Bilateral Control of Different Order Teleoperators

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This paper presents a bilateral control method for teleoperation systems where the master and the slave are modeled by different order transfer functions. The proposed methodology represents the teleoperation system on the state space and it is based in the state convergence between the master and the slave. The method allows that the slave follows the master, and it is able to establish the dynamic behavior of the teleoperation system. The first results obtained when the method is being applied to a commercial teleoperation system in which the master and the slave are modeled by different order discrete transfer functions are shown in this paper.

1 Introduction

Often, in a teleoperated system, the interaction force of the slave with the environment is reflected to the operator to improve the task performance. In this case, the teleoperator is bilaterally controlled [1]. The classical bilateral control architectures are the position–position [2] and force–position architecture [3]. Additional control schemes have been proposed in the literature, e.g. the bilateral control for ideal kinesthetic coupling [4] or the bilateral control based in passivity to overcome the time delay problem [5]. Usually the proposed bilateral control schemes consider simple master and slave models of the same order. They do not provide a design procedure to calculate the control system gains when the master and the slave are modeled by different order transfer functions.

In [6] we presented a bilateral control method of teleoperation systems with communication time delay. In this method, the teleoperation system is modeled on the continuous-time state space from nth-order linear differential equations that represent the master and the slave. Through the state convergence between the master and the slave, the control method achieves that

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the slave follows the master and it allows to establish the desired dynamics of the teleoperation system. However, this control method considers only teleoperation systems where the master and the slave are modeled by differential equations of the same order.

This paper explains how the state convergence methodology can be used to control teleoperation systems where the master and the slave are modeled by different order discrete transfer functions. In addition, in this paper, different from [6], the teleoperation system is modeled in the discrete-time domain, and the communication time delay is not considered in order to simplify the explanation. Clearly, the results presented in this paper could be directly applied to continuous-time teleoperation systems with communication time delay.

The paper is organized as follows. Section 2 describes the bilateral control methodology of teleoperation systems based in the state convergence. The application of this methodology to control different order teleoperation systems is explained in section 3. Section 4 shows the results obtained when a master and an slave with different order transfer functions have been controlled using the method proposed in the paper. Finally, section 5 summarizes the conclusions of this paper.

2 Bilateral Control by State Convergence

This section describes the bilateral control method of teleoperation systems based in the state convergence [6]. However, different from [6], a teleoperation system without communication time delay where the master and the slave are modeled by nth-order discrete transfer functions is considered. The control method is based on the state space formulation and it allows that the slave follows the master through state convergence. The method is able also to establish the desired dynamics of this convergence and the dynamics of the slave manipulator.

2.1 Modeling of the Teleoperation System

The modeling of the teleoperation system is based on the state space formulation, Fig. 1. The master system is represented in the state space like:

$$\begin{aligned} x_m(k+1) &= G_m x_m(k) + H_m u_m(k) \\ y_m(k) &= C_m x_m(k) \end{aligned} \tag{1}$$

and the slave system is represented similarly.

The matrices that appear in the model are: G_2, influence in the slave of the operator force; K_m and K_s, feedback matrices of the master and slave state; and R_m and R_s, interaction slave - master, and interaction master - slave.

