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Impedance-controlled teleoperation with haptic feedback for robotic manipulation

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Teleoperation is a method of remotely operating systems without being in their close physical proximity. This is a widely used approach in Learning from Demonstration (Lfd) paradigms where a task is demonstrated to a robot by a human operator. In this work, we implement a master-slave teleoperated robotic system whereby the user physically guides the master, which in turn controls a slave robot remotely to perform a desired action. The slave robot follows the master in the configuration space by virtue of an impedance control implemented via virtual elastic coupling. While the master remotely controls the slave, the force of interaction sensed by the slave is fed-back to the master side such that haptic feedback is always available to the user. Furthermore, to assist the human in manipulating the robot against the inertia and damping due to the power transmission, an assistive control is implemented on the master side. A reduction in the applied force by the user on the master side is observed which is backed by experimental analysis.

NOMENCLATURE

$\boldsymbol{q}_{fbk}, \dot{\boldsymbol{q}}_{fbk}$ = Feedback robot joint positions and velocities
$\boldsymbol{\tau}_{fbk}$ = Feedback torques from joint torque sensors
$\boldsymbol{q}_{cmd}$ = Commanded joint positions
$\boldsymbol{\tau}_{cmd}$ = Commanded joint torques
$\boldsymbol{\tau}_{ext}$ = External torques of interaction

C = Coriolis and centrifugal matrix
G = Gravity matrix
K = Stiffness of the virtual elastic coupling
K' = Amplification factor for the interaction torque from the slave robot
K_a = Amplification factor for the low-pass filtered assistive torque from the master
LPF = Low pass filter

1. Introduction

To perform human demonstrations of manipulation tasks involving contact such as assembly of various components, consideration of the task forces being recorded, is vital and more importantly isolating them from the human forces acting on the system. Kinesthetic teaching involves a human directly interacting with the robot and physically guiding it through the contact task. This however, results in the recording of the human forces coupled with the contact task forces. It is a challenge to separate these in order to isolate the contact task forces to perform any type of force control when generalizing. Therefore, we use two robots coupled through teleoperation control instead, so that the human operator interacts with the master robot and the slave robot deals with the contact task forces. The term 'Master-Slave' refers to the slave robot following the motion of the master robot in joint space to perform a task remotely, wherein the operator manually guides the master robot, thereby controlling the action of the slave robot which is in direct interaction with the environment. In fact, one of the pioneering applications of teleoperation control was manipulation for handling of radioactive materials from a safe distance in nuclear research [Niemeyer et al. 2016]. The necessity of teleoperated systems has now been recognized more than ever due to the COVID-19 pandemic, as isolation and social distancing gained importance [Yang et al. 2020].

Diving into the technical aspects, one of the main factors to consider in the implementation of such teleoperative control is whether the master and slave are similar or dissimilar robots. In case of unidentical robots, i.e., a difference in their mechanical construction, teleoperation must be implemented in the task space. This is not necessary if two robots of the same mechanical build are available, in which case joint-wise teleoperation is feasible.

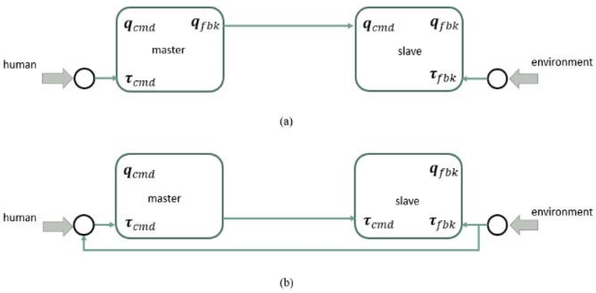

Fig. 1 (a) Position based teleoperation control, (b) Torque based teleoperation control with force feedback to human.

Recent advances in joint torque sensing in robots have made it possible to perform torque control at the joint level – which allows for implementation of human robot interactive behavior like gravity compensation and admittance control. Moreover, torque-control based teleoperation is preferable for contact tasks since position-based control does not account for the forces acting on the robots. Such a control strategy (Fig. 1 (a)) could result in damage to the environment, robots or even injury to the human performing the demonstration. By implementing safe operating torque limits, these risks can be avoided. Haptic feedback has also been found to improve the performance in manipulation of remote objects [Das et al. 1992], [Kuchenbecker et al. 2006] and in this study, we use this in the teleoperation as depicted in Fig. 1(b).

2. Joint-wise teleoperation between master and slave robots

Sensing in force-based teleoperation can be implemented in the following two ways – (a) by attaching a force/torque sensor to the flange of the robot to sense the end-effector forces [Geffard et al. 2000] and (b) with torque sensor built into every joint of the manipulator itself [Villani et al. 2016]. The latter approach was preferred due to the high costs of standalone six-axis F/T sensors. Instead, the robot construction was done with strain gauges at every joint of an industrial robot manipulator [Luh et al. 1983]. Joint torque sensors sense both the mechanics of the robot as well as the task, i.e., the effective robot payload which is determined by the maximum load limit of the base/proximal joint gets further divided between the robot inertia, mechanical resistance and the forces incident on the robot from the contact task.

