Experimental evaluation of several strategies for human motion based transparency control

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Abstract

Human interactive robots continue to improve human quality of life with their diverse applications. Their field includes, but is not limited to, haptic devices, force feedback tele-manipulation, surgical co-manipulation, medical rehabilitation, and various multi-degree of freedom robotic devices where the human operator and robot are often required to simultaneously execute tasks and collaborate with a specific share of forces/energy. More than tuning mechanical design, the robot control enhancement with a force sensor, is the key for increasing transparency (i.e the capacity for a robot to follow human movements without any human-perceptible resistive forces). With an ideal robot control, the interaction between robot and human would be extremely natural and fluid that the comanipulation of tasks would seem to be achieved with a transparent aid from the robot. For such, the classical force feedback control in certain cases still seems insufficient as is often limited by various factors (noise, bandwidth limitation, stability, sensor cost..etc). Our experiments are focused on evaluating the performance increase in terms of transparency of controller by using human motion predictions. We evaluate several ways to use predictive informations in the control to overcome present transparency limitations during a simple comanipulation pointing task.

1 Introduction

Our goal in this paper is so to study comanipulation between an human operator and a robot configured in a transparent mode, minimizing forces exchange at the interface. This kind of transparent robot control performance index that applies no resistance to a zero-resistance experiment is rightfully called transparency. This performance index is severely affected by friction, moment of inertia and system band-

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width. Our ideal situation where no forces are exchanged between robot and human operator, can appears strange and quite disconnected from real application but in fact, this kind of transparency mode could be really usefull in a lot of domains like haptic, rehabilitation, or basic comanipulation, where precises forces are needed to be applied only at certain times and we need to be sure not to alter the operator move the rest of the time. Indeed the early use of robotics in rehabilitation field should not make us forget that robots- like orthosis for upper limb rehabilitation- are presently mostly not enough transparent to be really sure not to disturb patient, to be precisely aware of applied forces on his body and to use the robot as a way of measuring patient movement characteristics [1]. Surgery robots can also require high level of transparency in order, for example, to confine a tool in a defined volume and to prevent any distortion of surgeon's motion. Indeed reaching high levels of transparency could be a great mean to seriously evaluate robot applied forces, because being able to effectively generate zero forces at the interface is proof of capabilitie for a system to produce a precise strengh.

But in any cases, friction and inertia, which are unavoidable, limit the overall system bandwidth and its transparency. The most popular solution to this problem is to include a force sensor mounted at the precise place where transparency is needed (usually between the wrist and the end effector for a serial manipulator) and to implement force feedback control. Force feedback control allows to cancel quite easily the static joint friction phenomenon. However, it suffers from several limitations : stability, drift, bandwidth limitations. In addition to discrete control problems and sensor noise, dynamics between actuators and force sensors drastically limits force controller performances [2]. Bandwidth limitations are the major problem of these controllers [3], which in turn address the antagonisms of the design such as rigidity vs inertia and friction. Moreover, to ensure robustness and stability, the control gains of robotic systems interacting with human, are generally limited. Indeed stability criterion like the passivity one [4] severely limits the performance of force controlled robotic systems.

Research works concerning overcoming force control bandwidth limitations with a new approach based on predictions of the subject's intended movement are appearing. The control principle is to overcome the force closed loop bandwidth limitations with a feedforward loop fed with predictive informations.

The general idea developed in this paper is so to exploit a high bandwidth low level controller in combination with a feedforward compensator based on a human motion prediction. Several ways to use prediction exist and need to be evaluated: One is to use a stiffness control feeded with the predicted trajectory generating an impedance around it, and the other is to use a computed torque feedforward.

Our experimental controller so combine a joint position compensator, a feedforward trajectory tracking, and a direct force feedback term. An experimental platform was then set up to evaluate this controller and the different loop combinations. Recall that our aim is not to predict movement, but to understand how to use this prediction at the control level. With this aim, a specific experimental protocol was defined (see Section 3). First, we record several movements of a subject repeatedly to realize a free planar reaching task; an averaged data set extracted from the free reaching tasks is then used as a prediction during the transparency experiment. The transparency experiments consist for a given human subject in repeating the same movement while being attached to a robot, while several combinations of the three control strategies are combined. Meanwhile, transparency is evaluated (i.e. the force magnitude at the interface is measured). The averaged experimental results obtained with a limited number of subjects are presented and compared in Section 4. Finally in Section 5, we discuss about the impact of introducing human motion prediction into transparency control and about the further experiment for endorsing and generalizing these first results.

