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EXPERIMENTAL COMPARISON OF TELEOPERATION SCHEMES FOR HYDRAULIC MANIPULATORS

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ABSTRACT

Many studies have been conducted for quantitative/qualitative analysis and comparison of various teleoperation schemes. Position-position, force-position and 4-channels are to name a few. However most of this research has been focused on electrically actuated manipulators. This paper documents the comparative study of various teleoperation schemes explicitly for hydraulic manipulators. Identical water-hydraulic actuators have been used as master and slave. Three popular schemes of teleoperation: position-position, force-position and 4-channels have been implemented and tested. The results are compared on the basis of criteria established by other researchers for electrically actuated manipulators. The study has been done using manipulators with single degree of freedom to emphasize the comparison. The research has been carried out with a goal to extend the number of degrees of freedom in future to obtain a practical water-hydraulic teleoperation system useful in industrial applications such as International Thermonuclear Experimental Reactor (ITER).

KEYWORDS

Teleoperation, Hydraulics, Haptic, Robotics

NOMANCLATURE

F_e : Environment force
F_m : Master force
F_{op} : Operator force
F_s : Slave force
F_{12} : Force tracking
h_{11} : Free motion impedance
h_{21} : Position tracking
K_p : Proportional gain
X_e : Environment position
X_m : Master position
X_{op} : Operator position
X_s : Slave position
Z_{11} : Max. transmittable impedance
Z_e : Environment impedance
Z_m : Master impedance
Z_{op} : Operator impedance
Z_s : Slave impedance

INTRODUCTION

Hydraulics is always a choice of interest in industrial applications where high forces are required with compact size actuators. Simple construction and high reliability are added advantages of hydraulics. It has been proving its worth in applications like automobiles, excavators and airplanes with a high degree of reliability and low maintenance. With the developments in water hydraulics (water is used as a pressure medium rather than oil), scope of hydraulic applications has widened further. The characteristic advantages of hydraulics together with the characteristics of water as the pressure medium (fire and environmentally safe, chemically neutral, not activated not affected by radiation) are highlighted in critical applications such as remote handling operations in International Thermonuclear Experimental Reactor (ITER) [1].

Remote handling adds another dimension in control of hydraulic manipulators. It leads to the imagination of adding haptic interfaces with force feedback on hydraulic manipulators. It has been reported that haptic-augmented interactive systems seems to give about a two-fold performance improvement over purely graphical interactive systems [2].

Many studies have been conducted for quantitative/qualitative analysis and comparison of popular teleoperation schemes [3][4]. However, most of this research has been focused on electrically actuated manipulators. With new apparent needs and with advancement of water hydraulic components, heavy duty hydraulic manipulators will soon be employed in teleoperation applications.

Much research has already been done in past to teleoperate hydraulic manipulators in many industrial "situations". Working hydraulic teleoperation systems are under operation across the world to deal with tasks in hazardous conditions. However, most of these teleoperation schemes were developed for custom made manipulators with specific teleoperation capabilities. In summary no off the shelf techniques or general solutions are available.

With the development of ITER, once again, the need of such investigation has become evident. The manipulator has to have 6 degrees of freedom composed of water hydraulic actuators.

In authors knowledge no comprehensive and detailed studies have been performed to develop and test methods for teleoperation of hydraulic manipulators. It is a first attempt to investigate the behavior of low pressure water hydraulic actuators under teleoperation. Both master and slave are identical water hydraulic cylinders (1 dof manipulators). The goal is to investigate and generalize the teleoperation techniques for water hydraulic manipulators, and widens the scope of application. The research will direct to extend the number of degrees of freedom to obtain a teleoperation system useful in industrial applications such as ITER.

In the following section we will discuss the implemented **teleoperation schemes**. A set of parameters will be mentioned under the section **evaluation criteria**. Hardware and software used for the experiment will be discussed under the heading of **experimental setup**. In the end **results** will be plotted and **conclusion**s will be drawn.

TELEOPERATION SCHEMES

Lawrence [5] introduced a general and fundamental architecture for teleoperation. In this architecture both force and position information can be exchanged bilaterally between master and slave. However, the architecture can be modified to fit into any general scheme by setting the parameter values. The architecture also provides the description of optimized transparency in a teleoperation scheme. Transparency is the measure: how much the operator can have the feel of the task. An ideal teleoperation system should be transparent.

From the teleoperation point of view there is no reason not to use the position and force information bilaterally. However, from control point of view it is not possible many times. The reason could be the unavailability of sensors. Also introduced communication delays suggest the use of minimum transfer of information for system stability.

Lawrence architecture can be modified and can be implemented with the absence of certain communication channels. Ming [6] has mentioned and experimented with several schemes in his work. In the following paragraphs we will discuss the schemes of our interest.

Position-position scheme

As the name implies only the positions of master and slave are bilaterally exchanged through transmission channels. The architecture is also referred as position error scheme in text. Figure 1 illustrates the implemented control system.