Instead of explicit force-control to track the haptics of contact task, we rely on the impedance characteristics of teleoperation to obtain the forces that the slave exerts on the environment. This is inherent in the master kinematics and is a key aspect of the proposed approach which allows for an open-loop playback of the assembly demonstrations given the task conditions do not vary.

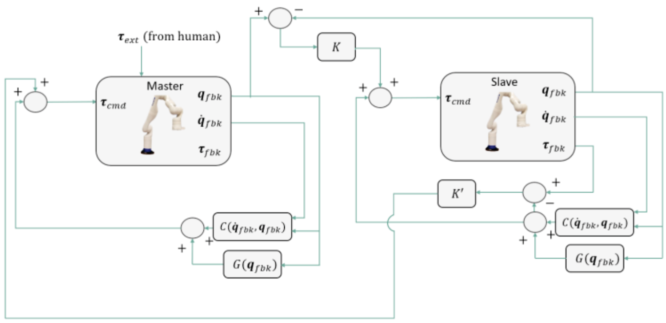

Fig. 2 Joint-wise teleoperation between master and slave robot.

With reference to Fig. 2, the master and the slave robots were operated in the gravity compensation mode (in addition to the Coriolis and Centrifugal compensation) owing to the availability of low-level torque control scheme for the robot. To achieve the 'master-slave' behavior, a virtual visco-elastic coupling was established between the joints of the two robots which caused a virtual torque ($\boldsymbol{\tau}_{cmd} = K(\boldsymbol{q}_{fbk}\,(master) - \boldsymbol{q}_{fbk}\,(slave))$) to drive the slave to emulate the master arm. The highlight of this approach is that the haptic feedback is always available to the user on the master side, which helps the user experience the forces/torques of interaction that are generated on the slave side. This is a significant feature for teaching contact-rich tasks such as insertion and assembly through demonstration.

3. Assistive control

For the operator to effortlessly guide the master around, it is important that the master robot is highly backdriveable. However, in practice, the friction and inertia of the power transmission components (e.g., gearbox) limits the backdriveability of the joints of the robot thereby requiring large forces to be applied by the operator to rotate the joints. To assist the user in guiding the robot effortlessly an assistive control scheme is devised and implemented.

With reference to Fig. 3, the torque applied by the user is first isolated from the sensed torques by removing the torques due to the rigid-body dynamics of the robot. The resulting toque is then passed through a low-pass filter (a moving average filter in this case) to eliminate the high frequency noises in the sensed torque. Subsequently, the filtered torque is amplified and input to the robot as a commanded torque to assist the human against the inertia and damping.

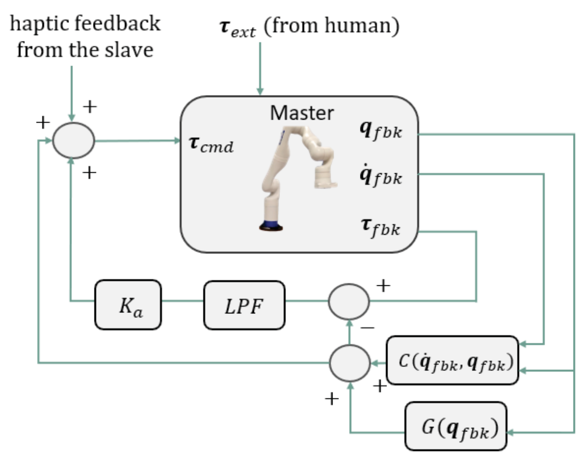

Fig. 3 Schematics for the proposed assistive control for the master robot.

4. Experimental analysis

4.1 Master-slave teleoperation

To test the master-slave framework, we perform a picking task of a cuboid object with the slave robot, remotely controlled by the user at the master side. The experimental setup is shown in Fig. 4.

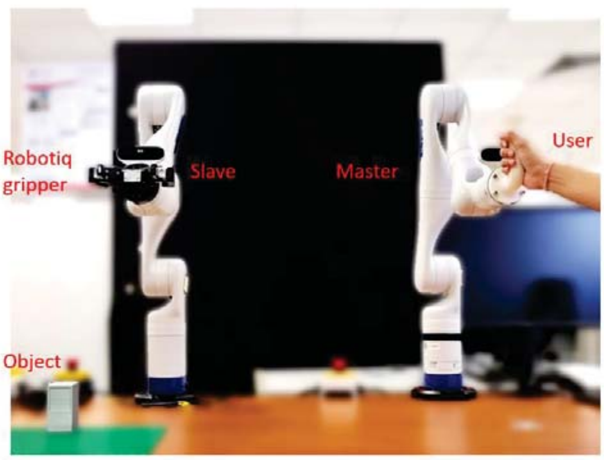

Fig. 4 Master-slave setup for teleoperation.

The proposed master-slave setup involves two 7-DoF Kinova Gen3 ultra-lightweight arms. The master robot arm is mounted with a handle for the convenience of the human operator guidance, whereas the slave is equipped with a standard 2F-85 Robotiq parallel gripper for object manipulation. Both robot arms are controlled in torque control mode from a single workstation at a frequency of 1kHz via TCP/IP communication. The stiffness (K) of the virtual elastic coupling for the master-slave setup was set to be 400Nm/rad.

