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Peg-in-a-hole by haptic teleoperation

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Abstract. This paper presents the experimental study on the application of the peg-in-a-hole task in the proposed haptic teleoperation system. Motion references from the user towards the remote manipulator and force feedback signals from the remote environment towards the user are transmitted through a virtual reality layer where the remote operation is simulated in real-time. Various physical interactions occurring in the bilateral loop are modelled and controlled through the introduction of virtual spring-damper elements. Modeling and controller design of the teleoperation system is made modular and straightforward with the use of identical virtual dynamics. The design approach combines the introduction of the middle layer of virtual reality and modeling of all interactions by identical virtual spring-dampers. The haptic teleoperation system is experimentally evaluated with experienced and unexperienced users in the bilateral loop. Experimental results show that stable peg-in-a-hole operation is achieved in presence of bounded time-delays in all communication channels between the user, virtual reality layer and remote environment. Improvements of the teleoperation performances in terms of position tracking and total operation time are also observed in experiments.

1. Introduction

Robotic teleoperation is a technique of remote control where a human-operator (user) is involved in the control loop. Actual and future applications of teleoperation systems are found in various fields such as space exploration, nuclear power plants, surgical operations, etc. [1-4]. In bilateral teleoperation of robots, the user transmits motion reference signals to the remote manipulator through convenient physical interfaces. In return, he/she is provided with the information on the state of the remote operation environment by various means of perception such as visual and tactile feedback.

Force feedback is an important information, necessary for satisfactory performance of robotic teleoperation. Therefore, haptic devices with multi-DoFs which provide the user with force feedback from the remote operation are widely used in bilateral teleoperation. Development of haptic teleoperation systems in bilateral and multilateral forms is a popular research topic where the stability and transparency are the fundamental performance criteria [5,6].

Time delays on communication channels between local and remote environments of the teleoperation systems have particular impacts on the stability and transparency of the bilateral control loops. Passivity-based and scattering based approaches [7-9], wave variables [10,11] and intelligent [12,13] methods are proposed in order to improve the stability and transparency against worsening effects of time delays in communication channels.

In our recent work on the design of haptic teleoperation, the proposed control system has been based on the introduction of a virtual haptic coupling between the local and remote sides of the bilateral loop [14]. Virtual interaction forces are then fed back to the user along with visual feedback from the remote operation environment. While the asymptotic stability of the proposed system is...
shown by a Lyapunov analysis, improvements of the performances in terms of position tracking and transparency with the proposed approach is also experimentally demonstrated.

The peg-in-a-hole task, simultaneously combining motion and force controls, is a representative operation for the general problem of assembly [15, 16]. Haptic guidance is a practical approach in trajectory tracking control of remote devices in teleoperation systems [17-20].

In this paper, design and application of a haptic teleoperation system for the peg-in-a-hole task is presented. The proposed design is based on an extended use of identical virtual haptic coupling structure which is explained in [14] in the bilateral loop. An additional haptic coupling is proposed in this design. The first virtual coupling is established between the user and remote environment, resulting with virtual interaction forces fed back to the user. Introduction of these virtual interaction forces contribute to the robustness of the teleoperation system against time delays in communication channels.

The second virtual coupling is established between the manipulated peg and the stationary hole, in order to guide the peg for a smooth assembly operation. Guidance of the peg through virtual forces resulting from this second coupling improves the performance of the peg-in-a-hole task by reducing the total operation time.

The expected contributions to the performances of the peg-in-a-hole task by haptic teleoperation are experimentally observed. Stable and transparent operation is achieved in the experiments with experienced and unexperienced users in the bilateral loop. Experimental results show that the proposed haptic coupling design improves the position tracking performance and reduces the interaction forces and total operation time of the peg-in-a-hole assembly.

In the following section, the haptic coupling design proposed for the peg-in-a-hole task is introduced. Section III presents the bilateral control scheme implemented for the haptic teleoperation system. Section IV presents the experimental setup and results with an evaluation of the peg-in-a-hole task. Finally, Section V gives the conclusion of the presented work.

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**Figure 1.** Haptic coupling between the local device and remote manipulator through the virtual reality layer.
2. Haptic Coupling Design

Interaction dynamics occurring in teleoperation systems is usually represented based on the behavior of mechanical spring-damper models. Simplicity of implementation and easy manipulation of these linear second-order models let the designer assign desired impedances in order to control physical interactions. Therefore, it constitutes a viable approach to the problem of haptic coupling between the local and remote sides of bilateral loops [21].

