frac{\partial v_2}{\partial v_1}\right]\Bigg|_{F_2=0} \quad h_{22} = \left[\frac{\partial v_2}{\partial F_2}\right]\Bigg|_{v_1=0}$$

Using these relations, Strassberg, Goldenberg and Millsgive the following definitions of transparency [14]:

1. Slave velocity depends only on master's velocity, times a scaling factor α: $v_2 = \alpha v_1$
2. Force reflection to the operator depends only on slave's force times a scaling factor β: $F_2 = \beta F_1$

From these considerations, one can define a *ideal hybrid matrix* as:

$$H = \begin{bmatrix} 0 & \beta^{-1} \\ \alpha & 0 \end{bmatrix} \quad (11)$$

For $\alpha = \beta = I$ it becomes:

$$H = \begin{bmatrix} 0 & I \\ I & 0 \end{bmatrix} \quad (12)$$

It must be noted that the sign of this matrix is opposite to the one defined in [1], and the two matrices are related by:

$$H_{Anderson,Spong} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} H_{Strassberg,Goldenberg,Mills} \quad (13)$$

To implement the ideal transparency, in [14] the authors propose an architecture that measures the operator force and the force applied by the robot to the environment with sensors. This architecture satisfies the transparency condition by using the force error $F_{error} = F_{1m} - G_6 F_{2m}$ as a velocity command for the master $v_{1c} = G_2 F_{error}$, and by using the master's velocity as a command for the slave $v_{2c} = G_5 v_{1m}$. The resulting hybrid matrix is:

$$H = \begin{bmatrix} G_2^{-1} & G_6 \\ G_4^{-1} G_5 & -(G_3 G_4)^{-1} J_s^T \end{bmatrix} \quad (14)$$

It approximates the ideal matrix if G_1, G_2 and G_3 are high enough and $G_4^{-1} G_5 = G_6 = I$.

4 Limitations of Current Architectures

The transfer matrix of the element connecting master and slave in the architecture described in Section2 is:

$$\begin{bmatrix} \tanh(sT) & \mathrm{sech}(sT) \\ -\mathrm{sech}(sT) & \tanh(sT) \end{bmatrix} \quad (15)$$

This matrix is different from the ideal matrix when $T \neq 0$, whereas for $T = 0$ we have:

$$\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \quad (16)$$

apart from the different signs due to two-port representation. Thus, this architecture is only transparent when $T = 0$, and it is not transparent when $T > 0$. To show this more clearly, one can consider that the effect of v_1 on F_1 depends on the value of the parameter $K = n^2$. In particular by computing F_1 with $F_2 = 0$ we have:

$$F_1 = \frac{K v_1 (1 - e^{-2sT})}{1 + e^{-2sT}} \quad (17)$$

showing that K determines the apparent viscosity perceived by the operator and the stability margin of the system. Therefore, when time delay increases, K must follow to keep stability, and this increases master's apparent viscosity.

The stability of the architecture [14] implementing the ideal hybrid matrix, is analyzed by including time delay T, represented by e^{-sT} term, in the transfer function of the communication line. The resulting transfer matrix is:

$$H = \begin{bmatrix} G_2^{-1} & G_6 e^{-sT} \\ G_4^{-1} G_5 e^{-sT} & -(G_3 G_4)^{-1} J_s^T \end{bmatrix} = \begin{bmatrix} 0 & e^{-sT} \\ e^{-sT} & 0 \end{bmatrix} \quad (18)$$

Applying Anderson and Spong convention for two-port circuits, we can transform it into

$$H = \begin{bmatrix} 0 & e^{-sT} \\ -e^{-sT} & 0 \end{bmatrix} \quad (19)$$

which represents a non-passive two-port circuit since its scattering operator is $\|S\| \to \infty$.

From this brief discussion, it follows that Anderson and Spong model, stable for all time delays, is increasingly non-transparent as time delay increases. Similarly, Strassberg, Goldenberg and Mills architecture, implementing the ideal hybrid matrix for a teleoperation system, is unstable for any time delay. In the following Section we will present a simple control that satisfies both stability and transparency within a useful frequency range.