2 Technical Approach

To derive a general control structure for a transparent interactive robotic device, we start from the trajectory of predicted movement of the human operator. The initial time of this movement, t0, is also known. When the real motion of the operator is denoted qr(t), for a perfect motion or the robot prediction is thus characterized by $\mathbf{q}_d(t) \equiv \mathbf{q}_r(t)$ where $\mathbf{q}_r(t)$ is the robot joint trajectory. Furthermore, the robotic device is supposed to be governed by the following dynamical equation :

$$\Gamma_m + \mathbf{J}^{\mathrm{T}}(\mathbf{q})\mathbf{F}_{ext} = \mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{b}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) + \Gamma_f \quad , \tag{1}$$

Having the dynamic equation, we applied three control strategies to increase the transparency of the system. The first is a force feedback control that uses a joint-level torque compensator where Γ_m is used to map the measured force $\mathbf{F}_{ext}$ into a joint equivalent as the reference to the force minimization performance during the experiments. The second is a trajectory control, for which the robotic device is programmed to precisely follow the desired trajectory $\mathbf{q}_d(t)$ with a joint position compensator $\mathbf{C}_p$.The third strategy that is implemented is a feedforward trajectory tracking where $\hat{\Gamma}_m(\mathbf{q}_d,\dot{\mathbf{q}}_d,\ddot{\mathbf{q}}_d)$ is the estimation of the torque that the actuator shall produce in order to follow the desired trajectory.

$$\Gamma_{m,1} = -\mathbf{C}_f \ \left[\mathbf{J}^{\mathrm{T}}(\mathbf{q})\ \mathbf{F}_{ext}\right] \quad , \tag{2}$$

$$\Gamma_{m,2} = \mathbf{C}_p \left[\mathbf{q}_d(t) - \mathbf{q}(t)\right] \quad . \tag{3}$$

$$\Gamma_{m,3} = \hat{\Gamma}_m(\mathbf{q}_d,\dot{\mathbf{q}}_d,\ddot{\mathbf{q}}_d) \quad , \tag{4}$$

Note that possible realization of the torque feedforward is:

$$\hat{\Gamma}_m(\mathbf{q}_d,\dot{\mathbf{q}}_d,\ddot{\mathbf{q}}_d) = \hat{\mathbf{H}}(\mathbf{q}_d)\ddot{\mathbf{q}}_d + \hat{\mathbf{b}}(\mathbf{q}_d,\dot{\mathbf{q}}_d) + \hat{\mathbf{g}}(\mathbf{q}_d) + \hat{\Gamma}_f \quad . \tag{5}$$

Again, with a perfect prediction and a perfect torque estimation, one gets $\mathbf{q}(t) \equiv \mathbf{q}_d(t) \equiv \mathbf{q}_r(t)$. Moreover, with this approach, in contrary to the first strategy, a small discrepancy between the predicted and real motions will not produce high forces at

the interface. This is why we expect this approach to provide a better feeling of the transparency.
In the rest of the paper, the controller will be a weighted sum of the three strategies described in Equations (2), (3) and (4):

$$\Gamma_m = \alpha_1 \Gamma_{m,1} + \alpha_2 \Gamma_{m,2} + \alpha_3 \Gamma_{m,3}, \tag{6}$$

where $\alpha_i \in [0,1]$, for $i \in \{1..3\}$. Tuning the parameters α_i is a way of applying the different strategies, alone or in combination.

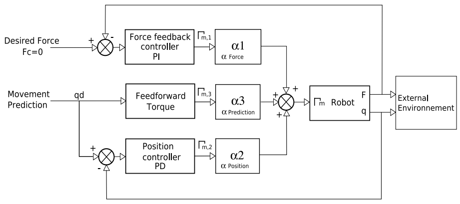

Fig. 1 Three strategies controller

3 Experiments

3.1 General approach

A combination of three control strategies is tested with a planar manipulation task. For the task execution, we used a commercial haptic device fitted with a custom made handle mounted with position and force sensors. After performing the same simple point-to-point movement, the result are collected for averaging and filtering to synthesize a movement model of the subject trajectory. This model is later used as a prediction for the transparency experiment.

