PARALLEL IMPEDANCE CONTROL FOR HYDRAULIC TELEOPERATION SYSTEMS

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ABSTRACT
A new type of control architecture for hydraulic teleoperation systems called parallel impedance control is proposed. It is completely different from the conventional bilateral control, which couples the master and slave manipulator as an entity to realize an ideal tool for the operator. The key ideal of our work is that the slave manipulator should mimic the abilities of the operator. The hydraulic teleoperation system is partitioned into an operator-master part and a slave-object part to produce parallel two subsystems such that the slave manipulator can emulate the operator and the master manipulator can transmit the object impedance encountered by the slave manipulator to the operator, thereby providing transparency. The proposed control architecture is applied to a hydraulic teleoperation system and its validity is proved by the experimental results.

KEY WORDS
Parallel, Impedance, Control, Hydraulic, Teleoperation Systems

NOMENCLATURE
\[ b : \text{viscous coefficient (Ns/m)} \]
\[ F_m : \text{applied force by the operator on the master (N)} \]
\[ F_c : \text{contact force of the slave (N)} \]
\[ k : \text{stiffness (N/m)} \]
\[ m : \text{inertia (kg)} \]
\[ U : \text{actuator driving force (N)} \]
\[ V : \text{(reference) velocity (m/s)} \]
\[ Z : \text{impedance (Ns/m)} \]
\[ F_p^* : \text{mean force of the operator muscle (N)} \]

Subscripts
\[ m : \text{master} \]
\[ s : \text{slave} \]
\[ p : \text{operator} \]
\[ e : \text{object} \]
INTRODUCTION
The main aim for the designer of a hydraulic teleoperation system is to achieve “transparency”, which is the feeling that the operator can not distinguish between maneuvering the master and maneuvering the object. The more commonly used teleoperation system is a two-port framework [1-5], which couples the master, the controller block, and the slave into a single entity. This type of two-port framework usually utilizes a four-channel architecture [1-3]. As an alternative approach, a control architecture in which the teleoperation system is partitioned into an (operator+master) part and a (slave+environment) part, has been proposed in [6]. Their control architecture approximates the traditional bilateral force reflection type architecture and models the master, the operator hand and arm as a block.

In this article, contrasting with the two-port framework that couples the master, the controller block, and the slave into an entity, a new type of control architecture is proposed, in which the hydraulic teleoperation system is partitioned into an [operator-master] part and a [slave-object] part to make parallel two subsystems. The principle behind the kernel of the proposed approach lies in building parallel two subsystems. Therefore, the proposed control architecture is called Parallel Impedance Control (PIC). In PIC, the slave impedance is adjusted to match the impedance of the operator (i.e. the operator arm) such that the slave can reproduce the versatile operator motions in the remote site. In this paper, as the first step of our research, a pseudo-operator is introduced into the design of the control architecture instead of operator impedance estimators in order to make the control architecture practical and feasible.

This paper is organized as follows: PIC is described in section 2. The pseudo-operator is described in section 3 and experimental results using a hydraulic teleoperation system to verify the approach are presented in section 4. Conclusions and recommendations for future work are made in section 5.

PARALLEL IMPEDANCE CONTROL

Design Guide
The objective of this study is to make the slave emulate the operator and the master transmit the object impedance encountered by the slave to the operator, as shown in Figure 1. To realize this, the teleoperation system is partitioned into parallel two subsystems, i.e. O-M subsystem [operator-master] and S-O subsystem [slave-object].