The user guided the master robot to try and pick an object from a table with the slave robot. The joint positions were logged from the encoders and are plotted against time in Fig. 5. It can be observed that the slave follows the master in the configuration space.

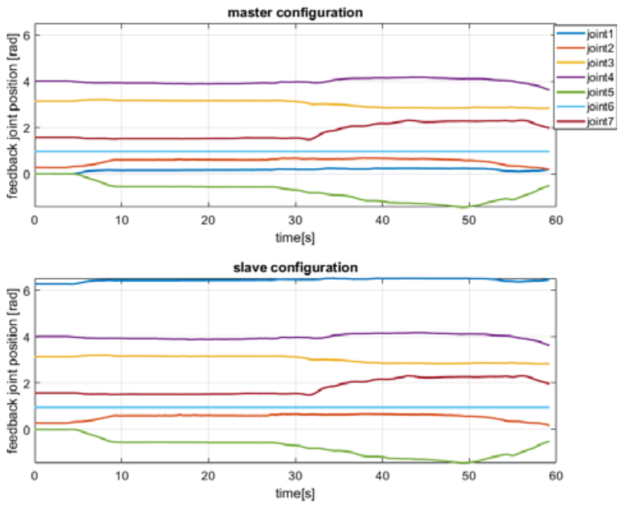

Fig. 5 Feedback joint positions from the master and the slave robots.

4.2 Assistive control

In this work, we test the proposed assistive control only for the end-effector joint (7th joint) of the robot. With the setup being the same as in the previous section, the user was initially asked to rotate the end-effector joint of the master to complete one full cycle, without the assistive control. Subsequently, the assistive control was enabled, and the user was asked to perform the same motion again. In both the cases, the torques sensed by the joint sensor were logged.

With a window side of 300 for the moving average filter and an amplification (K_a) of 10, the torque applied by the user before and after the assistive control is shown in Fig. 6.

It can be observed that with the assistive control the force/torque that user applied brought down significantly.

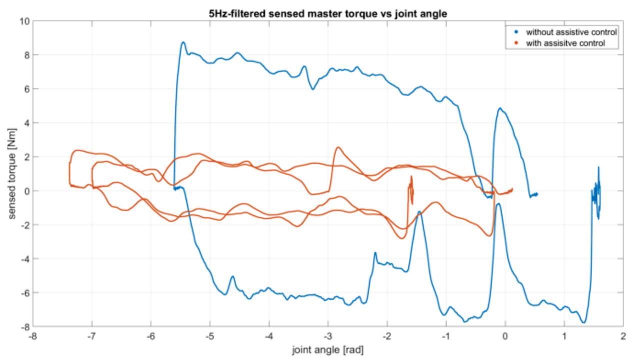

Fig. 6 Torque sensed by the end-effector joint sensor of the master robot (with and without the assistive control) while the user tries to rotate the joint for 360 degrees.

5. Conclusions

In this work, we have designed and implemented a teleoperated master-slave robot system for manipulation tasks. The developed framework was based on the joint space impedance control of the slave robot which helps in following the master robot configuration. The highlight of the proposed approach was the haptic feedback provided to the user to perceive the interaction forces on the slave side. The method was tested on two Kinova Gen3 ultra-lightweight robots and the master-slave successfully.

In addition, to ease the manipulation of the master robot against the internal dynamics of the robot, an assistive control scheme was designed and implemented. The effort from the user side was observed to be brought down with the assistive control making it easier for the user to manipulate the master robot.

ACKNOWLEDGEMENT

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REFERENCES

1. Das, H., Zak, H., Kim, W. S., Bejczy, A. K., & Schenker, P. S. (1992). Operator performance with alternative manual control modes in teleoperation. *Presence: Teleoperators & Virtual Environments*, *1*(2), 201-218.

2. Geffard, F., Andriot, C., Micaelli, A., & Morel, G. (2000, April). On the use of a base force/torque sensor in teleoperation. In *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No. 00CH37065)* (Vol. 3, pp. 2677-2683). IEEE.

3. Kuchenbecker, K. J., & Niemeyer, G. (2006). Induced master motion in force-reflecting teleoperation.

4. Luh, J. Y. S., Fisher, W., & Paul, R. (1983). Joint torque control by a direct feedback for industrial robots. *IEEE Transactions on Automatic Control*, *28*(2), 153-161.

5. Niemeyer, G., Preusche, C., Stramigioli, S., & Lee, D. (2016). Telerobotics. In *Springer handbook of robotics* (pp. 1085-1108). Springer, Cham.

6. Villani, L., & De Schutter, J. (2016). Force control. In *Springer handbook of robotics* (pp. 195-220). Springer, Cham.

7. Yang, G., Lv, H., Zhang, Z., Yang, L., Deng, J., You, S., ... & Yang, H. (2020). Keep healthcare workers safe: application of teleoperated robot in isolation ward for COVID-19 prevention and control. *Chinese Journal of Mechanical Engineering*, *33*(1), 1-4.