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Achieving Transparency for Teleoperator Systems under Position and Rate Control

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Abstract

A four-channel data transmission structure has been suggested in the literature to achieve "transparency" for master-slave teleoperator systems under position control. In this paper, the result is generalized to include teleoperator systems that are under rate control or more general master-slave kinematic correspondence laws, such as a mixed position/rate mode. A one degree-of-freedom example is given to outline the design and analysis of such a system for transparency and stability.

1 Introduction

From its early use in the remote manipulation of radioactive materials, the meaning of teleoperation has expanded to include manipulation at a different scale and in virtual worlds [1, 2, 3]. Teleoperation systems have the potential to play an important role in future remote or hazardous operations such as space and undersea exploration and servicing, forestry and mining, as well as in delicate operations such as microsurgery and microassembly.

Most of the early teleoperation system designs had kinematically similar master and slave because of the simplicity of the required controller. Corresponding joint servos between the master and the slave were tied together through electrical means. As a result, only position control in which the position of the master is interpreted as a position command to the slave could be used. Later, multi-degree-of-freedom joysticks were used as input devices to command the slave manipulators [4]. Joysticks can be used universally, take little space by comparison to kinematically equivalent masters, and are less tiresome to use. Rate control, in which the position of the master is interpreted as a velocity command to the slave, can be used to position the slave in resolved-motion mode. Conventional resolved-motion position control can also be implemented over a limited motion range. For example, the space shuttle remote manipulator system is provided with both position and rate control modes [5].

Contact information is helpful to the operator in reducing contact forces, and therefore reducing damage to the manipulated object. It also helps an operator in probing an uncertain environment, and reduces task completion time [6]. Although this information can be provided by a visual display, the haptic channel is faster and more natural when multiaxial operation is involved. When the contact force is reflected via the master actuator to the operator's hand, the teleoperator system is said to be bilateral or force-reflecting.

Two fundamental requirements on bilateral teleoperator systems are stability and transparency. The need for stability is obvious. By "transparency", it is meant that the master should feel to the operator as if the task were being manipulated directly. Appropriate meanings for "transparency" have been pursued in [7]. In general, the requirement has been that the position/force responses of the teleoperator master and slave be identical. Clearly, this definition only applies to those teleoperator systems in which the slaves are controlled to follow the motion of the masters faithfully. In many applications, the position mapping between the master and slave needs to be scaled either down or up, or rate control needs to be used, especially if the master has a limited workspace. For such situations, transparency is better quantified in terms of the match between the mechanical impedance of the environment encountered by the slave and the mechanical impedance transmitted to or "felt" by the operator at the master [8], [9].

Lawrence has analyzed the position-controlled bilateral teleoperators in [9], showing that none of the conventional control "architectures" (position-position, position-force, etc.) leads to transparency as defined by impedance matching between the environment and transmitted impedance. Instead, a "four-channel" architecture using the sensed master and slave forces and positions is required. Trade-offs between teleoperator transparency and stability robustness have also been examined in [9].

In this paper, the formalism from [9] is used to show that perfect transparency, defined as matched environment-transmitted impedance, can be achieved by teleoperator systems that are not necessarily controlled in position mode. In particular, systems that operate in rate control mode (the slave velocity tracks the master position), a combination of rate and position mode, or a general frequency weighted master-slave kinematic correspondence law, can still transmit an impedance to the master that perfectly matches the environment impedance encountered by the slave. The paper is structured as follows: Section 2 reviews the network equivalent representation of teleoperators, Section 3 reviews the formalism presented in [9], Section 4 describes the design and analysis of a transparent four-channel architecture for position control, Section 5 gives conditions for transparency in rate mode or other kinematic correspondence modes and Section 6 presents some simulation results. Finally, Section 7 draws conclusions and suggests future work.