Impedance matching between O-M subsystem and S-O subsystem is accomplished, as suggested in Figure 2. The master impedance in O-M subsystem is adjusted to match the object impedance in S-O subsystem such that the operator can operate as if he is interacting directly with the remote object, since the “feel” of the object is embodied in the master impedance. Accordingly the approximate contact force at the slave is displayed to the operator, without the usual force-reflection. Here it is assumed that the object impedance is known in advance. On the other hand, the slave impedance in S-O subsystem is adjusted to match the operator impedance in
O-M subsystem such that the slave can imitate the operator in the remote object. Besides, the mean force of the operator muscle in O-M subsystem (the determination of which will be discussed in subsection 2.2), exists as a reference input on which the reference velocity of the master is dependent. Similarly, this mean force of the operator muscle in O-M subsystem should also be added to S-O subsystem as a virtual input. As a result, the reference input and total impedance of O-M subsystem and SO subsystem are tailored so as to be equal. Therefore it can be concluded that the reference velocity of the master and the slave will be guaranteed to be identical.

As discussed in section 3, the introduction of this virtual input to S-O subsystem induces flexibility in the design of PIC.

Analysis

A teleoperation system consists of a master, a slave, an operator and an object. In order to make the equations derivation more intuitive, a one-degree of freedom teleoperation system is considered. Concentration is focused on the analysis of the master and the slave in rate mode control. The same analysis can also be applied to the position mode control.

The dynamics of the master and the slave are modeled as follows in the form of impedance:

\[ U_m + F_m = Z_m(s)V_m \]  
\[ U_s - F_s = Z_s(s)V_s \]

where

\[ Z = ms + b + k \frac{1}{s} \]

is the impedance model in terms of mass, viscous coefficient and stiffness. Assuming that the slave may not depart from the object, the dynamics of the object interacting with the slave is modeled by the following equation:

\[ F_s = Z_e(s)V_s \]

Where \( Z_e \) is the object impedance. It is supposed that the dynamics of the operator can be approximated as a simple linear spring-damper-mass system in terms of the operator impedance \( Z_o \):

\[ F_p^* - F_m = Z_o(s)V_m \]

The detailed discussion of the parameters of the operator impedance \( Z_o \) in Eq. (5) is postponed to section 3.

The control block diagram is shown in Figure 3, in which it is given that the local velocity controllers of the master and the slave exhibit ideal responses. It is also assumed that the master and the slave are controlled respectively by the local velocity-based impedance controllers so that they hold the following dynamics with appropriate compensations:

\[ F_m = Z_e(s)V_m \]  
\[ F_p^* - F_s = Z_p(s)V_s \]

It is possible to calculate the reference velocity of the master \( V_m \) from Eq. (6), when the master impedance is adjusted to \( Z_e \) and the force applied by the operator \( F_m \) is sensed by the force sensor. Accordingly, the mean force of the operator muscle \( F_p^* \) can be calculated from Eq. (5) supposing that the operator impedance \( Z_o \) is appropriately selected. It is therefore possible to calculate the reference velocity of the slave \( V_s \) from Eq. (7) when the mean force of the operator muscle \( F_p^* \) is added to S-O subsystem as a virtual input and the slave contact force \( F_s \) is sensed by the force sensor. It should be noted that the slave contact force \( F_s \) is only used locally at the slave site for impedance control, and the measured force \( F_s \) is not reflected to the master site. The master and the slave are controlled so as to track the reference velocities \( V_m \) and \( V_s \).

By selecting parameters of \( Z_o \) appropriately, the motion deviation \( (V_m - V_s) \) converges to zero independently of \( F_m \) and \( F_s \). In other words, the motion of the slave converges asymptotically to that of the master.

Concerning stability, it can be concluded that the teleoperation system is stable if the slave is stable because O-M subsystem and S-O subsystem form a parallel structure, and the operator can usually handle a tool (i.e. the impedance controlled master without force reflection) stably. The transfer function from \( F_p^* \) to \( V_s \) at the slave site can be stated as follow:

\[ \frac{V_s}{F_p^*} = \frac{1}{Z_o + Z_e} \]
From Eq. (9), stability of the slave can be guaranteed with appropriate selection of $Z_p$. How to select $Z_p$ is discussed in section 3.