In this work, virtual spring-damper models with identical structure are used for three different purposes as shown in Figure 1. The first purpose is the design of the coupling between the local haptic device and the virtual load, i.e. the peg, visually represented in a real-time simulation environment. Resulting virtual forces from this coupling are fed back to the user in order to induce a feel of inertia, which in turn helps filtering out high frequency motion inputs from the user.

The second coupling is established between the virtual hole and the end-effector of the remote manipulator handling the peg. Resulting virtual forces here are fed to the virtual peg in order to reflect position errors in the remote side of the teleoperation system.

Finally, the third coupling is established between the virtual peg and virtual hole. This coupling is activated when the peg in a hole process approach. Resulting virtual forces are fed back to the user in order to guide the peg-in-a-hole task against various disturbances, e.g. modeling errors in the reconstruction of the remote environment in the simulation layer.

The real-time simulation environment constitutes a virtual reality layer between the local and remote sides of the teleoperation system. This layer implemented in an open-source simulation software provides the user with a real-time visual representation of the remote environment during teleoperation. The simulation software computes the forward and inverse kinematics of the remote manipulator as well. Then, in this proposed bilateral scheme, the user directly commands the task space motions necessary to execute the peg-in-a-hole task, without taking care of the manipulator joint trajectories.

The dynamics introduced in the bilateral loop between local haptic device and virtual remote manipulator and the dynamics introduced between the peg and hole is given as follows:

\[ m\ddot{x}_{vp} + B_r\dot{x}_{vp} + K_r x_{vp} = B_h\dot{x}_h + K_h x_h \]  
\[ m\ddot{x}_{vh} + B_r\dot{x}_{vh} + K_r x_{vh} = B_{ph}\dot{x}_{vh} + K_{ph} x_{vh} \]  

where \( x_{vp} \), \( x_{vh} \) and \( x_h \) represent the position vectors of the virtual peg, virtual hole and local haptic device respectively. \( K_h \) and \( B_h \) are the spring and damper coefficients between the local haptic device and virtual peg, \( K_r \) and \( B_r \) between the virtual peg and end-effector of the remote manipulator, and \( K_{ph} \) and \( B_{ph} \) between the virtual peg and virtual hole.

The resulting haptic coupling force vector \( f_c \) can be calculated up to the fed coupling type by the Equations 3 and 4.

\[ f_c = K_h(x_h - x_{vp}) + B_h(\dot{x}_h - \dot{x}_{vp}) \]  
\[ f_c = K_{ph}(x_{vh} - x_{vp}) + B_{ph}(\dot{x}_{vh} - \dot{x}_{vp}) \]

The total feedback force vector \( f_h \) to be fed back to the haptic interface is then given as follows:

\[ f_h = f_c + f_{fbk} \]

where \( f_{fbk} \) is the measured remote manipulator's end-effector force vector.

3. Control System Design

The proposed bilateral control scheme describing the teleoperation of the peg-in-a-hole task with a single local haptic device and one remote manipulator is given in Figure 2.
A 6-axis industrial robot is used to execute the peg-in-a-hole task. Decentralized PIDs with gravity compensation are implemented as the joint controllers for the motion control of the remote manipulator. The reference joint trajectories are computed by the manipulator model in the virtual reality layer. The PID control law in joint space is given as follows:

$$\tau_i = K_p e_{q_i}(t) + \frac{1}{T_i} \int e_{q_i}(t) + T_d \frac{de_{q_i}(t)}{dt} + \tau_g$$  \hspace{1cm} (6)$$

where $K_p$, $T_i$ and $T_d$ are the diagonal matrices of PID parameters, $\tau_g$ represents the gravity compensation torque, $e_q$ is the vector of joint position errors and $i$ defines joint number. Closed-loop dynamics of the bilateral teleoperation system can be represented as follows:

$$A_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m = \tau_m - \tau_{user}$$  \hspace{1cm} (7)$$

$$A_b(q_b)\ddot{q}_b + C_b(q_b, \dot{q}_b)\dot{q}_b = \tau_b$$  \hspace{1cm} (8)$$

$$A_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + \tau_g = \tau_s - \tau_e$$  \hspace{1cm} (9)$$

where $A(q)$ is the inertia matrix, $C(q, \dot{q})$ is the matrix of Coriolis and centrifugal forces, $\tau_g$ is the vector of torque due to gravity. In above equations 7-9, indices $m$, $b$ and $s$ denote respectively the local haptic device, virtual model and remote manipulator. $\tau_e$ is the vector of interaction force between the remote manipulator and environment, and $\tau_{user}$ the generalized force applied by the user through the haptic interface. Control inputs to be applied to the local and remote manipulators are $\tau_m$ and $\tau_s$ respectively. Here, $\tau_m = J^T f_h$ and $\tau_s$ is calculated using the Equation 6.