2 Network Representation of Teleoperator Systems

In network theory, an *n*-port is characterized by the relationship between effort, f (force, voltage) and flow, v (velocity, current). For a linear time-invariant (LTI) lumped one port network, this relationship is specified by its impedance, $Z(s)$, according to

$$Z(s) = \frac{F(s)}{V(s)} \ , \qquad (2.1)$$

where $F(s)$ and $V(s)$ are the Laplace transforms of f and v respectively. An LTI lumped two-port network can be represented by its hybrid matrix which is defined as

$$\begin{bmatrix} F_1 \\ -V_2 \end{bmatrix} = H(s)\begin{bmatrix} V_1 \\ F_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}\begin{bmatrix} V_1 \\ F_2 \end{bmatrix} . \qquad (2.2)$$

A suggested network representation of a master and slave telemanipulation system is a two-port connected between two one-ports, the operator and the environment [10, 11], as shown in Figure 1.

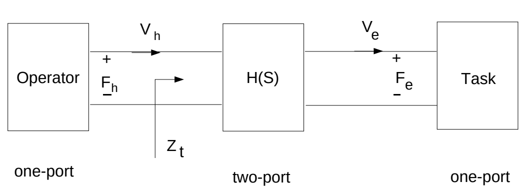

Fig. 1 Network representation of teleoperator system

Using the hybrid matrix of the two-port and the task impedance

$$Z_e = \frac{F_e}{V_e} \qquad (2.3)$$

we can express the impedance "felt" by the operator as

$$Z_t = \frac{F_h}{V_h} = \frac{h_{11}(1 + h_{22}Z_e) - h_{21}h_{12}Z_e}{1 + h_{22}Z_e} \ . \qquad (2.4)$$

Thus we have the following necessary and sufficient condition for transparency [11]:

$$\begin{aligned} h_{11} &= h_{22} = 0 \\ h_{12}h_{21} &= -1 \ . \end{aligned} \qquad (2.5)$$

3 General Teleoperator Structure

In a conventional position control teleoperator system, either the contact force or the slave position is fed back to the master to provide force reflection. The first is called direct force feedback method, and the second is called coordinating force method. From the network point of view, there are no specific reasons for not using the position and force information bilaterally. Such a "four-channel" communication scheme gives more freedom to achieve the hybrid matrix desired for transparency. The formalism presented in the earlier work by Lawrence [9] is adopted here. A block diagram of a general teleoperator structure is shown in Figure 2. We can see the position-position and position-force structures are two special cases of this general structure.

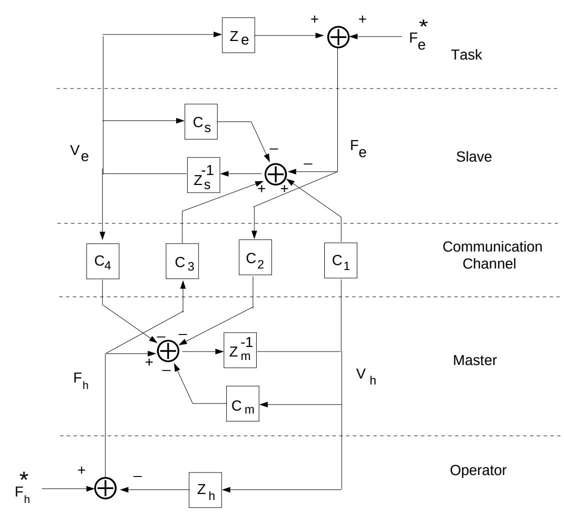

Fig. 2 General teleoperator structure: After Lawrence, 1992

Motivated by [12], the models for the master and slave dynamics are approximated by simple masses. The symbols in Figure 2 are defined as follows:

$$\begin{aligned} Z_m &= M_m s \\ C_m &= B_m + K_m/s \\ Z_s &= M_s s \\ C_s &= B_s + K_s/s \\ Z_h &= \text{ the impedance of the operator's hand} \\ Z_e &= \text{ the impedance of the environment} \end{aligned} \qquad (3.6)$$

where M_m and M_s are the masses of the master and the slave respectively, C_m and C_s are the transfer functions of the local controllers, and F_h^* and F_e^* are exogenous forces, hand and environment, respectively.