5 Stable, Transparent Time-delay Teleoperation

To solve the problem of simultaneous stability and transparency, we use the two-port model and compensate the potential instability of the communication line with two additional elements, as shown in Figure 3. If we represent the two-port elements A, *Line* and B with the following matrices:

$$H_A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \quad (20)$$

$$H_{Line} = \begin{pmatrix} 0 & e^{-sT} \\ -e^{-sT} & 0 \end{pmatrix} \quad (21)$$

$$H_B = \begin{pmatrix} f & g \\ h & k \end{pmatrix} \quad (22)$$

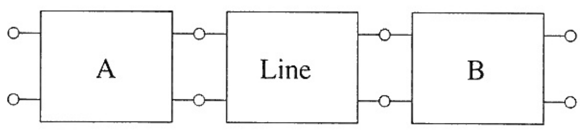

Figure 3: Two-port series with the *Line* element.

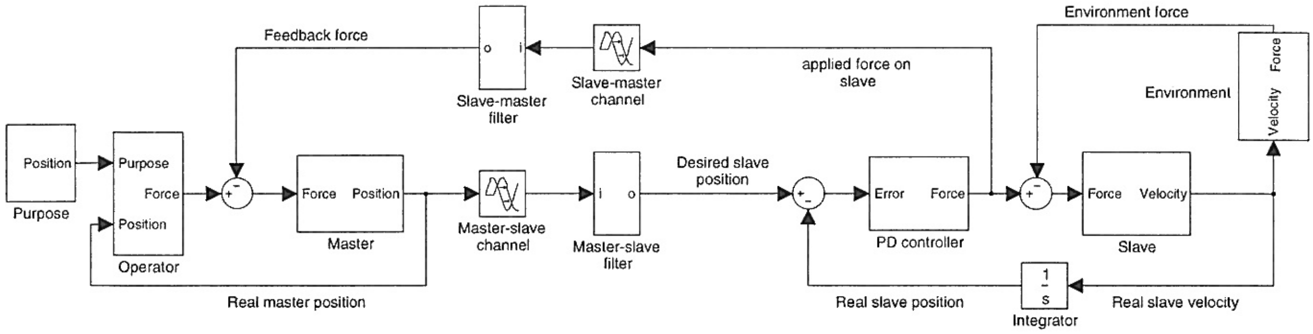

Figure 2: Complete block diagram of the teleoperation system.

the resulting series of the three elements is:

$$H_{eq} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \tag{23}$$

where:

$$h_{11} = a - \frac{bcfe^{-sT}}{1+fde^{-2sT}} \tag{24}$$

$$h_{12} = bge^{-sT} - \frac{bdfge^{-sT}}{1+fde^{-2sT}} \tag{25}$$

$$h_{21} = -\frac{che^{-sT}}{1+fde^{-2sT}} \tag{26}$$

$$h_{22} = k - \frac{dghe^{-sT}}{1+fde^{-2sT}} \tag{27}$$

By assigning proper values to the coefficients of A and B, the resulting matrix H_{eq} can be made passive and transparent. The design conditions are:

$$\begin{cases} h_{11} = 0 \\ h_{12} = m \\ h_{21} = \frac{1}{m} \\ h_{22} = 0 \\ Re(h_{11}) \geq 0 \\ 2Re(h_{12}h_{21}) \geq \|h_{12}h_{21}\| + Re(h_{12}h_{21}) \end{cases} \tag{28}$$

This system does not have a unique solution, but by adding the following constraints:

$$a = 1, \quad b = m \tag{29}$$

$$c = \frac{1+e^{-2sT}}{me^{-sT}}, \quad d = 1 \tag{30}$$

$$f = 1, \quad g = \frac{1+e^{-2sT}}{me^{-sT}} \tag{31}$$

$$h = 1, \quad k = 1 \tag{32}$$

the matrix of the equivalent two-port model becomes:

$$H_{eq} = \begin{pmatrix} 0 & m \\ -\frac{1}{m} & 0 \end{pmatrix} \tag{33}$$

This matrix is equal to the ideal hybrid matrix, except for the sign, due to the different velocity convention.