Asymptotic stability of the proposed bilateral haptic teleoperation system in simple manipulation tasks is shown by a Lyapunov analysis as given in ref. [14].

4. Experiments

4.1. Task Description

The peg-in-a-hole task is achieved in four successive steps as illustrated in Figure 3. In the approach phase, the manipulator freely moves in its workspace in order to pick up the peg from its initial position. The handling phase starts with the grasping of the peg by the manipulator. In this second phase, the manipulator brings the peg in a certain neighborhood of the hole. The haptic coupling 1 is activated in these first two phases of the manipulation. The third phase is the execution of the peg-in-
a-hole operation. When the peg becomes sufficiently close to the hole, the bilateral controller switches from the haptic coupling 1 to the haptic coupling 2 (Figure 2. Here, the proposed coupling generates virtual forces along directions normal to the peg and hole axes in order to help aligning them. Finally, the manipulator pulls back the peg from the hole in order to release it in its initial position. Once the peg is separated from the hole, the haptic coupling 1 is reactivated instead of the haptic coupling 2 in the controller.

4.2. Experimental Setup
The experimental setup consists of a 6-DoF Phantom Premium 1.5 High Force as the local haptic device, a Stäubli Rx160 [22] robot as the remote manipulator and the Blender as the open-source virtual reality software (Figure 4). The remote manipulator is equipped with a 6-axis ATI F/T transducer and a single-DoF on/off gripper.

The sampling frequencies of the robot controller, and the haptic interface are 250Hz and 1kHz respectively. The UDP/IP protocol is used in all communications between the local, virtual, and remote environments. Experimentally measured time delays are as follows: $T_1 = 0.7 - 0.8ms$, $T_2 = 0.1 - 0.16ms$, $T_3 = 0.7 - 0.8ms$. The sampling frequency of the robot controller being 250 Hz, these time delays correspond to up to $%20$ of one sampling period with $T_1$ and $T_3$ and up to $%40$ with $T_2$.

In the proposed bilateral loop, the Blender is used for the following purposes: 1) Computation of the forward and inverse kinematics of the remote manipulator, 2) Real-time simulation and visualization of the remote environment for the user, 3) Computation of virtual forces resulting from the proposed haptic couplings.

The use of an open-source software executing the above-mentioned tasks as a middle layer between the local and remote sides of the teleoperation system results in a modular design of the programming environment. Due to the simple structure of the proposed system with Blender, kinematic parameters of the remote manipulator and parameters of the virtual haptic couplings can be easily modified by the user. In the case of the remote manipulator being replaced by others, the Blender virtual environment offers a user-friendly redesign of the bilateral loop.

4.3. Experimental Results
The proposed teleoperation system is implemented for the peg-in-a-hole task described in this section. The manipulated peg has the mass $m_p = 0.64kg$, and the position and force scaling factors are implemented as $K_x = 30$ and $K_f = 1/50$ respectively. The parameters of the virtual spring-damper model used in the haptic coupling are $m = 1$, $B_h = 35$, and $K_h = 600$, resulting in the damping ratio $\zeta_h = 0.714$ and natural frequency $\omega_h = 24.5rad/s$. The parameters of the virtual spring-damper designed around the peg-in-a-hole operation are $m = 1$, $B_{ph} = 15$, and $K_{ph} = 1500$, resulting in the damping ratios are $\zeta_{ph} = 0.194$ and natural frequency $\omega_{ph} = 38.73rad/s$. 
The PID parameters $K_p$, $T_i$, and $T_d$ of the remote manipulator position controller given in Eq. 6 are experimentally tuned as $K_p = [3500 8000 6500 2500 1000 1000]$, $T_i = [150 250 250 40 30 30]$ and $T_d = [0.2 0.04 0.02 0.025 0.025 0.001]$. In order to evaluate the performance of the proposed control system given in Figure 2, two cases are considered in experiments. In the first case, the haptic coupling 1 only is activated during the entire teleoperation. In the second case, the switching between haptic couplings is applied as described in this section.

