HAPTIC TELEMANIPULATION WITH IMPEDANCE CONTROL AND ITS APPLICATION IN HOMECARE ROBOTICS

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ABSTRACT
Telemanipulation concerns manual operation of a device from a remote location through suitable communication links. In haptics, the communication link is two-way with force feedback from the manipulated object to the human operator. This paper presents a new application of telemanipulation, as used in homecare robotics. For the specific application, a telemanipulation scheme with impedance control at both ends of the communication link—object interface (slave end) and human interface (master end)—is investigated. On the master side, impedance with damping is tuned with the environmental impedance to reduce the energy input by the operator. On the slave side, an adaptive impedance controller based on estimation of the dynamics at the telemanipulated object interface is suggested. The proposed impedance controllers can guarantee desired force tracking in one direction. Simulation results show the applicability of the control strategy.

Keywords: Impedance control, haptic telemanipulation, homecare robotics.

INTRODUCTION
A telemanipulation system consists of a local master and a remotely controlled slave robot. Telemanipulation was first introduced by Goertz [1] to extend human manipulation capability to handle nuclear waste. In a telemanipulation system, the human operator can command the master device by a force or velocity (position) input. Through a communication channel, this command is transmitted to the remotely located slave robot. The slave robot will follow the command from the master and interact telemanipulate the object as desired. To enhance the performance of such system and to form a closed-loop control system, some kind of feedback should be provided from the slave side to the master side. This is the essence of haptics. If such feedback is available, the telemanipulation system is said to be controlled bilaterally; otherwise, unilaterally. Visual feedback or force feedback may be used. To provide more intuitively and natural feeling to the human operator, force feedback is preferred. The force feedback can be provided to the human operator by use of a haptic device.

Telemanipulation is used in a variety of applications such as tele-surgery and undersea exploration. A typical telemanipulation system is shown in figure 1.

A good telemanipulation system will enable the operator to feel as if they were operating the remote manipulator directly and manually at the remote location. Then the telemanipulation system is said to be transparent. An ideal telemanipulation system may be thought of as the operator is connected directly to the slave system by a weightless rod with infinite stiffness [2].

![Fig. 1: A typical telemanipulation system.](image1)

With wide application of service robots, telemanipulation may also be used in homecare robotics. This application is described in the scenario shown in figure 2. A homecare robot is located in a home and can be telemanipulated by a trained person in the central control room, possibly at a medical center. For example, first aid tasks including heart massaging and attention to injury may be carried out in this manner.

![Fig. 2: Telerobotic homecare scenario.](image2)

The task space may be divided into three subspaces. In the Z direction, the manipulator is expected to exert a desired level of force, while in the X and Y directions, the manipulator seeks to change the location while keeping the interaction forces in these two directions bounded at acceptable levels. In short, in the Z direction, force control is essential while in the X and Y directions, position tracking is important.
**SYSTEM MODELING & INVERSE KINEMATICS FOR DECOUPLING**

Most telemanipulation schemes in literature consider a single degree-of-freedom (DOF) model for simplicity [7]. In practice, due to the complicity of the task, multi-DOF slave robots should be applied. Then, the dynamics of each DOF are coupled. To simplify the controller design problem, it is desirable to decouple each DOF. Robust inverse kinematics [8] is used for decoupling and making the system behave like a linear time-invariant (LTI) one. The dynamic behavior of each DOF can be controlled independently.

For the master side in task space, it can be modeled as

$$\ddot{M}_m(q_m)\ddot{X}_m + \ddot{C}_m(q_m, \dot{q}_m)\dot{X}_m + \ddot{G}(q_m) = \ddot{F}_n - \ddot{F}_{cm}$$  \hspace{1cm} (1)

$$\ddot{M}_m(q_m) =$$ Master inertia matrix; \(\ddot{C}_m(q_m, \dot{q}_m) =\) Christoffel terms; \(\ddot{G}(q_m) =\) Gravity vector; \(\ddot{F}_n =\) Interaction force between the human operator and master side robot; \(\ddot{F}_{cm} =\) Control torque generated by the actuators in the haptic device.

Equation (1) can be written in the linear-in-parameter format

$$\ddot{M}_m(q_m)\ddot{X}_m + \ddot{C}_m(q_m, \dot{q}_m)\dot{X}_m + \ddot{G}(q_m) = Y(\ddot{X}_m, \dot{X}_m, X, \theta)$$  \hspace{1cm} (2)

where \(Y(\ddot{X}_m, \dot{X}_m, X, \theta) =\) is a regressor matrix, and \(\theta =\) is a vector of unknown parameters.