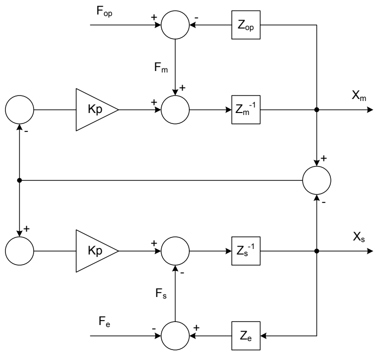

Figure 1 Position-position scheme

The forces acting on master and slave can be equated as in (1) and (2) below:

$$F_m = X_m - X_s \tag{1}$$

$$F_s = X_m - X_s \tag{2}$$

In some cases a scaling factor is required before the forces are reflected. However in this case it is set to one, so same forces are reflected at master and slave.

Force-position scheme

In this scheme position of master is transmitted to the slave, which tries to follow it as efficiently as possible. In the other direction force experienced by slave is transmitted to master, which is felt by the operator. The architecture is also referred as force reflection scheme by some authors.

The reflected force can be scaled up or down as per requirement. However, in this case the scaling factor is set to one, so the same force is experienced by master as by slave. Figure 2 depicts the control system of implemented scheme.

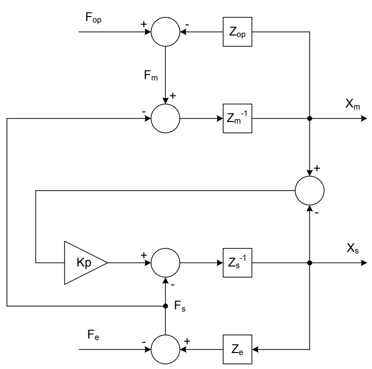

Figure 2 Force-position scheme

Forces acting on master and slave are described by equations (3) and (4) below:

$$F_m = F_s \tag{3}$$

$$F_s = X_m - X_s \tag{4}$$

4-channels scheme

As the name of the scheme suggests all the four channels of information mentioned in Lawrence [5] architecture are utilized to exchange information. Forces as well as positions of both master and slave are bilaterally exchanged. The presence of position and force sensors in both master and slave manipulators is thus compulsory.

The implemented scheme is shown in Figure 3. It can be observed that all the parameters are quite coupled together. It is hard to predict the behavior of the system if any one of them is modified.

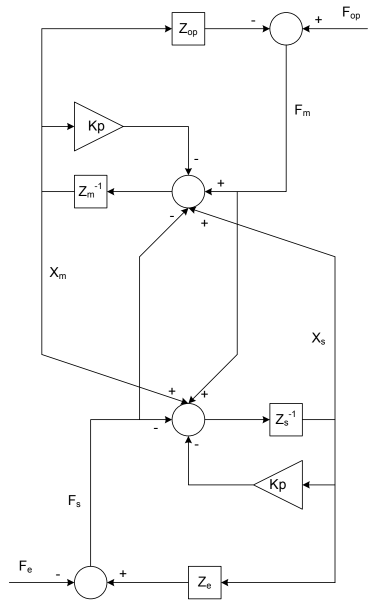

Figure 3 4-channels scheme

Figure 3 also indicates that no controllers have been implemented for communication channels. As both master and slave manipulators are connected to same control system, so the communication delays are neglected in this case. Also as master and slave are identical, so no scaling is required.

Equations (5) and (6) describe the forces acting on master and slave manipulators.

$$F_m = -F_{op} + F_s + X_m + X_s \qquad (5)$$

$$F_s = F_e - X_s + F_m + X_m \qquad (6)$$

EVALUATION CRITERIA

The sole criteriaon to evaluate the performance of master-slave systems is the operator, who can notice the difference in efficiency of various teleoperation schemes. However, from analytical point of view quantitative evaluation of such systems is important.

Aliaga [4] in his work has established criteria to evaluate and quantify the performance of a teleoperation system. According to him performance of a master-slave system can be experimentally evaluated by operating them under two basic conditions:

1. Unconstrained movement: Slave is moved freely in its environment. Mathematically this condition can be established in equation (7).

$$F_s = 0 \qquad (7)$$

2. Hard Contact: Slave is made to contact and apply force against an infinitely hard surface. Mathematically this condition can be established in equation (8).

$$X_s = 0 \qquad (8)$$

The four established parameters are obtained from the two-port representation matrices of a teleoperated system. He also has shown how a teleoperation system can be completely expressed in terms of these four parameters.

Aliaga [4] has tested the criteria with electrically actuated master-slave manipulators. However, in our case, the objective is to analyze the established parameters with hydraulic actuators. The parameters are summarized in Table 1 below.

Table 1 Evaluation parameters

Test Condition	Parameter	Relationship	Desired Value
Unconstrained Movement	Free motion impedance	$h_{11} = \left.\frac{F_m}{X_m}\right\vert_{F_s=0}$	$\to 0$
	Position tracking	$h_{21} = \left.\frac{X_s}{X_m}\right\vert_{F_s=0}$	$\to 1$
Hard Contact	Force tracking	$F_{12} = \left.\frac{F_m}{F_s}\right\vert_{X_s=0}$	$\to 1$
	Maximum transmittable impedance	$Z_{11} = \left.\frac{F_m}{X_m}\right\vert_{X_s=0}$	$\to \infty$

EXPERIMENTAL SETUP

Two identical water hydraulic cylinders presented in Figure 4 have been used to form a master-slave teleoperation system. Both cylinders are equipped with identical position encoders and force sensors.