The transmitted impedance felt by the operator can be derived in terms of the block transfer functions as

$$Z_t = \frac{[(Z_m + C_m)(Z_s + C_s) + C_1 C_4] + Z_e(Z_m + C_m + C_1 C_2)}{(Z_s + C_s - C_3 C_4) + Z_e(1 - C_2 C_3)} \tag{3.7}$$

with the difference of Z_t and Z_e being interpreted as a measure of transparency.

Stability of the closed-loop system can be checked by applying the Nyquist criterion to its loop gains. Assuming the task is just a passive impedance, the block diagram of the general teleoperator system can be reorganized as shown in Figure 3.

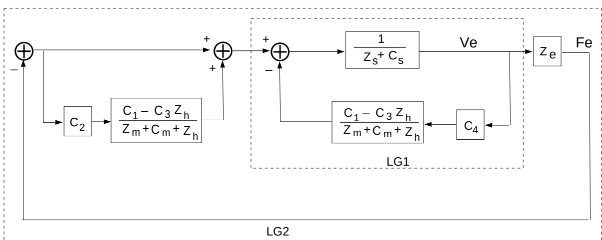

Fig. 3 Closed-loop stability analysis

4 Transparency Under Position Control

For position control, it can be easily shown from (3.7) that a fully transparent teleoperator system, i.e.,

$$Z_t = Z_e \text{ for any } Z_e \tag{4.8}$$

can be achieved if we set

$$\begin{aligned} C_1 &= Z_s + C_s \\ C_2 &= 1 \\ C_3 &= 1 \\ C_4 &= -(Z_m + C_m) \end{aligned} \tag{4.9}$$

Although not mentioned in [9], it is interesting to note that the end point impedance of the system viewed from the slave side equals:

$$Z_{end} = -\frac{F_e}{V_e} = Z_h \tag{4.10}$$

which is the impedance of the human hand. In robotics control, the goal of impedance control of a manipulator is to create a desired impedance at its end-effector. However, in practice, it is not very clear what the best impedance for the manipulator to contact its tasks is. Experience shows that human hands offer adjustable impedances, which makes them ideal for manipulating almost any object without encountering stability problems. Thus, from the impedance control point of view, the above fully transparent teleoperator structure provides a way to reconstruct the human impedance at the manipulator end-effector.

From

$$\begin{aligned} F_h - F_e &= (Z_m + C_m)(V_h - V_e) \\ F_h - F_e &= (Z_s + C_s)(V_e - V_h) \quad , \end{aligned} \tag{4.11}$$

the position error dynamics can be formed as

$$s(Z_m + C_m + Z_s + C_s)(x_h - x_e) = 0 \tag{4.12}$$

where x_h and x_e are the positions of the master and slave respectively. With Z_m, Z_s, C_m and C_s as defined in (3.6), the slave tracks the master position asymptotically.

However, the above teleoperator control strategy requires acceleration measurement in order to implement C_1 and C_4. Furthermore, it needs accurate knowledge of the mass of master and slave in order to completely compensate for their dynamics. This makes it difficult to implement in practice. On the other hand, complete transparency might not be desirable since an infinitely stiff and weightless mechanical bar would drift around if it is not connected to a load and an operator. As suggested in [13], a small centering force is desirable to “fix” the master and slave system to prevent drifting. This, in fact, can be interpreted as an intervenient impedance [7]. Consequently, a small force is always needed to move the telemanipulator even without payload. As we shall see, the addition of intervenient impedance makes it unnecessary to measure accelerations.

