Load Self-Sensing Control Scheme for Telemanipulation - Part 1: Theory

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Abstract: The paper presents a novel approach to a control design of bilateral teleoperation systems with force-feedback dedicated only for a sensor-less weight sensing. The problem statement, analysis of research achievements to date, and the scope of the study are presented. The new design of a control unit for a master-slave system with force-feedback was based on a dynamics inverse model. The model was used to subtract a value of force in the force-feedback communication channel that the system might generate during free-motion. A substantial part of the paper, is focused on a development of a mathematical model covering phenomena occurring in the investigated control scheme.

Keywords: telemanipulation, force-feedback, inverse modeling, telerobotics, remote control

1. Introduction

Researcher's attempts to ensure safe operation of various machines have led to the development of master-slave control systems with force-feedback. The applications of master-slave systems are widespread, including performing tasks in environments hostile to man as: (1) contaminated sites; (2) in the depths of oceans and seas; (3) radioactive interiors of nuclear power plants; and even other applications like (4) medical rehabilitation.

Most of master-slave systems are unilateral [11–16, 21, 28, 30, 32, 36–38]; i.e. a device that is being controlled (slave) should behave exactly as the device that controls it (master). However, as research continued, it was noticed that the operator, that enters into interaction with the master subsystem/manipulator should be able to feel the haptic effect of the environment on the slave subsystem side.

The haptic effect problem posed significant challenges in its practical application, due to large distances and the inevitable time delay [1–5, 9, 10, 17, 18, 20–22, 26–31, 33, 39, 45, 46]. This specific branch of robotics faces many challenges that have been tackled by scientists all over the world for many years. The main problem that arises in the communication channel between actuation devices is a time delay, which inhibit their communication. The problem is particularly pronounced, while sending information over large distances. Another challenge is the stability of such systems, given known or unknown delays in the communication channel.

So far, sensor-less bilateral teleoperation solutions are mainly based on piezoelectric crystals. Piezoelectric crystals can work at the same time as actuator, body and a force sensor. Especially, when we are developing devices from a large group of single crystals. For the first time in 1998, Tadao Takigami et al.; the authors of the paper, introduced a self-sensing actuator which was a new concept for intelligent materials, where a single piezoelectric element simultaneously performs as a sensor and an actuator at the same time [40]. In 2006, Yugo Cui, discovered that the displacement of a micro-motion worktable driven by a piezo-ceramic actuator could be measured by the self-sensing method in the absence of an independent sensor [44]. Finally in 2007, Wei Tech Ang, found that the effective employment of piezoelectric actuators in micro scale dynamic trajectory-tracking applications was limited by two factors: (1) the intrinsic hysteretic behavior of piezoelectric ceramic; and (2) structural vibration as a result of the actuator’s own mass, stiffness, and damping properties [41]. Then, Yusuke Ishikiyama and T. Morita in 2010, published a paper about self-sensing control method of piezoelectric actuators that compensate for the hysteresis characteristics by using the linear relationship between the permittivity change and the piezoelectric displacement [7]. Also in 2010, Micky Rakotondrabe focused his research on the dynamic self-sensing of the motion of piezoelectric actuators [24]. The proposed measurement technique was subsequently used for a closed-loop control. Aiming to obtain a self-sensing scheme that estimates the transient and steady-state modes of the displacement, the author extended a previous static self-sensing scheme by adding a dynamic part. Again in 2011, Micky Rakotondrabe, developed a new micro-gripper dedicated to micromanipulation and micro-assembly tasks [23]. Based on a new actuator, called a thermo-piezoelectric actuator, the micro-gripper presented high-range and high-positioning resolution. Finally, Micky Rakotondrabe continue his studies and in 2015, presented his work about a self-sensing technique, using...
an actuator as a sensor at the same time [24, 32]. This was possible for most actuators with a physically reversible principle, such as piezoelectric materials.

So far, the main presented control schemes for bilateral teleoperation systems with force-feedback have some defects. These defects mean the use a large number of sensors mediating between the environment and the bodies of the slave manipulator, especially in rotary joints. A situation in which the environment affects one degree of freedom in accordance with that degree of freedom, is relatively simple by using a single sensor. However, where the design of the manipulator depends on many degrees of freedom, and moves in the three-dimensional space, use of a single or multiple sensors single or multiple sensors could be considered as expensive, or not adequate for the proper operation of such a system.

