Theoretical and experimental overview of bilateral teleoperation control laws

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Abstract

This paper presents the application and the comparison of bilateral teleoperation laws applied on a device made of two industrial systems equipped with force sensors. Theoretical study of these kinesthetic couplings were carried on and experimental results are presented showing forces interactions during movements. A poor connection is found between the accuracy of the force sensor and the quality of the haptic feedback.

1. Introduction

The applications of kinesthetic coupling for master-slave manipulators are nowadays widely spread, using dedicated haptic interfaces as master arm and sometimes converted industrial robots. These “not-specifically-designed” master arms benefit of their large availability in the industry and their high robustness, such as [9]. However they have drawbacks like sensors non-suitable for bilateral control laws hence the possibility to improve them with few additional, or cheap, equipments is an important field of research.

The time delay is another big issue in teleoperation research, [7], but this issue appears only for long distance teleoperation or network communications whereas many of the industrial teleoperation applications are co-located, meaning the operator and the remote arm are less than a few meters far-off. For these situations the most efficient solution is to use a single DSP board despite its material limitation. The issue is then to realize a bilateral controlled master-slave system which makes do with the single DSP board capacities and the discretization of the electric signals which can induce instability.

Although stability is a primal point when considering bilateral control law and can lead its setting up like in [5], it can also be a simple condition of well behavior for the coupling [12]. Moreover passivity is sufficient to ensure stability if it is assumed that the operator and the environment can be described as passive components [4], then this condition will not be specifically stressed on below despite its importance.

Among various ways to compare the characteristics of bilateral couplings the fidelity defined by Çavuşoğlu in [2] is a very interesting solution, following and completing the works of Lawrence [5] and Yokokohji [12], and this metric can also be used as an optimization parameter. But it depends on the task and on the environment’s impedance which makes it not very well-suited for our needs.

This paper explains the practical study of two dif-
ferent classes of teleoperation laws. The first one is called Position-Position, also named Symmetric Position in [12], and the second one is called Force-Position. Sections 3 and 4 emphasize the implantation of these kinesthetic couplings: their theoretical issues and the results of the tests carried on. To begin this article, section 2 describes the master-slave manipulators used as testbed.

2. Description of the experimental device

The control laws proposed in the following sections have been tested on two electromechanical linear positioning systems (EMPS) presented on figures 1 and 2. An EMPS is composed of a 24V-40W DC motor connected to a screw through the medium of a compliant coupling which can compensate small misalignments. The linear motion of the carriage is created by the ball screw and its 2.5mm slope, which is equivalent to a screw gear ratio of $2513 \text{rd} \cdot m^{-1}$. Position and speed are read by an incremental encoder and a tachometer, but the tachometers are not wired for our experiments. The original incremental encoder, at the right end of the device, has a resolution of 250 impulsions per rotation, on two tracks in quadrature. With transition detections, the accuracy is of more than $159 \text{pt} \cdot \text{rd}^{-1}$. But the two devices are not totally mechanically identical because one of them is equipped with a 500 points incremental encoder instead of the tachometer, which modification can only increase accuracy.

The mechanical and electrical parameters of the two EMPS devices were previously identified by Pham in [8], based on the work developed by Gautier in [3]. Its numerical continuous model is drawn in yellow in the box on figure 3, its mechanical and electrical parameters are defined in table 1.

Both EMPS and sensors are plugged to a DS1102 dSPACE DSP board, which is controlled via Matlab-Simulink and the toolbox Real Time Workshop.

A force sensor was screwed on each EMPS. One of them is an ATI 6 axis force/torque sensor and the other one is a linear potentiometer fused to a spring. The ATI has, according to the constructor, a sensing range of $\pm 165 \text{Newtons}$ with a resolution of $7.8 \times 10^{-3} \text{N}$, but due to the lack of ADC/DAC channels on the DS1102 only the 3 most important components for our experiment (one axis movements and forces) among the 6 axis of the ATI sensor are read. So its accuracy is slightly reduced but is still satisfactory, especially compared to the linear potentiometer whom accuracy was previously evaluated to $0.5 \text{N}$.

The use of two different technologies will let us evaluate the need of a high precision sensor for haptic tasks.

Four more points have to be explained before the experimental developments:

- Throughout all the experiments all the signals from the sensors were filtered in-line, using Chebyshev or FIR numerical filter. Those filters were designed with a cutoff frequency based on the results of physiological studies like [10] and [11], and to introduce as little delay, due to phase difference, as possible considering the sample rate of 2kHz.

- Through the rest of this paper, the EMPS with the ATI force sensor is marked out arbitrarily as "master" and the other one with the linear potentiometer is marked out as "slave", these names were only a useful convention for the experiments but do not indicate that the operator has to use the EMPS + ATI device as the master arm. It will be explicitly pointed out if the control law creates a difference between the two parts of the device.