With low-gain PD Control, the master and slave subsystems become

$$\begin{aligned} Z_m &= M_m s + B_{mc} + K_{mc}/s \\ Z_s &= M_s s + B_{sc} + K_{sc}/s \end{aligned} \tag{4.13}$$

and set the block transfer function as

$$\begin{aligned} C_1 &= C_s \\ C_2 &= C_3 = 1 \\ C_4 &= -C_m \quad . \end{aligned} \tag{4.14}$$

If we have identical master and slave subsystem, that is $Z_m = Z_s$, the transmitted impedance becomes

$$Z_t = Z_m + Z_e \quad . \tag{4.15}$$

Thus the operator indeed feels the object’s impedance and an intervenient impedance, as expected. The end point impedance of the system viewed from the slave side equals

$$Z_{end} = -\frac{F_e}{V_e} = Z_m + Z_h \quad , \tag{4.16}$$

which is the impedance of the human hand plus an intervenient impedance.

Since

$$F_h - F_e = Z_m V_h + C_m(V_h - V_e)$$
$$F_h - F_e = Z_s V_e + C_s(V_e - V_h) \quad , \tag{4.17}$$

in the case of identical master and slave, that is $Z_m = Z_s$, the position error dynamics can be formed as

$$s(Z_m + C_m + C_s)(x_h - x_e) = 0 \tag{4.18}$$

thus the slave tracks the master's position asymptotically.

The stability can be checked starting from the inner loop with characteristic equation

$$LG_1 + 1 = \frac{(Z_s + C_s + C_m)(Z_h + Z_m)}{(Z_m + C_m + Z_h)(Z_s + C_s)} = 0 \tag{4.19}$$

thus the inner loop is stable. For the outer loop, if we assume the master and slave subsystems are identical $Z_m = Z_s$, then

$$LG_2 + 1 = \frac{(Z_h + Z_m + Z_e)(Z_m + C_m + C_s)}{(Z_m + Z_h)(Z_s + C_s + C_m)} = 0 \tag{4.20}$$

therefore the outer loop is stable.

However, the above stability analysis is based on the assumption that the master subsystem is exactly the same as the slave subsystem, and the force feedback and feedforward is accurate. Depending on the hand and environment impedances, [12] reports that errors of only 5% in the force feed forward could drive the system unstable. In addition, time delays are always a destabilizing factor in the system. The robust implementation of the above scheme needs further study.

5 Transparency Under General Master-Slave Kinematic Correspondence

The position-force structure does not provide transparency, nor does the rate-force structure. As discussed before, for position control, the bilateral communication of force information is important to achieve transparency. Here we extend the previous result to include a more general kinematic correspondence between the master and slave. We assume identical master and slave throughout.

If we select the control laws

$$C_1 = \frac{C_s}{G}$$
$$C_2 = G$$
$$C_3 = \frac{1}{G} \tag{5.21}$$
$$C_4 = -GC_m \quad ,$$

where G is a transfer function, the transmitted impedance is

$$Z_t = Z_m + Z_e \quad , \tag{5.22}$$

and the teleoperator system is transparent.

The hybrid matrix of the master-slave system can be computed as

$$H = \begin{bmatrix} Z_m & G \\ -\frac{1}{G} & 0 \end{bmatrix} . \tag{5.23}$$

The transfer function between the master and slave velocities can be derived as

$$\frac{V_e}{V_h} = \frac{1}{G} \quad . \tag{5.24}$$

We see that the transfer function G defines the kinematic correspondence between the master and the slave.

Stability can be checked as before, using the loop transfer functions. With $Z_m = Z_s$, we have the following characteristic equations,

$$LG_1 + 1 = \frac{(Z_m + Z_h)(Z_s + C_s + C_m)}{(Z_m + C_m + Z_h)(Z_s + C_s)} = 0 \tag{5.25}$$

$$LG_2 + 1 = \frac{(Z_m + C_m + C_s)(Z_h + Z_m + Z_e)}{(Z_m + Z_h)(Z_s + C_s + C_m)} = 0 \; . \tag{5.26}$$

Therefore, if the operator's hand can be modeled as a constant mass, spring and damper system, the inner and outer loops are stable.