4.3.1. First Case. In an experimentation with an experienced user in the loop, the tracking performance of the remote manipulator in task space is obtained as given in Figure 5. Figure 6 shows the haptic feedback force $f_h$ computed as defined in Eqs. 3 and 5. Here, the user completes the teleoperation in 66.4s and durations of successive phases are 0-1s: Approach, 1-25s: Handling, 25-52s: Peg-in-a-hole, 52-66 s: Return of the peg to its initial position.

4.3.2. Second Case. In an experimentation with an experienced user in the loop, the tracking performance of the remote manipulator in task space is obtained as given in Figure 7. Figure 8 shows the haptic feedback force $f_h$ computed as defined in Eqs. 3, 4 and 5. The total operation time is 61.5s and durations of successive phases are 0-1s: Approach, 1-20 s: Handling, 20-39 s: Peg-in-a-hole, 39 - 61 s: Return of the peg to its initial position. Experimentations of the peg-in-a-hole task with unexperienced users in the loop are also achieved. Experimental results in terms of considered performance criteria with three unexperienced and one experienced user are given in the following.

Figure 9 shows the position tracking error performances with one experienced and 3 unexperienced users. The average position tracking error and standard deviation of tracking errors are decreased with the introduction of the second haptic coupling. The average position tracking error with unexperienced
users is 7.8 mm in the first case, and it drops to 7.5 mm with the introduction of haptic guidance in the second case. Average errors recorded with the experienced user are 7.6 mm and 6.3 mm respectively.

Figure 10 gives the feedback forces applied to the local haptic device. The average feedback force and standard deviation of feedback forces are decreased as well with respect to those observed in the first case. The attenuation of feedback forces means that the peg-in-a-hole task is achieved with smoother physical interaction between the peg and hole. The average feedback force with unexperienced users is 7.4 N in the first case, and it drops to 4.3 N with the introduction of haptic guidance in the second case. Average feedback forces recorded with the experienced user are 6.2 N and 3 N respectively.

![Figure 6](image.png)

**Figure 6.** Feedback force ($f_h$) to the local haptic device, with haptic coupling 1 only.
Figure 7. Reference and actual task space trajectories of the remote manipulator, with switchings between haptic couplings.

Figure 8. Feedback force ($f_h$) to the local haptic device, with switchings between haptic couplings.
Figure 9. Bounds of position tracking errors of the remote manipulator with three unexperienced and one (4th) experienced users.

Table 1 presents the total time spent by the users to complete the peg-in-a-hole operation. It is observed that switchings between couplings result with faster teleoperation with experienced and unexperienced users. The average operation time with unexperienced users is 81.3 s in the first case, and 66.5 s in the second case. The operation time with the experienced user are 66.4 s and 61.5 s respectively.

Table 1. Peg-in-a-hole operation time (in seconds).

| Experiment                        | User 1 | User 2 | User 3 | User 4 |
|-----------------------------------|--------|--------|--------|--------|
| First Case (w/o haptic guidance)  | 99.20  | 70.29  | 74.30  | 66.38  |
| Second Case (with haptic guidance)| 66.66  | 67.57  | 65.23  | 61.46  |

Experimental results show on the one hand that the contribution of the haptic guidance, established by the switchings between couplings, is nearly negligible in position tracking performance of the remote manipulator. On the other hand, a greater impact of the haptic guidance is observed in the feedback forces. In fact, the haptic guidance contributes to reducing the feedback forces, which in turn enables smoother physical interaction between the peg and hole. As a consequence, the total teleoperation time is reduced with the proposed haptic guidance by switching of the haptic couplings.

5. Conclusion
Design and implementation of the haptic teleoperation system for the peg-in-a-hole task is successfully achieved. In the experiments, stable operations are observed in presence of one experienced and multiple unexperienced users in the bilateral loop. Furthermore, contributions expected from the proposed controller design are also observed. Experimental results show that position tracking performance of the remote manipulator is improved with the introduction of the proposed haptic coupling. Besides, the interaction forces fed back to the user are attenuated and faster teleoperation of the peg-in-a-hole assembly are obtained independently from the user experience on the teleoperation system.

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