- It should also be stressed out that this paper does not treat of force homothety because the type of haptic tasks selected requires much similarity as possible between the forces felt by the operator and the interaction forces between the slave arm’s tool and its environment. Moreover homothety has only little influence on the characteristics of bilateral control laws.

<table>
<thead>
<tr>
<th>Definition</th>
<th>Value</th>
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<tbody>
<tr>
<td>$j_m$ Equivalent inertia of the system</td>
<td>$4.8 \times 10^{-6} \text{kg} \cdot \text{m}^2$</td>
</tr>
<tr>
<td>$g_r$ Gain between voltage and torque</td>
<td>$1.14 \times 10^{-2} \text{Nm} \cdot \text{V}^{-1}$</td>
</tr>
<tr>
<td>$f_s$ Coulomb friction coefficient</td>
<td>$5.3 \times 10^{-3} \text{Nm} \cdot \text{rd}^{-1}$</td>
</tr>
<tr>
<td>$f_v$ Viscous friction coefficient</td>
<td>$2.1 \times 10^{-5} \text{Nm} \cdot (\text{rd} \cdot \text{s}^{-1})^{-1}$</td>
</tr>
</tbody>
</table>

Table 1. Parameter definitions

Figure 2. Sketch of the EMPS
Three others expressions used below have to be defined: "free fly stage", "contact stage" and "transition stage". The contact stage refers to the movements of the master arm when the slave arm is in contact with the environment, in contrast the "free fly" stage refers to the motions done by the operator when the slave arm is in contact with the environment (soft or hard object, fixed or not). The transition stage refers to movements with intermittent contact between the slave arm and its environment.

3. Position-Position

This is the most "natural" teleoperation law, because it is totally symmetric and its tuning is based on classical PID control design such as those developed in [1]. Moreover the passivity of this kind of system is easy to keep up [6] and will not be explicitly treated here.

3.1. Transparency

The first step in the set up of a teleoperation system using position-position control law is to make both master and slave robots as transparent as possible, i.e. to set their internal impedance at the lowest level [5]. Impedance, defined by \( Z = \frac{\text{Force}}{\text{Speed}} \), is the characteristic which represents the system response to the force applied by the operator.

To achieve transparency a forward compensation of the friction and inertia would be, theoretically, efficient. But for the type of manipulations we focus on, motions in haptic utilizations are often alternative and of little amplitude, it won’t work, even using a tachometer, due to the constant changes of directions. So according to the model of an EMPS equipped with a force sensor in figure 3, the impedance can be written as:

\[
Z = \frac{K \times (kv g_0 + j m s)}{kp kv g_t + K \times 0.8(2.5 \times 10^{-4})^2}
\]

where:
- \( s \) is the Laplace variable,
- \( K \) is the spring stiffness,
- \( kp \) and \( kv \) are, respectively, proportional and derivative gains of the PD controller.

To achieve transparency \( Z \) must be very low, \( Z < 10^{-2} \), and to ensure the stability of the system, its phase margin should be around \( 45^\circ \). After the choice of this two parameters, the expressions of \( kv \) and \( kp \) are still functions of \( s \), i.e. the pulsation. But it is assumed that the device is used for haptic teleoperation hence it works only under low frequencies orders and the frequency term of \( kp \) and \( kv \) can be neglected.

The calculation gives for the EMPS with the ATI force sensor \( kp = 4 \times 10^9 \) and \( kv = 0.09 \), and for the EMPS with the linear potentiometer \( kp = 3000 \) and \( kv = 0.09 \), for the experiment these last two values were slightly reduced. The two EMPS had different performances using the same force sensor so the problem was caused by the lower precision of the original encoder on the EMPS. The simulation results are represented on figure 4 and show that the EMPS with transparency has still a little inertia but far less friction than real.

The value of \( Z \) is the key factor for the transparency of the system, if its value is too high the device will be able to support more noise but it won’t appear without inertia or friction.
3.2. Teleoperation

Once the two parts of the teleoperation device are "virtually" transparent, the bilateral position-position control law can be applied to it. Based on the Simulink sketch of the coupling on figure 5, its tuning is very simple: the master and the slave have good transparency and can be treated as similar passive elements with low inertia and damping. The whole system can be represented by two masses sliding on a very low friction surface linked in parallel by a spring and a damper, where the proportional gain $k_p$ is the spring and the derivative gain $k_v$ the damper. The classical PD setting gives $k_p = 13$ and $k_v = 0.06$, theses values were very slightly reduced during the tests to eliminate vibrations induced by the original encoder.