Transparency can be quantified in terms of the match between the impedance of the object encountered by the slave and the impedance transmitted to or felt by the operator. Comparing Eq. (4) and Eq. (6), it can be concluded that transparency is achieved. From Eq. (5) and Eq. (7), it can be concluded that the slave not only replays the motions of the operator but also mimics the dynamics of the operator. Therefore the objective shown in Figure 1 can be realized.

The discussion above does not consider force-reflection and has applications similar to those of [7]. In [7], a mixed force and motion command-based space robot teleoperation system is proposed in which a haptic interface displays the force to the operator based on a virtual world model.

**PSEUDO-OPERATOR**

The operator impedance $Z_p$ was used in the controllers design in the analysis of PIC, as suggested in the block diagram in Figure 3. Therefore it is necessary to define the parameters of $Z_p$ before the controllers can be designed. For simplicity, it is assumed that the operator impedance model in Eq. (5) is linear in section 2. However it should be noted that the parameters of the operator impedance $Z_p$ may change during operation. For example, it has been reported that the viscous coefficient and stiffness of $Z_p$ in Eq. (5) are proportional to the sum of the forces exerted by the flexor and extensor muscles [8].

Recalling the process for calculating the reference velocity of the slave $V_s$ in Eq. (7), the mean force of the operator muscle $F_p^*$ is calculated from Eq. (5) and is then used as a virtual input in Eq. (7). Accordingly $F_p^*$ is only an intermediate variable. If there is change to the parameters of the operator impedance $Z_p$, it causes only the resultant change in the value of the intermediate variable $F_p^*$, and has no influence on the calculation of the reference velocity $V_s$. This conclusion is verified by Eq. (8). Therefore it can be concluded that there is flexibility when selecting the parameters of the operator impedance $Z_p$ and there is no actual need to sense or estimate the “real” parameters of the operator impedance $Z_p$ in PIC. In [9], the pseudo-operator is used and assumed to be passive but not otherwise arbitrary when analyzing the stability of the teleoperation system. By using the flexibility in selecting the parameters of the operator impedance $Z_p$ mentioned above, it is possible to use the pseudo-operator instead of the “real” operator in PIC design and the stability analysis while the conclusions in section 2 holds. In the subsequent discussion, the pseudo-operator impedance $Z_{pp}$ is used instead of the operator impedance $Z_p$.

Infinite choices exist in the selection of the parameters of $Z_{pp}$, so the definition process is difficult. It is known that the impedance of the manipulator should be adjusted to suit the object impedance for stable contact. One of the objectives in PIC related studies is to providing the slave with the ability to deal with various objects stably. Although many methods exist for the calibration of the operator impedance $Z_p$ [10], the operator impedance model is mimicked in this study, and no attempt is made to estimate or sense the parameters of $Z_p$. Using $Z_{pp}$ instead of $Z_p$, Eq. (9) yields that:

$$\frac{V_s}{F_p^*} = \frac{1}{Z_{pp} + Z_e}$$

(10)

It is suggested that $Z_{pp}$ can be defined by adjusting the damping ratio of Eq. (10) with consideration of the object impedance $Z_e$. In other words, the slave impedance is adjusted to suit the environment (high or low impedance). In this case, it is clear that Eq. (8) is also stable.

It is known that the operator impedance changes to fit the object when handling the object, which is also regarded as an operator skill. In future applications, if the operator skill can be modeled in terms of the parameters of the operator impedance, those parameters can be applied in the determination of $Z_{pp}$, and in return the slave will reproduce the versatility of the operator motions when handling the remote object.

**EXPERIMENTAL RESULTS**

Experiments were performed to verify the applicability of the proposed technique. Figure 4 is the photographs of the experimental setup in which the master was a one-degree of freedom lead screw mechanism (LM-GUIDE) driven by an AC servomotor and the slave was a two-degree of freedom hydraulic manipulator. For simplicity, the object was a spring.