It is clear the transparent position control structure previously addressed is just a special case where the transfer function G is set to be unity. Position scale down or up can be achieved easily by using $G = k$ where k is the scale factor. Other type of kinematic correspondence between the master and slave can be realized by setting the proper transfer function G under the condition that the system is stable. We give the following as an example in which a transparent rate control can be achieved.

A perfect rate control of teleoperator system requires that

$$\frac{V_e}{V_h} = \frac{1}{K_v s} \tag{5.27}$$

where K_v is a scale factor. Based on previous results, in order to achieve transparency with perfect rate control, an improper transfer function must be implemented since

$$C_2 = G = K_v s \tag{5.28}$$

Instead, a first order filter can be used to achieve rate control with reasonable accuracy, that is

$$G = \frac{K_v s}{1 + Ts} \tag{5.29}$$

where T is a small time constant which sets the useful frequency range.

6 Simulation Results

Dynamic simulations using Simulink™ were carried out to test the response of the transparent teleoperator system addressed above. As an example, we assume the operator's hand to be a constant mass, spring and damper system which has impedance:

$$Z_h = 0.5s + 70 + \frac{2000}{s} \quad . \tag{6.30}$$

Both the master and slave are assumed to be the University of British Columbia (UBC) magnetically levitated wrists [14] which , under nominal controllers, have impedances

$$Z_m = Z_s = 0.62s + 0.1 \tag{6.31}$$

The local controllers C_m and C_s are chosen as

$$C_m = C_s = 10 + \frac{0.1}{s} \quad . \tag{6.32}$$

The first set of simulations were used to test the free motion behavior of the position control system with

$$G = 1 \tag{6.33}$$

and the rate control system with

$$G = \frac{s}{1 + 0.02s} \quad . \tag{6.34}$$

The operator's hand force F_h^* is a square wave for both cases. Plots of the time domain responses are shown in Figure 4. Figure 5 illustrates cases similar to the previous ones, except that a soft environment impedance was connected to the slave, given by

$$Z_e = 10s + 100 + \frac{200}{s} \quad . \tag{6.35}$$

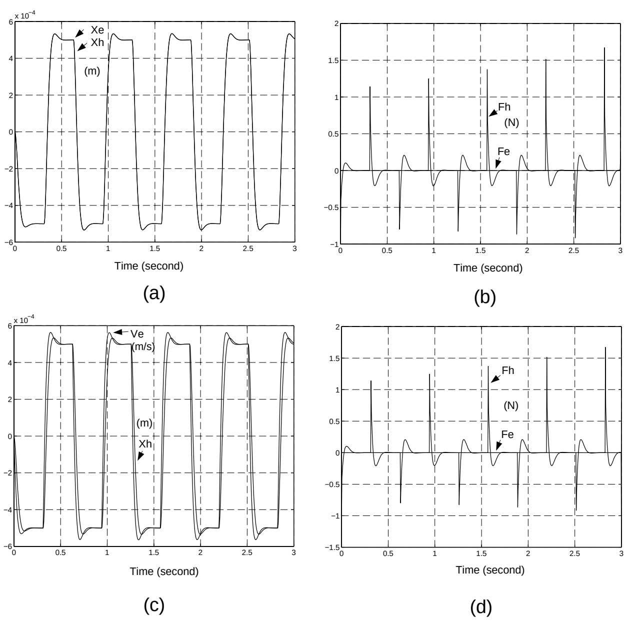

Fig. 4 Transparent teleoperation: slave in free motion. (a) and (b): position control; (c) and (d): rate control.