"In hand" performances of this control law, which are drawn on figure 6, are good: the tracking error is only about 1% even for the trajectories with the largest amplitudes, indexed "large movements", which is tolerable for a practical use. These good position results imply that the force transmissions between the master arm and the slave are good, hence the haptic feedback is good. And transparency is still completed since the force needed to move the master arm is very low during "free fly stage" (the peak force on figure 6 is 5N for high speed movements).

The application of this class of control law is very efficient, and regarding to its symmetrical design, it appears obvious that both arms can be used as master or slave.

But as can seen on figure 5, the two force sensors are not used for the teleoperation law but only to make both parts of the device transparent. So it would be easier, and may be cheaper, to use a intrinsically transparent device instead of an electrically one and the bandwidth of the system would be theoretically larger.

4. Force-Position

The second class of teleoperation law tested is asymmetrical so its theoretical aspect was not treated by the PID tuning method as previously but using the state model of the system and the pole placement technique. The pole placement technique was chosen because the two EMPS are not locally controlled by a similar law but since their are still interacting the whole regulation has to be calculated at one time.

Because the two force signals are used to calculate the consign for the slave motor, the transparency block-set cannot be used for the master arm which is position controlled. Then it is obvious that the behavior of the
two arms are not the same, especially the reaction time of the master which could be very frustrating for the operator if not well tuned, making this class of teleoperation law simply unusable.

The Simulink diagram of the force-position law can be seen on figure 7, the state equation of this system can be written as:

\[
\dot{X} = \begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & -1/t_m & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & -1/t_m
\end{bmatrix}
X + \begin{bmatrix}
0 & 0 & 0 & 0 \\
g_s \times k & 0 & 0 & 0 \\
0 & 0 & 0 & g_s
\end{bmatrix}
U
\]  \tag{1}

with
\[
X = \begin{bmatrix}
f_{\text{potentiometer}} \\
f_{\text{potentiometer}} \\
q_m \\
q_m
\end{bmatrix}
\text{ and }
U = \begin{bmatrix}
v_{\text{ir}} \\
v_{\text{ir}}
\end{bmatrix},
\]

- \(k\) is the spring stiffness,
- \(q_m\) and \(q_m\) are the articular position and speed of the master arm, and similarly \(q_s\) and \(q_s\) for the slave arm,
- \(1/t_m = f_r + f_s \times \text{sign}(q_s)\) \(j_m\),
- \(f_{\text{potentiometer}}\) is the force applied on the linear potentiometer and \(f_{\text{potentiometer}}\) its derivative,
- \(v_{\text{ir}}\) and \(v_{\text{ir}}\) are the currents applied, respectively, on the slave and the master motors.

This type of teleoperation law is not unconditionally stable because of the force sensor signal. So to ensure the stability of the device, a stability criterion (Lyapunov stability theorem) was applied using a spring-mass model for the environment.

With a spring stiffness of \(k \approx 230N.m^{-1}\), the state-feedback matrix is

\[
K = \begin{bmatrix}
k_1 \\
k_2 \\
k_3 \\
k_3
\end{bmatrix} = \begin{bmatrix}126 \\ 1.95 \\ 11.6 \\ 0.18\end{bmatrix}.
\]

The results of the tests carried on with the control law calculated above can be seen on figure 8. The graphs show that it is less precise than the position-position law tested previously, with a peak tracking error of 6% for the first test and of 24% for the second one. An error of 24% could be crippling but because it occurs during "free fly" stage, the operator do not perceive any lack of realism in the force reflection and this position error equals to a time delay between the master and the slave of less than 50 ms so it is humanly imperceptible. And during contact or transition stage the haptic feedback is good : the tracking error is very low at the beginning of the first graph.

As written before, the two arms are not theoretically equivalent and in fact a difference appears in the accuracy of the coupling only for large and alternatives moves when using the position controlled arm, such as in the second graph, figure 8, but this decreasing of the performances is not sensible for the operator.

5. Conclusions

Two different bilateral control laws have been implemented on the testbed, and their results are similar with a little advantage for the position-position law in position tracking error. But since it uses the force sensors for transparency, the force tracking error can not be displayed, and for this parameter the comparison is decidious.

Through this study, it appears that a force sensor is nearly compulsory to realize kinesthetic coupling with arms not designed for these tasks, but the need of a very accurate one was not pointed out since the transparency and bilateral teleoperation tests were carried out using an ATI force sensor or a linear potentiometer linked to a spring. But the study highlights that a poor resolution of the encoders can be very detrimental for the teleoperation performances.

During the experiments, various doublets of \((k_p, k_v)\) were tested with the position-force control law...
and “nearly inverted” pairs (meaning low kp and high kv) have preliminary good results in contact stage, of course these pairs were calculated before to ensure stable servo-control. These doublets seem particularly good in force transmitting and further studies of the advantages and drawbacks of high damping toward high stiffness seem useful.

References


Figure 8. Two different movements of the two EMPS, the position tracking error and the forces applied on the devices