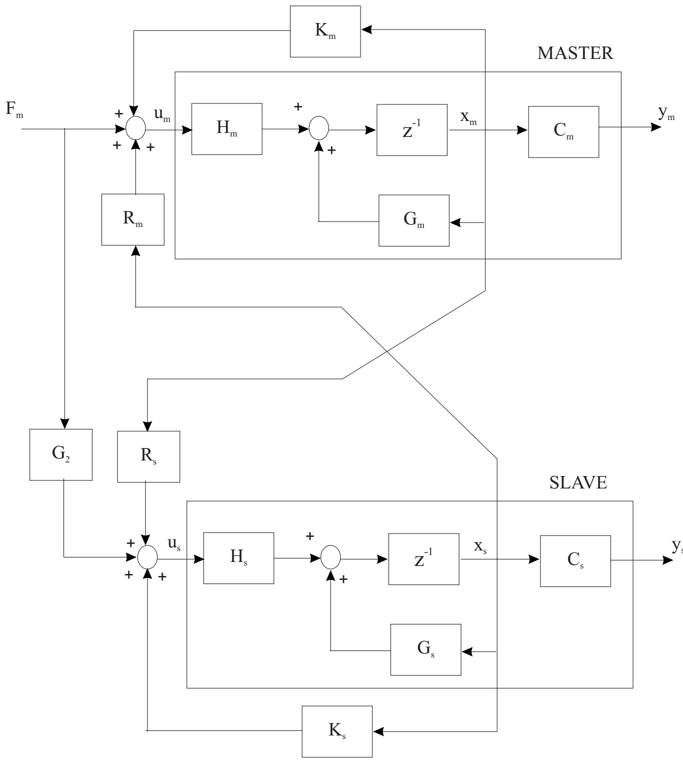

Fig. 1. Modeling of the teleoperation system

From the model shown in Fig. 1, the next state equation of the teleoperation system is obtained:

$$\begin{bmatrix} x_s(k+1) \\ x_m(k+1) \end{bmatrix} = \begin{bmatrix} G_s + H_s K_s & H_s R_s \\ H_m R_m & G_m + H_m K_m \end{bmatrix} \begin{bmatrix} x_s(k) \\ x_m(k) \end{bmatrix} + \begin{bmatrix} H_s G_2 \\ H_m \end{bmatrix} F_m(k) \tag{2}$$

where F_m represents the force that the operator applies to the master.

The master and the slave are modeled by nth-order discrete transfer functions. The representation of the master is given by:

$$G_m(z) = \frac{b_{mn-1} z^{n-1} + \cdots + b_{m1} z + b_{m0}}{z^n + a_{mn-1} z^{n-1} + \cdots + a_{m1} z + a_{m0}} \tag{3}$$

and the representation of the slave is analogous. The master and the slave are modeled in the state space using the controller canonical form.

Considering this master and slave represention, the matrices K_m, K_s, R_m and R_s are row vectors of n components, and G_2 is a real number.

If the environment is modeled by means of a stiffness (k_e), the matrix K_s can be used to incorporate in the teleoperation system model the interaction of the slave with the environment. In the same way, the matrix R_m can be used to consider force feedback from the slave to the master assuming a force feedback gain k_f.

2.2 Control Method Through State Convergence

In the teleoperation system model shown in Fig. 1, there are $3n+1$ control gains that are necessary to obtain: K_m (n components), K_s (n components), R_s (n components) and G_2 (one component). To calculate these control gains it is necessary to get $3n+1$ design equations.

Applying the next linear transformation to the system (2), the error state equation between the master and the slave is obtained:

$$\begin{bmatrix} x_s(k) \\ E_s x_s(k) - E_m x_m(k) \end{bmatrix} = \begin{bmatrix} I & 0 \\ E_s & -E_m \end{bmatrix} \begin{bmatrix} x_s(k) \\ x_m(k) \end{bmatrix} \tag{4}$$

where $E_s = diag\{b_{s0}, \cdots, b_{sn-1}\}$ and E_m is similar to E_s.

Let $x_e(k)$ be the error between the slave and the master, $x_e(k) = E_s x_s(k) - E_m x_m(k)$. If the error converges to zero, the slave output will follow the master output. From the error state equation, $n+1$ design equations can be obtained to achieve that the error evolves as an autonomous system, and the slave output follows the master output. In addition, $n-1$ conditions between the numerator coefficients of the master and slave discrete transfer functions can be derived. If these conditions are not satisfied, there will be an error between the master and slave output.