If the control law is selected as

$$\ddot{F}_{cm} = \ddot{F}_n + Y(\ddot{X}_m, \dot{X}_m, X, \theta)\hat{\theta} - K_d\rho$$  \hspace{1cm} (3)

with

$$\ddot{X}_r = \dot{X}_d - \Lambda\ddot{X}_m, \quad \dot{X}_m = X_m - X_d, \quad \rho = \dot{\ddot{X}}_m + \Lambda\dddot{X}_m$$

$$X_d = X_m - L^{-1}\left((M_m s^2 + B_m s + K_m)^{-1}(\dddot{F}_n + \dddot{F}_{cm})\right)$$

and the parameter update law, the dynamic model can be linearized as

$$M_m\dddot{X}_m + B_m\dddot{X}_m + K_mX_m = F_n - F_m + \eta$$  \hspace{1cm} (4)

with the uncertainty \(\eta\) bounded. All the parameters in equation (4) are diagonal and thus decoupled. \(X_m, F_n, F_m\) can be viewed as the corresponding parameters of a low pass filter. Similarly, in the slave side in the joint space, it can be modeled as

$$\dddot{M}_s(q_s)\dddot{X}_s + \dddot{C}_s(q_s, \dot{q}_s)\dot{X}_s + \dddot{G}_s(q_s) = \dddot{F}_{cs} - \dddot{F}_e$$  \hspace{1cm} (5)

All the components have corresponding meanings to those in the master side.

\(F_e =\) Interaction force between the manipulator and the telemanipulated object.

Based on the linearized dynamic models of the master and slave robots, each degree of freedom can be controlled independently. For analytical convenience, the dynamic equations in the joint space are converted into the task space. The dynamic models of the master and slave sides can be expressed as:

$$M_m\dddot{X}_m + B_m\dddot{X}_m + K_mX_m = F_n - F_m$$  \hspace{1cm} (6)

$$M_s\dddot{X}_s + B_s\dddot{X}_s + K_sX_s = F_s - F_e$$  \hspace{1cm} (7)

where \(M_i, B_i, K_i (i = m, s)\) are the corresponding mass, damping, and stiffness components in the two sides. \(F_i\)
\( i = m, s \) are the corresponding equivalent forces produced by the haptic device and the slave robot actuators in the interface.

**IMPEDEANCE CONTROL AT BOTH SIDES**

The dynamics of a system under impedance control can be described by a virtual mass, damper and spring system, driven by the interaction force or the force tracking error. For the master side, the desired impedance characteristics can be expressed as

\[
M_{md} \ddot{X}_m + B_{md} \dot{X}_m + K_{md} X_m = F_h - F_e \tag{8}
\]

where \( M_{md}, B_{md} \) and \( K_{md} \) are the desired impedance components, \( F_h \) and \( F_e \) are the interaction force at the master side position vector, and \( F_e \) is the interaction force at the slave side.

As pointed out in [9], large damping causes fatigue in the human operator. In unconstrained motion, the damping should be made small in order to reduce the human effort. In constrained motion, it is suggested to tune the desired damping element in the impedance of the master side according to the telemanipulated object stiffness.

The harded the telemanipulated object, the bigger the damping value should be, to avoid oscillatory contact behavior. It is known that

\[
B_{md} = 2 \zeta \sqrt{M_{md} (K_e + K_{md})} \tag{9}
\]

where \( K_e \) is the environment stiffness, which needs estimation. This will be discussed in the design of the slave side impedance controller. \( \zeta \) is the virtual damping ratio which can be determined by the mass, damping and stiffness components in the desired impedance. We set \( M_{md} = M_m \) and \( K_{md} = K_m \).