Furthermore, the three-element series, $A-Line-B$, does not modify its input when communication time delay changes. in fact, the norm of the scattering operator of H_{eq} is:

$$S(s) = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{pmatrix} 0 & m \\ -\frac{1}{m} & 0 \end{pmatrix} = \begin{pmatrix} 0 & m \\ \frac{1}{m} & 0 \end{pmatrix} \tag{34}$$

whose eigenvalues are:

$$\sup_{\omega}(\lambda^{\frac{1}{2}}(S^*(j\omega)S(j\omega))) = 1 \tag{35}$$

Further simplifications lead to the final form of the matrix:

$$\begin{bmatrix} 0 & 1 \\ -\frac{e^{sT}}{m} & 0 \end{bmatrix} \quad \begin{bmatrix} 0 & me^{sT} \\ -1 & 0 \end{bmatrix} \tag{36}$$

Unfortunately, the control scheme implementing this matrix is not realizable, and in the next Section we will introduce a suitable approximation.

5.1 Feasibility of the proposed controller

The proposed controller contains exponential terms e^{sT} which would imply a forward time shift and therefore cannot be physically realizable. However, within a limited bandwidth *lead* filters provide an acceptable approximation to the desired transfer function. The typical transfer function of a lead filter is:

$$G(s) = K_c \frac{1 + aTs}{1 + Ts} \tag{37}$$

with $a > 1$. This transfer function induces a positive phase change in the input signal and therefore it compensates the negative phase change due to time delay.

To select the upper frequency limit for the filter, we consider the perception limit of human operators and fix the cutoff frequency of the filter at 300 Hz. Obviously this limit will affect the quality with which remote environments are displayed to the operator. We plan to study the implications of this design choice in the continuation of this research.

The delay T is represented by a Padé approximation of the third order. The complete model of the teleoperation system with the compensator implemented by a lead filter is shown in Figure 2. The root locus for this architecture is shown in Figure 4, showing system stability characteristics. The lead filter increases the stability margin by an order of magnitude with respect to the case without filter. Stability of the lead filter compensation is satisfactory, whereas trasnparency is only guaranteed within the chosen frequency range. Uncertainty in parameters and time delay estimation are compensated by the good stability margins provided by this control scheme.

6 Simulation Results

To verify system performance, we simulate an impact of the slave robot with a rigid obstacle, in the presence of a time delay of $T = 150\,ms$. In the simulations, we assume that the operator intends to move the master to $x_{master} = 15$ rad. The remote environment is characterized by a rigid obstacle positioned at $x_{slave} = 10$ rad. The overall length of the simulation is 60 s. Figure 5 shows the oscillations due the impact with the obstacle, but master position follows quite accurately the slave's. At about $t = 5$ s there is an inflexion point due to the decrease of the slave's speed, as shown more clearly in 6. Figure 7 shows force profiles at slave and master sides. Master force is reflected from the remote site, whereas slave force depends on the position error between master and slave. The inflexion point in the position plot corresponds to the insurgence of force at the slave side.

7 Conclusion

The paper presents a simple control architecture which guarantees stability and accurate response in a force feedback teleoperation system, in the presence of communication time delay. This research is motivated by the observation that two leading methods for time delay compensation and transparent teleoperation do not satisfy each other's criteria. Thus the need for the compromise solution presented in this paper. The proposed control scheme relies on the addition of lead compensators to the teleoperation system, thus increasing the stability margin without affecting the mechanical impedance perceived by the operator. The analytical derivation of this model is presented together with stability analysis of the control scheme and computation of its transparency properties. Simulation results verify the analytical derivation and show the effectiveness of the proposed approach. We are currently in the process of performing experimental validation of this method, and to extend it to teleoperation via Internet.