When the error evolves like an autonomous system, the characteristic polynomial of the system can be calculated. From this polynomial, $2n$ design equations can be obtained to establish the slave and the slave-master error dynamics. These $2n$ equations plus the $n+1$ previous equations, form a system of $3n+1$ equations. Solving this equations system, it will be possible to obtain the $3n+1$ control gains. With these control gains, the slave manipulator will follow the master and the dynamics of the error and the slave will be established.

3 Application to Teleoperation Systems of Different Order

The control methodology that considers teleoperation systems where the master and the slave are modeled by discrete transfer functions (DTFs) of the same order has been presented in the previous section. This section explains how to use the design equations to control teleoperation systems where the master and the slave are modeled by different order DTFs.

If the master and the slave are modeled by DTFs of the same order the control method allows that the slave follows the master, and it is able also to establish the dynamics of the slave and the slave-master error (i.e. to fix the n poles of the slave and the n poles of the error). If the master and the slave are modeled by different order DTFs, there are two options to design the control system: to increase the order of the smaller DTF, or to reduce the order of the higher DTF. Next, each option is explained describing its effects in the control system.

3.1 To Increase the Order of the Smaller DTF

In this option the order of the smaller DTF is increased to achieve that it has the same order of the higher DTF. The order is increased adding the necessary pole-zero pairs. Pole-zero pairs are added to avoid the increment of the delay attached to the system. The pole is placed in such a way that it does not affect to the system dynamics. The zero is placed near the pole, but avoiding the exact cancellation, in order to increase really the DTF order. It must be checked that the increased DTF has the same static gain that the original DTF.

Below the effects of increasing the order of the smaller DTF in the control are described. First, if a zero is added, the conditions to achieve the evolution of the error as an autonomous system could not be verified, and a constant error between the master and the slave could exist. This is not a problem, because, e.g., in a teleoperation system where the master dimensions are smaller than the slave dimensions, and the output of both was the cartesian position, it will not be desirable that both positions were the same. The effects of increasing the master order are:

- The slave dynamics is completely established.
- All the desired error poles are fixed. However, because of the fact that the error has the same number of poles that the slave order, and the master order is smaller, part of the error depending on the master would be artificially established.

On the other hand, the effects of increasing the slave order are:

- Additional poles of the slave dynamics are established because the slave order has been increased. This is not a problem because all the poles of the original slave dynamics are fixed.
- All the desired error poles are established. However, in a similar way to the previous case, part of the error depending on the slave would be artificially established

3.2 To Reduce the Order of the Higher DTF

In this option the order of the higher DTF is reduced to achieve that it has the same order of the smaller DTF. That is, the same number of pole-zero pairs that there are in the smaller DTF will be considered to design the control system. Therefore some pole-zero pairs of the higher DTF will be removed in the design. In order to remove a pole-zero pair it would be desirable to select the pole further from the dominant poles, and to select a zero near the pole to consider a pole-zero cancellation.

Below the effects of reducing the order of the higher DTF in the control are described. First, if a dominant pole is removed, or a zero that is not near the pole selected is removed, the reduced DTF will be very different to the original DTF and the control gains obtained could not be applied to the real teleoperation system. In addition, when a zero is removed, the conditions to achieve the evolution of the error as autonomous system could not be verified. The effects of reducing the slave order are:

- The slave dynamics is not completely established, because fewer poles have been considered in the design phase.
- Only the number of error poles fixed by the master order can be established. Therefore, part of the error depending on the slave will not be established.

On the other hand, the effects of reducing the master order are:

- The slave dynamics is completely established.
- Only the number of error poles fixed by the slave order can be established. Therefore, part of the error depending on the master will not be established.