Comparing equations (4) and (6), the master side control input should be

\[
F_m = F_e + (B_{md} - B_m) \dot{X}_m \tag{10}
\]

For the slave side, the desired impedance model is

\[
M_{sd}(\ddot{X}_r - \ddot{X}_s) + B_{sd} (\dot{X}_r - \dot{X}_s) + K_{sd} (X_r - X_s) = F_d - F_e \tag{11}
\]

The telemanipulated object dynamics can be modeled as

\[
F_e = K_e (X_s - X_e) \tag{12}
\]

where \( M_{sd}, B_{sd} \) and \( K_{sd} \) are the desired slave side impedance components, \( F_d \) is the desired interaction force in the last section, \( X_s \) is the slave side position vector, \( K_e \) is the telemanipulated object stiffness, and \( X_e \) is the telemanipulated object position in the task coordinate in the absence of deformation. Clearly, \( K_e \) and \( X_e \) are position dependent and time varying, which require adaptive estimation. \( X_e \) is the reference trajectory, which depends on the task requirement. As discussed previously, in the Z direction, the main objective is to exert some desired force onto the human body, while the position tracking is secondary. As pointed out in [6], \( X_e \) should be tuned based on the stiffness of the environment according to:

\[
X_e = X_e + K_e^{-1} F_d \tag{13}
\]

in order to exert the desired force onto the telemanipulated object if it is under impedance control as described by equation (11). However, since \( X_e \) and \( K_e \) are unknown or time varying, we should develop an adaptive estimation scheme to estimate them.

The estimation algorithm for stiffness and position is given by

\[
\hat{F}_e = \hat{K}_e (X_e - \hat{X}_e) = \hat{K}_e X_e - \hat{K}_e \hat{X}_e \tag{15}
\]

The parameters to be identified are

\[
\hat{\theta} = \left[ \hat{K}_e \ -\hat{K}_e \hat{X}_e \right]^T \tag{16}
\]

The estimation error is given by

\[
\hat{\theta} = \hat{\theta} - \theta = \left[ \hat{K}_e - K_e \ -\hat{K}_e \hat{X}_e + K_e \ e X_e \right]^T \tag{18}
\]

The force estimation error is

\[
e_f = \hat{F}_e - F_e = \left[ X_s \ 1 \right] \left[ \begin{array}{c} \hat{K}_e - K_e \\ -\hat{K}_e \hat{X}_e - (-K_e X_e) \end{array} \right] \tag{19}
\]

The following update law is used:

\[
\dot{\hat{\theta}} = -\gamma e_f \tag{20}
\]

where \( \gamma \) is a vector with positive elements to be decided.

To show the convergence of the estimation, a candidate Lyapunov function is defined as follows:

\[
V = \frac{1}{2} \hat{\theta}^T P \hat{\theta} \tag{21}
\]

\[
\dot{V} = \hat{\theta}^T P \dot{\hat{\theta}} \tag{22}
\]

Substitute the adaption law, \( \dot{V} = \hat{\theta}^T P \hat{\theta} = -\hat{\theta}^T P \gamma \hat{F}_e - F_e \).

Selecting \( \gamma = P^{-1} \left[ \begin{array}{c} X_s \\ 1 \end{array} \right] \), we get

\[
\dot{V} = -(\hat{F}_e - F_e)^2 \leq 0 \tag{23}
\]
Thus the estimation will converge to the actual value. For simplicity, assume that $P = I_2$. The update law for the estimated parameters is

$$\dot{\hat{K}}_e = -X_e (\hat{F}_e - F_e)$$

$$\dot{\hat{X}}_e = \frac{\hat{F}_e - F_e}{K_e} (1 + X_e \hat{X}_e)$$

(24)

(25)

Note that even though this stiffness estimation is used not only to generate the reference trajectory but also to reflect to the master side in order to reduce the energy output requirement by the operator.

The implementation of this impedance controller under the dynamic uncertainties and disturbances will be based on the immersion and invariance approach. Position tracking while keeping the interaction force bounded in the $X$ and $Y$ directions will be addressed in another paper.

**SIMULATION RESULTS**

For $M_{sd} = 30$, $B_{sd} = 1$, $K_{sd} = 60$, $M_{md} = 0.25$, $K_m = 10$, figure 4 shows the force tracking performance with the variation of environment static position and stiffness.

![Fig. 4: Force tracking in the Z direction (N).](image)

From the results it is seen that the desired force can be exerted onto the telemanipulated object despite the change in the telemanipulated object.

**CONCLUSIONS**

A telemanipulated homecare robotics system was proposed in this paper. The critical control requirements in the telemanipulation system were analyzed. To provide a natural, smooth and safe interaction between the manipulator and the manipulated object, impedance control was suggested for force control in the slave side. The telemanipulated object stiffness was estimated to generate the reference trajectory for the impedance controller. Based on the estimated stiffness, the damping element in the master side impedance can be tuned and the desired interaction force under impedance control can be achieved. Simulation results showed the effectiveness of the proposed controller.

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