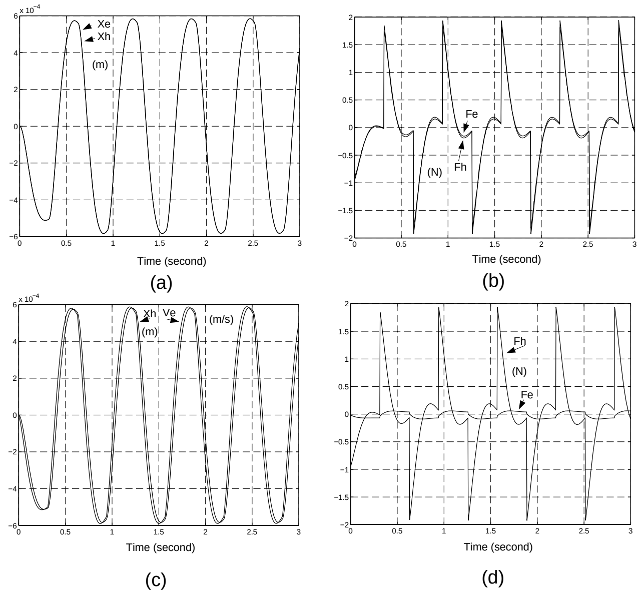

Fig. 5 Transparent teleoperation: slave in contact of soft environment. (a) and (b): position control; (c) and (d): rate control.

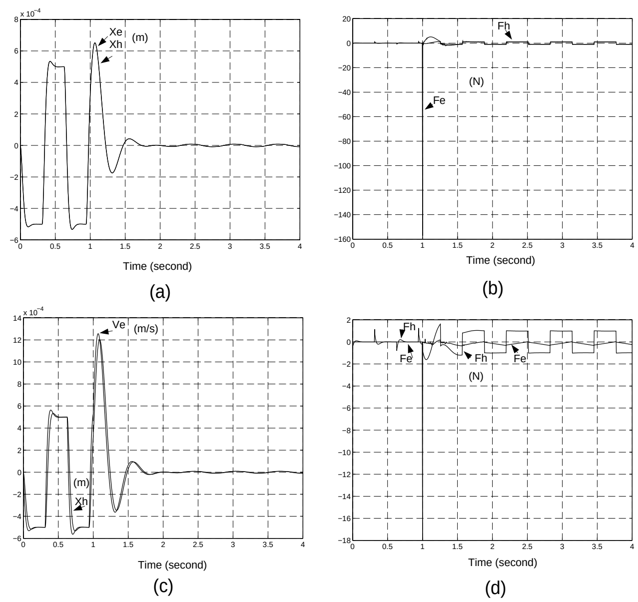

Fig. 6 Transparent teleoperation: slave is in free motion for the first 1 second, and then makes hard contact for the last 3 seconds. (a) and (b): position control; (c) and (d): rate control.

The third simulation was performed to show the hard contact behavior of position and rate control, shown in Figure 6. The slave is in free motion for the first second, then makes hard contact for the last 3 seconds. The stiffer task impedance has the following value:

$$Z_e = 1000s + 10000 + \frac{200000}{s} \quad . \tag{6.36}$$

These results clearly demonstrate excellent position (for position control) and rate (for rate control) tracking capacity of the proposed transparent teleoperator system. In both cases, the position response of the master is simply a second order mass, spring and damper system as expected.

7 Conclusions

The performance of a teleoperator system can be greatly improved by feeding the operator applied force to the slave. With four-channel data transmission, the task impedance can be faithfully reconstructed at the slave side to make the system transparent. The kinematic correspondence between the master and slave could be more general other than a simple position to position correspondence. In addition, if impedance scaling is desired, a local force feedback at the slave side can be used. As two special cases, the design and analysis are given in this paper to achieve teleoperation transparency for both position and rate control.

However, the transparency/stability robustness tradeoffs have not yet been treated here. Neither has the effect of time delay in the system been considered. These issues still need investigation.

8 Acknowledgment

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