3.3 Comparison of Options

If the order of the smaller DTF is increased, the control method can completely establish the dynamics of the teleoperation system, i.e. the slave and the error dynamics is fixed. On the other hand, if the order of the higher DTF is reduced, the dynamics of the teleoperation system can not be completely established. In this case, part of the error dynamics depending on the reduced DTF can not be fixed. In addition, if the slave order is reduced, the slave dynamics will not be completely established. In both options, when the DTF order is increased or reduced, the conditions to achieve the evolution of the error as autonomous system could not be verified, but this is not a problem. Therefore the best option to design the control system of a teleoperator where the master and the slave have different order is increasing the order of the smaller DTF.

The control gains that are obtained modifying the master or the slave DTF in the design phase must be used to control the real teleoperation system. The state convergence methodology allows that the control gains can be directly applied to the real teleoperation system because of the robustness of the control method to the uncertainty of the design parameters [7]. On the other hand, state observers must be designed to apply the control. In the case of the reduced DTF, the state observer must estimate the number of state variables fixed by the higher DTF, so it must be designed using the increased DTF.

4 Experimental Results

The EL (Elbow Pivot) joint of the Grips teleoperation system has been bilaterally controlled in simulation mode using the state convergence methodology. The Grips manipulator system from Kraft Telerobotics is a six DOF teleoperator with force-feedback. The slave is an hydraulic manipulator, and the master is powered by electrical motors. The identified DTFs for the EL joint of the master and the slave, considering a sample time of $T = 0.0005$s, are, respectively:

$$G_m(z) = \frac{3.79 \times 10^{-7} z^2}{z^3 - 2.974z^2 + 2.948z - 0.9741} \tag{5}$$

$$G_s(z) = \frac{1.357 \times 10^{-5} z}{z^2 - 1.9928z + 0.9928} = \frac{1.357 \times 10^{-5} z}{(z-1)(z-0.9928)} \tag{6}$$

The process of identification has been done using the corresponding Matlab Toolbox. Both DTFs have been identified considering the Box-Jenkins model.

As it has been previously explained, when the order of the master and slave DTF is different, the best option to design the control system is increasing the order of the smaller DTF. Therefore the order of the slave DTF must be increased. A pole-zero pair has been added in the slave DTF. The pole has been added far from the dominant poles to avoid that it affects to the system dynamics. And the zero has been placed near the pole:

$$G_s(z) = \frac{1.357 \times 10^{-5} z(z-0.93)}{(z-1)(z-0.9928)(z-0.9302)} = \frac{1.357 \times 10^{-5} z^2 - 1.262 \times 10^{-5} z}{z^3 - 2.923z^2 + 2.8465z - 0.9235} \tag{7}$$

In order to solve the design equations of the control method, all the numerator coefficients of (5) and (7) must not be null. In this case, the coefficients $\{b_{m1}, b_{m0}, b_{s0}\}$ are null, i.e. there are some zeros placed in $z = 0$. For this reason, the zeros placed in $z = 0$ have been slightly modified, and the DTFs considered for the design are the following:

$$G_m(z) = \frac{3.79 \times 10^{-7} z^2 + 10^{-8} z + 10^{-8}}{z^3 - 2.974z^2 + 2.948z - 0.9741} \tag{8}$$

$$G_s(z) = \frac{1.357 \times 10^{-5} z^2 - 1.262 \times 10^{-5} z + 10^{-8}}{z^3 - 2.923z^2 + 2.8465z - 0.9235} \tag{9}$$

In addition, to verify the conditions of the control method between the numerator coefficients of $G_m(z)$ and $G_s(z)$, and to achieve the evolution of the error as autonomous system, the numerator coefficients of $G_s(z)$ in (9) have been modified for the design in this way:

$$G_s(z) = \frac{1.357 \times 10^{-5} z^2 + 3.58 \times 10^{-7} z + 3.58 \times 10^{-7}}{z^3 - 2.923z^2 + 2.8465z - 0.9235} \tag{10}$$

The control gains have been obtained considering that the force feedback gain is $k_f = 0.1$, the slave interacts with a soft environment ($k_e = 10Nm/rad$), and that the poles of the error and the slave are placed in $z = 0.95$.