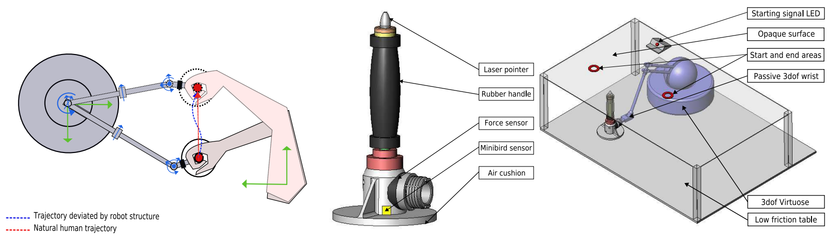

Fig. 2 Left: Simple point-to-point movement. Right: 3D view of the handle and of the experimental setup

A specific apparatus was used in order to focus subject attention on the start signal and the start and end areas and for the robot availability not to be known by the subject and so not to hinder the experimental results: As seen in Figure 2, an opaque surface was installed hiding the hand of the subject. In order to allow the subject to see his/her hand position through the opaque surface placed over the table and the robot, a laser pointer is placed inside the handle and projects a spot on the surface. Starting and ending locations are always visible over the opaque surface throughout the experiment. For all the tasks, no particular speed was instructed so that the test results display that of the most natural human wrist movement with a handle. The experiments were performed with a random combination of the control configurations.

3.2 Experimental setup

The experimental campaign was performed with a Virtuose manipulator from Haption, which has a three active degrees of freedom and a passive wrist possessing three rotation axes intercepting at point W. The handle is mounted on the end effector extremity. Between the handle and the effector, a force sensor is installed in order to measure the force exerted by the subject on the robot and inversely. This measured force is used to compute the control law (2) where the Jacobian is computed at point W.

The 6-axis force/torque(F/T) sensor is an ATI Nano43 Transducer allowing us to reconstruct the 3 forces and 3 torques components. The handle is also fitted with a magnetic position and orientation sensor (Minibird, Ascension Technology), which is installed under the force sensor, the fixed magnetic emitter being placed under the table. It provides position and orientation measurements at a 100Hz frequency and compute speed of the handle during the experiments. It allows the controller to learn movement characteristics of the subject during the pre-experimental part, but is not used during the transparency tests. As the experiment deals with low level-forces, a particular attention has been given to minimize friction. This is why the lowest part of the handle was designed with an air cushion system, in the purpose of reducing friction between the handle and the table, in case the subject strongly pushes against the sliding surface.

3.3 Three experimental phases

The experiments were cut in three different phases: Two pre-experimental step and the concrete controller combination evaluations. During the pre-experiments, the

subject is first asked to perform the same movement from the start area to the end area (marked up over the opaque surface by 3cm diameter circles). This is repeated five times in a row. Five attempts are enough to extract general features of the subject movement, as it was experimentally verified that healthy subjects performing free upper-limb movements produce quite repeatable motions.
Data are filtered and then interpolated from 100Hz record (maximum data rate of the minibird sensor) to a 1kHz data trajectory compatible with the control loop clock.
Another important data extracted is the reaction time of the subject (the time laps needed by a subject to initiate the movement after the visual start signal is turn on). Indeed, the ”anticipation” is done by reinjecting a recorded characteristic move. It is thus important to perfectly synchronize when the subject starts to move and the point of the recorded motion $\mathbf{q}_d$ starts. The knowledge of that reaction time t_0 is made during the learning phase and allows us to synchronize robot anticipation with the subject move during the evaluations experiments. Figure 3 shows the result for a representative subject. experiments. The second pre-experimental step consist

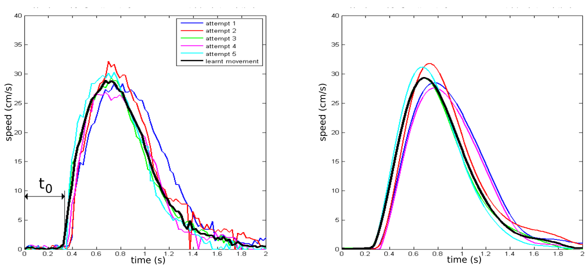

Fig. 3 Graphics of measured and interpolated speeds for the same simple point-to-point movement for one subject

in computing $\hat{\Gamma}_m$. Instead of sorely calculating $\hat{\Gamma}_m$ with equation (5) and a model parameter identification that will lead to imprecision, we decided to use a simple experimental method which had the double advantage of good precision and no model requirement.