The paper presents an approach to design of a control scheme for a master-slave system with force-feedback. The difference between sensor methods thus far is that, in the case of the proposed control scheme, there are no sensors mediating between the manipulator body and the environment, relative to papers [6, 19, 34, 35, 42, 43]. The same thing can be noticed in self-sensing and piezo-ceramic micromanipulators used for micromanipulation in an impedance control methods [7, 8, 23–25, 40, 41, 44]. The only sensors used in whole system are position encoders and pressure sensors. Whole manipulator body is considered as perfectly rigid body. In this paper, the operator needs to feel the manipulator load, but also a haptic effect of a contact and pressure. Modified system is described in details in Fig. 3.

During analysis, the Slave subsystem is a duplicate of the Master subsystem under conditions of kinematics, dimensions and mass. This subsystem also moves in the same environment as the Master subsystem. Slave manipulator is described by its mass \( M_s \), gravity force \( G_s \), position \( x_s \), control force \( F_s \) (theoretically including Slave actuator) that is generated by the actuator, and the environmental impact – by force \( F_e \). The transfer function \( B_i \) that describes dynamics of both manipulators, can be presented as the equation (1):

\[
B_i = \frac{1}{(M_i s + h_i)s},
\]

where \( i \) – index, index \( m \) for Master subsystem, index \( s \) for Slave subsystem, \( s \) – Laplace operator, \( M_i \) – mass.

2. Self-Sensing Control Scheme for Teleoperation with Perfectly Rigid Bodies

The presented sensor-less control scheme for bilateral teleoperation consists two subsystems - the Master subsystem and the Slave subsystem. Both subsystems, the Master (a) and the Slave (b) are considered as simple rigid objects described by their inertia, and are presented in the Fig. 1.

These manipulator bodies move in an environment described by the dissipative element \( h_i \). The damper represents any type of motion resistance. The bodies of the manipulators move without the friction between them, and the world frame. Master subsystem acts as a motion scanner which sends information about its own position \( x_m \) to the Slave manipulator.

Master subsystem motion depends on three forces applied to the body of Master manipulator. The first is the gravity, described as \( G_m = M_m g \), where \( g \) is the acceleration of gravity and \( M_m \) is the mass of the body. The second force, is the force applied by the operator \( F_h \), to the body of the Master manipulator. Last force applied to the body of Master manipulator is \( F_s \) which is transferred in communication channel from Slave subsystem. For theoretical analysis transmittance of Master subsystem actuator, resisting operators motion was not considered.

3. Telemanipulation control schemes

In the paper, system do not measure environmental force impact, but it estimates its value based on the control signals of the slave controller and current Slave manipulator position. Modified structure of the telemanipulation system is presented in Fig. 2.

In the Figure 2, system has an additional block. The estimation block, calculates the force of environmental impact based on the force value computed by the model of the Slave subsystem. The force-feedback estimation block, subtracts measured control signal of the drive, from that estimated by the model in free motion. This measured force could be a hydraulic pressure, a voltage or like it is presented in this paper – a pneumatic air pressure. Modified system is described in details in Fig. 3.

The primary problem of methods using force sensors and rotary joints is that, that the control unit needs a large amount of the force sensors placed on the manipulator arm. This feature is crucial to deliver correct value of environmental torque impact in each rotary joint. In this paper, the method computes...
value of environmental force impact on the slave manipulator to the operator which is measured in the drive track in each joint of the Slave manipulator independently. Presented system requires as many sensors of current, voltage or pressure, as many dimensions of freedom are included in the Slave manipulator structure. Rotary or linear joints do not make difference for presented method of estimation environmental forces, on each joint, in the force-feedback communication channel. In the result the system, based on the presented method of estimation in the force-feedback channel (equipped with an ideal model), will send to the Master manipulator zero value of force, during free motion of Slave manipulator. This conclusion will find its proof in the next section of the paper.

4. Theoretical system analysis

To investigate the effectiveness of presented method it is required to find the Slave subsystem closed-loop and the inverse model transmittances, by reducing the Slave subsystem transmittance to a simple transfer function. First step of transmittance analysis, the relation of two signals $x_m$ and $x_s$, which is the position of Master, send to Slave and the $x_s$ which is the position of the Slave manipulator. The transmittance $x_m/x_s$ is presented as follows (2):

\[
\frac{x_m(s)}{x_s(s)} = \frac{K(s)}{(M_s h_s)s + K(s)}.
\]  

Equation (2) describes the closed-loop system of the Slave manipulator, including transfer function of the position controller $K(s)$. The controller transfer function is unknown for the transmittance analysis, because it is possible to use many structures of controllers like simple proportional P, PI or even PID. Different linear controller structure would not change presented method result.

In a continuation of transmittance analysis, the Slave subsystem closed-loop transfer function is determined as (2). The second transmittance, including the inverse model of force-feedback estimation block and the closed-loop of Slave subsystem, is determined as (2). The transmittance analysis, because it is possible to use many structures of controllers like simple proportional P, PI or even PID. Different linear controller structure would not change presented method result.