![Figure 4 Experimental setup](image-url)
(1500N/m), with one end connected through a force sensor (sensing the contact force \( F_s \)) to the tip of the slave, and the other end fixed to the ground. A force sensor was mounted on the handle of the slider of the master to measure the force applied by the operator \( F_m \). Considering that the master has just one-degree of freedom, the motion of the slave was confined to the vertical axis. The experiment was performed using PIC.

**EXPERIMENT 1**

On the master site, according to Eq. (6), the master impedance should be tailored so as to be identical to the object impedance \( Z_e \), holding pure spring property. However, considering that the mass is the denominator in the numerical integral calculus, the mass was set as 10kg. To ensure safety and smooth operation, the damping coefficient was set as 100Ns/m. That is, the parameters of the master impedance were set as mass=10kg, viscous coefficient=100Ns/m and stiffness=1500N/m. Since the operation of the master is at low frequencies, the response was dominated by the “stiffness” component of the master impedance, which was verified by the “feel” of the operator in the experiment. On the slave site, regarding the impedance of the pseudo-operator \( Z_{pp} \), the parameters were set as mass=200kg, viscous coefficient=1000Ns/m and stiffness=2000N/m, following consideration of the adjustment of the damping ratio in Eq. (10) to an appropriate value of 0.6. Consequently, according to Eq. (7), the slave impedance is set to be equal to \( Z_{pp} \) as mass=200kg, viscous coefficient=1000Ns/m and stiffness=2000N/m. Figure 5 illustrates the force and position tracking performance, with the solid lines representing the properties of the master and the dashed lines representing the properties of the slave. The slave positions and forces faithfully track those of the master without loss of stability. In the force response result, the dotted line presents the time history of the calculated result \( F_p^* \) which is the virtual input for the slave impedance control. Additionally, the relationship between the position response of the master and the force applied by the operator \( F_m \) is demonstrated in Figure 6, which shows approximately a spring property.

**Table 1 Parameters for Experiment 2**

<table>
<thead>
<tr>
<th></th>
<th>Mass (kg)</th>
<th>Damping (Ns/m)</th>
<th>Stiffness (N/m)</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master</td>
<td>10</td>
<td>100</td>
<td>1500</td>
<td>-</td>
</tr>
<tr>
<td>A</td>
<td>200</td>
<td>200</td>
<td>2000</td>
<td>0.12</td>
</tr>
<tr>
<td>B</td>
<td>200</td>
<td>1000</td>
<td>2000</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**EXPERIMENT 2**

Using the same spring as the object, the influence of the impedance of the pseudo-operator \( Z_{pp} \) (equal to the slave impedance) on stably handling of the object by the slave was investigated. The master impedance was set to be identical to that in experiment 1. The viscous coefficient of \( Z_{pp} \) was selected for two cases (i.e. case A and B), the parameters of which are displayed in table 1. The parameters in case B are identical to those in experiment 1. An ideal force step input (calculated by computer instead of applied by the operator) was added at the master and the contact
force response of the slave was measured, the results of which were shown in Figure 7. The viscous coefficient in case A was small and oscillations were observed. The viscous coefficient in case B was greater than that in case A and oscillations were not observed. Flexibility in the selection of the impedance of the pseudo-operator $Z_{pp}$ is advantageous for handling different objects and is a distinct benefit of using PIC.

**CONCLUSIONS**

The authors have proposed a new kind of control architecture PIC for hydraulic teleoperation systems. The key idea underpinning the study is that the teleoperation system is partitioned into two parts to make parallel two subsystems so that the slave can emulate the operator and the master can transmit the object impedance to the operator. A pseudo-operator is used in the controllers to increase the simplicity and applicability of the proposed control architecture. The results of the experiments show that PIC is a feasible method for the control of a hydraulic teleoperation system. Design and stability analysis with regards to the time-delay, and seeking better adjusting rules of the pseudo-operator impedance remain to be the future work.

![Figure 7 Influence of Damping with Force Response in Slave](image)

**REFERENCES**