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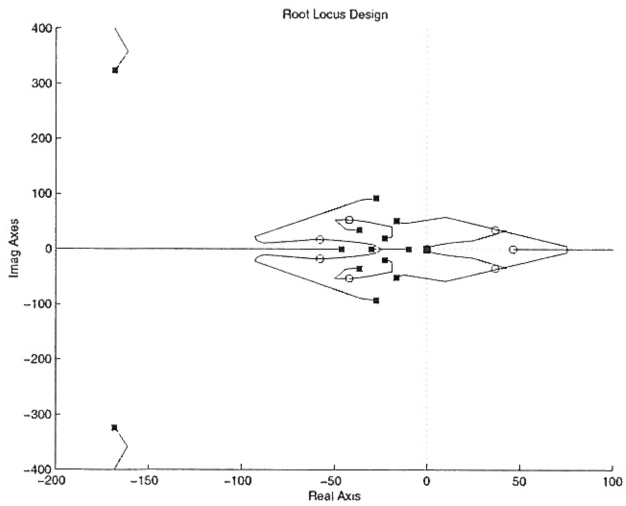

Figure 4: Root locus with lead filter, free slave and 100 ms delay.

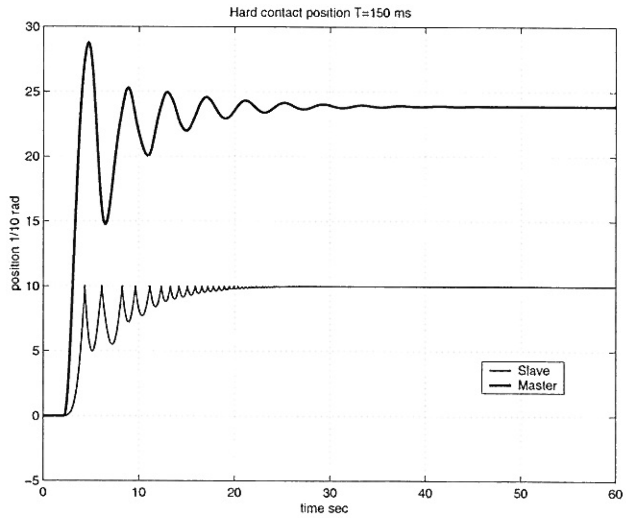

Figure 5: Master and slave positions with rigid obstacle and delay $T = 150$ms.

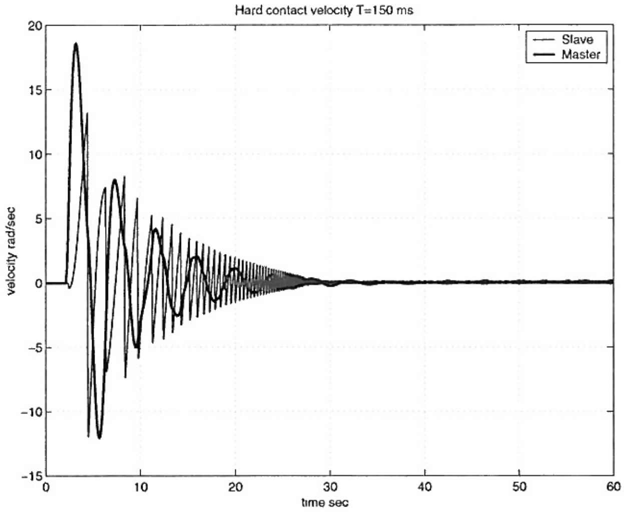

Figure 6: Master and slave velocities with rigid obstacle and delay $T = 150$ms.

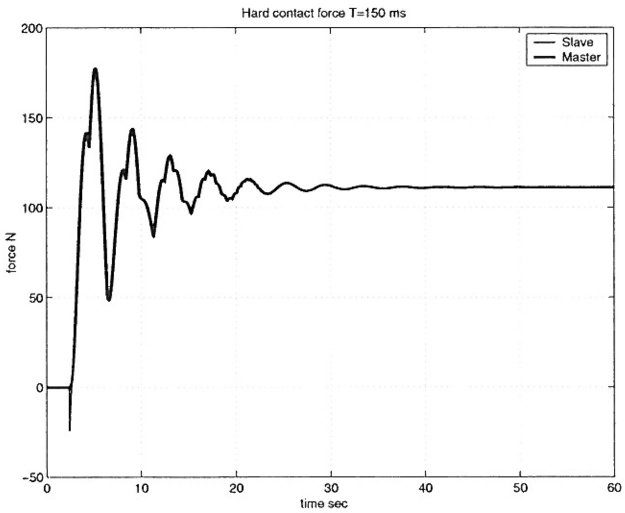

Figure 7: Master and slave forces with rigid obstacle and delay $T = 150$ms.

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