If the control gains are applied to the teleoperation system considered for the design, DTF (8) and (10), the slave follows the master without error, left part of Fig. 2. However, if they are applied to the increased original system, DTF (5) and (7), the slave follows the master, but there is a constant error because the conditions to achieve the evolution of the error as autonomous system are not verified, right part of Fig. 2. In both cases, a unitary constant operator force has been considered.

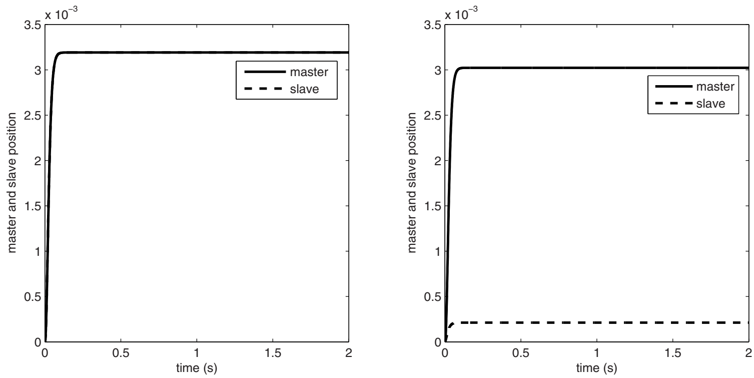

Fig. 2. Master and slave position considering DTF (8) and (10) (left part), and DTF (5) and (7) (right part)

In order to verify the performance of the control over the original teleoperation system, two state observers have been designed for the identified DTFs of the EL joint (DTF (5) and (6)). Both state observers must estimate three state variables. The design of the state observer for the DTF (5) is straight. However, as the order of the DTF (6) is two, the observer has been designed from the DTF (7). In the left part of Fig. 3 the position evolution of the original teleoperation system using the designed observers is shown. It can be verified that the results obtained are the same as the shown in the right part of Fig. 2. The control signals applied to the master and the slave are shown in the right part of Fig. 3. In this figure, the slave control signal has initial values close to zero, but not null.

These results allow verify that the control method by state convergence can be applied to teleoperation systems where the master and the slave are modeled by different order DTFs.

5 Conclusions

This paper has presented a bilateral control method for teleoperation systems where the master and the slave are modeled by different order transfer functions. It has been verified that the order of the smaller DTF must be increased

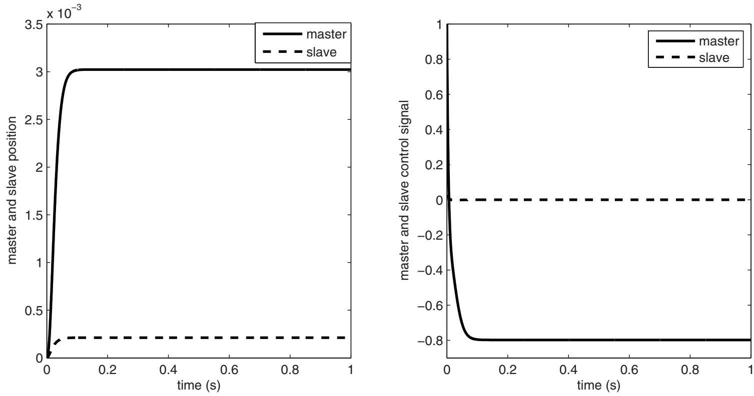

Fig. 3. Master and slave position (left part), and control signal (right part)

to design the control system. Then, state observers that estimate the number of state variables fixed by the higher DTF must be designed in order to apply the control. The control method allows that the slave follows the master, and it is able to establish the dynamic behavior of the teleoperation system.

In the paper the performance of the control scheme has been tested in simulation mode over the EL joint of the Grips teleoperation system. The next work is controlling the real joint. The final aim is controlling all the joints of the system applying the state convergence methodology.

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