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\]  

Equation (3) describes one of two, characteristic transfer functions, the function that is responsible for reducing the value of force in a force-feedback communication channel. The force in the communication channel of manipulator system using rotary joints without additional force-feedback estimation block, sends to the operator and Master subsystem a value of force used to achieve the desired configuration of Slave manipulator. This force will depend on actual position of each joints, and also acceleration and velocity, including inertia of individual bodies and motion resistance. This feature appears only during free-motion condition.

Next step, requires finding the transmittance of closed-loop Slave system, which senses the control signal $F_s$ from the controller’s block $K(s)$ output. Theoretically, this signal is just the control force, applied to the body of the Slave manipulator. In practice, the control signal on the Slave side could be a voltage, a current or a pneumatic air pressure. To find this transfer function, it is required to find a solution of two equations presented as (4):

\[
\begin{align*}
F_m(s) &= K(s) h_s x_m(s) \\
x_m(s) &= \frac{F_s}{(M_s h_s)x_s(s)}
\end{align*}
\]  

where $e(s)$ is a Slave subsystem position error, described as $e(s) = x(s) - x_s(s)$. Looking for a solution of the equations (4) by a ratio of $F_m(s)/x_m(s)$, we obtain an equation (5):

\[
\frac{F_m(s)}{x_m(s)} = \frac{K(s) h_s}{(M_s h_s)x_s(s)}
\]  

exactly the same as transmittance (4). This means that sub-system Slave during free-motion in remote environment, calculates zero value in the force-feedback communication channel. This is confirmed by the transmittance difference, which is represented as force-feedback estimation block in the Fig. 3, and by the equation (6):

\[
\frac{F_m(s)}{x_m(s)} = \frac{K(s) h_s}{(M_s h_s)x_s(s)}
\]
\[ F_s = \frac{F(s) - F_m(s)}{x_m(s)} = 0. \]  
(6)

For the operator of a system, which uses presented method, this situation is comfortable, but requires very accurate dynamics inverse model of Slave subsystem. It is important to show, that the slave subsystem which is under influence of the environmental force, sends to the operator exactly the force of the environmental impact. Of course, in a case of theoretical analysis of ideal system presented in the Fig. 3.  
The force-feedback transparency analysis, requires external forces to be taken into account. This forces are included in equations (3) and (5). Two new equations are obtained (7) and (8), which describes the Slave subsystem in the Fig. 3, including external forces:

\[ \frac{F_m(s) - G_s}{x_m(s)} = \frac{K(s)(M_s + h_s)s}{(M_s + h_s)s + K(s)} \]  
(7)

\[ \frac{F(s) - G_s - F_s}{x_m(s)} = \frac{K(s)(M_s + h_s)s}{(M_s + h_s)s + K(s)}. \]  
(8)

Subtracting equations (7) and (8) and after simplifying them, we obtain the equation (9):

\[ F(s) - F_m(s) = F_i(s). \]  
(9)

where the difference \( F(s) - F_m(s) \) according to the control scheme of Fig. 3, corresponds to the signal of force-feedback communication channel \( F_i \), presented as the equation (10):

\[ F_i = F_s. \]  
(10)

5. Conclusion

This paper is a part of the theory proof, that if it is possible to use a high accurate mathematical model of the Slave subsystem, it is possible to transmit the value of the environmental force impact, to the operator by using the presented method. Note, however, that getting a model that exactly corresponding to the real object, is in practice very difficult or even impossible, so the value of estimated environmental force in the force-feedback communication channel by using presented method or system, strongly depends on the accuracy of this model.

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Układ sterowania samowyznaczający obciążenie dedykowany dla zdalnej manipulacji – część 1: teoria

**Streszczenie:** W artykule przedstawiono nowe podejście do projektowania sterowania dwustronnym systemem teleoperacji z siłowym sprzężeniem zwrotnym, dedykowanym tylko do wykrywania obciążenia w postaci ładunku. Opis problemu, analiza dotychczasowych osiągnięć badawczych oraz zakres badania został zaprezentowany w pracy. Nowy projekt jednostki sterującej dla systemu Master-Slave z siłowym sprzężeniem zwrotnym oparty został na dynamicznym modelu odwrotnym. Model został użyty do odkrywania wartości siły w kanale komunikacyjnym sprzężenia zwrotnego, który może generować system podczas ruchu swobodnego. Ważna część pracy została poświęcona analizie matematycznej obejmującego zjawiska zachodzące w badanym schemacie kontroli.

**Słowa kluczowe:** zdalna manipulacja, siłowe sprzężenie zwrotny, odwrotne modelowanie, telerobotyka, zdalne sterowanie

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