Cylinders are connected to a real time system for control and data accusation, which operates at a frequency of 1 KHz. Position controllers have been implemented for master and slave. A stiffness value of 0.25 N/m has been chosen for both cylinders. A hard contact surface has been provided for the slave. Teleoperation schemes mentioned before were implemented.

During the experiment the master cylinder is operated by the operator randomly; first in free motion region of slave and then slave against the hard contact surface. The position and force data from master and slave is acquired for a time period of 60 seconds. The obtained results are plotted in following section.

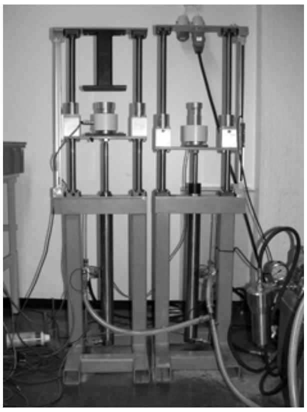

Figure 4 Master-slave hydraulic cylinders

RESULTS

Parameters h_{11} (free motion impedance), h_{21} (position tracking), F_{12} (force tracking) and Z_{11} (maximum transmittable impedance) have been obtained for each teleoperation scheme as per Table 1.

Figures 5, 6 and 7 show the plots of these parameters for each of the scheme.

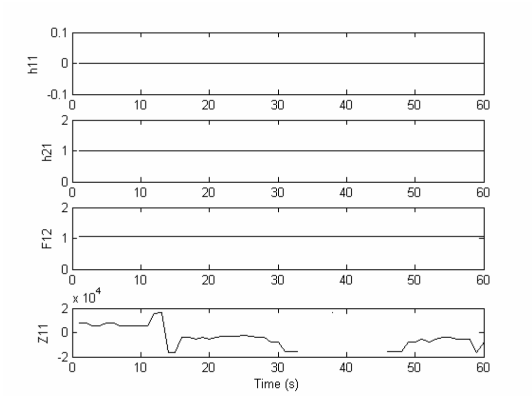

Figure 5 Position-position scheme

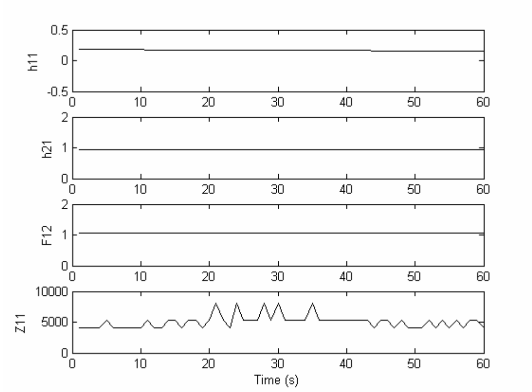

Figure 6 Force-position scheme

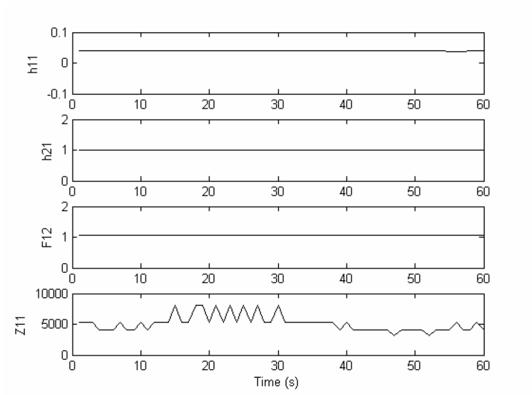

Figure 7 4-channels scheme

The plots establish the fact that same set of parameters (h_{11}, h_{21}, F_{12} and Z_{11}) can be utilized for the evaluation.

Position-position and 4-channels schemes provide the optimal performance. Results from force-position scheme are also satisfactory, apart from parameter h_{11} which is less closer to zero. Position-position scheme provides the best values of maximum transmittable impedance in this case.

CONCLUSION

Three schemes of teleoperation; position-position, force-position and 4-channels are implemented for the first time using identical low pressure water hydraulic cylinders as master and slave. Proposed criteria for the evaluation of teleoperation schemes have been used to analyze the master-slave system. The criteria had already been tested for electrically actuated manipulators. However the idea was to understand the utilization of same criteria for a hydraulic master-slave system.

It has been shown that mentioned parameters can be utilized for the evaluation of hydraulic teleoperation systems. Evaluation parameters have been obtained for each of the teleoperation schemes and used for the comparison purpose.

All master-slave schemes seem to give satisfactory performance. Highest values of maximum transmittable impedance were obtained with position-position scheme. Position-position and 4-channels schemes provide much lower values of unconstrained movement impedance than force-position scheme. All schemes provide good conformance of position and force tracking.

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