Once the trajectory $\mathbf{q}_d(t)$ is available, the robot end-effector extremity is placed on the start area with a standard PD position controller (see Eq. 3). Then the recorded interpolated average trajectory is fed to the robot controller. During the robot movement, the motor currents are recorded. In fact, during this experiment, the position control loop calculates the necessary torques to apply to actuators to move the robot structure along the human subject trajectory. The resulting output is $\hat{\Gamma}_m$, which will be used as an open-loop feedforward signal to realize the prediction feature of the controller.

4 Results

During the experiments we used a PD compensator for the position controller which was tuned manually to provide satisfactory trajectory tracking, and a PI compensator for the force control loop, which was tuned manually to perform stably and fast enough in the whole workspace. For each subject, we evaluated interaction forces on the handle for a simple point-to-point movement with α_1= 0 or 1, α_2= 0 or 0.2 or 1, and α_3= 0 or 1, as depicted in Figure 4. The experiments were performed in a random order.

Experiment #	1	2	3	4	5	6	7	8	9
α_1	0	1	0	1	0	1	0	1	1
α_2	0	0	1	1	0.2	0.2	0	0	0.2
α_3	0	0	0	0	0	0	1	1	1

TABLE I
GAINS USED FOR THE 9 EXPERIMENTS

Fig. 4 The different tested combinations

In the following figures the mean for the ten evaluated subjects of the planar force norm, $f = \sqrt{f_x^2 + f_y^2}$ are presented and analyzed. Our references during the experiments, in terms of the magnitude of forces at the interaction port, are shown in Experiment 1, where the null current is applied on the robot during the move, so that only the residual friction of the haptic device together with its inertia are felt and in Experiment 2, where force feedback controller is used alone (α_1=1 and $\alpha_2 = \alpha_3 = 0$). We show in Figure 5 the norm of the planar force mean which is observed during these two experiments.

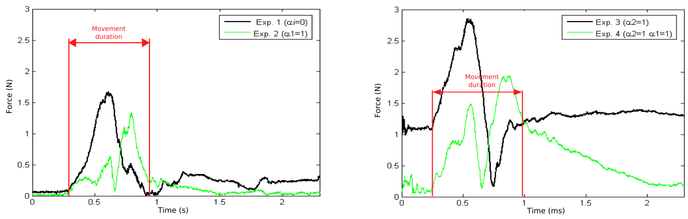

Fig. 5 Left: Norm of the force at the interface during point-to-point movement with null current (EXP1) and force feedback controller alone (EXP2). Right: Norm of the force at the interface for Experiments 3 and 4

As expected, force feedback control provides a better level of transparency by limiting the forces during the experiment mainly the average force level. Regardless of the level of exchanged forces, we can observe a force peak at the start of the move. Indeed, the beginning of the motion requires sudden large forces to initiate movement and the force feedback controller is finally slow to react due to its bandwitdh limitations. In spite of the level of performance obtained by the reversible haptic device and a low level force feedback controller, these experiments lead us to think that we can continue minimizing the interaction force by using trajectory prediction in the controller.

The first way to exploit this predictive information is to use a rigid joint position compensator (α_2=1). We thus performed two experiments.Experiment 3 involves the trajectory controller alone (α_2=1 and $\alpha_1 = \alpha_3 = 0$) while Experiment 4 simultaneously uses position and force control by setting $\alpha_1 = \alpha_2 = 1$ and $\alpha_3 = 0$. As we can observe in Figure 5, the use of a rigid joint position compensator alone leads, as expected, to large forces at the interface at the beginning of the motion. The smallest discrepancy between the prediction and the real motion lead to large forces. Of course, the force controller added in Experiment 4 compensates for this effect, but the result of this experiment, when compared to Experiment 2 where force feedback is used alone, shows that using $\alpha_2 = 1$ is of no interest. The use of force feedback

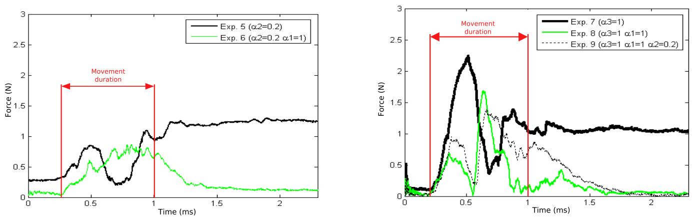

Fig. 6 Right: Norm of the force at the interface for Experiments 5 and 6. Left: Norm of the force at the interface for Experiments 7 to 9

control allow a minimization of the average force level, but the rigidity of the joint position compensator minimize the dynamic response of force feedback loop.
As we supposed that this is mostly due to the rigidity of the controller, we therefore proposed to run two new experiments similar to Experiments 3 and 4 while α_2 was set to 0.2. The results for Experiments 5 and 6 are plotted in Figure 6. When compared to the results of Experiments 1 and 2, respectively, they emphasize a clear decrease of the peak force. In Experiment 5, minimized gains of the joint position compensator allow a better tolerance to small time-lags and path errors but due to robot low but constant impedance, the average force level stay important after the motion end. This can be easily explained by the fact that small position errors often appears at the end of the move. Adding the force feedback in the Experiment 6, allow once more to minimize - even if it has a weak dynamic - the force exchanged average level. We have here a controller which stifness varies according to motion prediction : When the predicted motion is a stop, the rigidity is null due to the effect of the integrative term of the force feedback controller.
Anyway, Experiment 5, is also good clue that the transparency can be increased through low stiffness position tracking when no force sensor is available.

As rigidity seem to be the major problem of the previous controller combinations, we also evalute an other way to use predictive informations with the use use of a feedforward torque resulting from the desired trajectory to assist subject motion. Three experiments were finally performed: feedforward alone (Exp. 7), feedforward plus force feedback control (Exp. 8) and feedforward plus force feedback control plus low stiffness trajectory tracking (Exp. 9). Results for these three experiments are given in Figure 6.
Experiment 7 tend to show that when the feedforward term is used alone, the operator badly reacts to the robot open loop activity, which leads to rather large interaction forces. Even if force control is used in conjunction with the feedforward term, the force level stay too important as obeserved in Exp. 8. The rigidity added by the joint compensator in Exp. 9 seen not to be enough to compensate the bad reaction of the subject to open loop torques. This can appear strange but several points need to be precised to understand the phenomenon and at the same time put into perspective the conclusions emanating from these experiments:

- The problem of robot structure that seem not to be enough rigid to allow high bandwidth force control .
- In our experiments, the 3 DOF passive wrist seem to badly impact the results. Indeed during the experiments, some subjects seem to reach their higher transparency level with feedforward tracking coupled to force feedback control. This can also be show in [5]. A kind of non-linearity in the transmission of the torque due to the uncontrolled wrist sometime appears in these conditions and it could badly impact experiments.

In Figure 7,the graphs summarize the results of the nine experiments, clearly shows that the peak forces are minimized for Exp. 6.

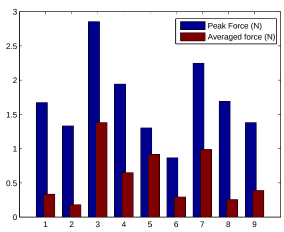

Fig. 7 Peak force and average force during the nine experiments for the ten evaluated subjects

5 Conclusions and Outlook

Finally quite interesting observations are extracted from the current results (Figure 7). The coupling of low stiffness joint position compensation fed with predictive trajectory and force feedback control seems rewarding in terms of transparency, with a real efficiency at the beginning of the move. These results lead us to think that the controller could use two strategies along a trajectory :

1. The beginning and the ending of the motion requires large forces to initiate and stop movement which is difficult to compensate by using force feedback alone. Thereforee the addition of a limber joint position compensator produces the best transparency.
2. In the middle of the trajectory, very little forces are needed, human haptic sensibility is thus enhanced. Even a little desynchronization between the applied anticipation and the real movement may be disturbing to the subject. Moreover, the acceleration is small which limits the force error due to the bandwidth limitation. Therefore during this second phase, the force feedback seems to be enough to maximize transparency at the interface.

Thus, it could be interesting to use time varying $\alpha_i(t)$ in order to maximize the predictive strategy at the beginning and the end of the motion, and minimize the effects during the rest of the movements.
If joint position compensation with a low stiffness coupled with a force feedback control allow better transparency than force loop alone, the use of feedforward trajectory tracking should theoretically give as good results allowing to cancel the problem of rigidity in the control, main source of forces at the interface and so of weak transparency level. Some first exploratory experiments made on rigid two DOF robot have shown that feedforward was intrusting for increasing transparency and lead us to evaluate the phenomenon on that 3DOF haptic interface, chosen for its better mechanical design. Therefore a new campaign of experimentations need to be done with a completely active robot or a blocked passive wrist, to concretely evaluate the effect of feedforward tracking in human robot interaction control.
We leave this to future investigations, which shall also include a statistical results analysis based on a larger number of subjects.

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