Design and Implementation of a Cartesian Impedance Control in a Bilateral Telemanipulation System Using UR10e Robots

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Abstract. This paper presents an overview of a work-in-progress project, where a telemanipulation system is designed and its stability, delay and transparency are discussed. In this telemanipulation system a cartesian impedance control system was implemented, tested and evaluated.

Keywords: Impedance control · Telemanipulation · Robot-environment interaction · UR10e

1 Introduction

The basic objective of impedance control is to achieve a desired dynamic relationship between the robot motion and the external forces acting on it [1]. This relationship plays a major role in the field of telemanipulation, where interaction with the robot, and transparency of feedback forces are essential. The main concept of this controller can be derived from the physical behavior of a mass-spring-damper system.

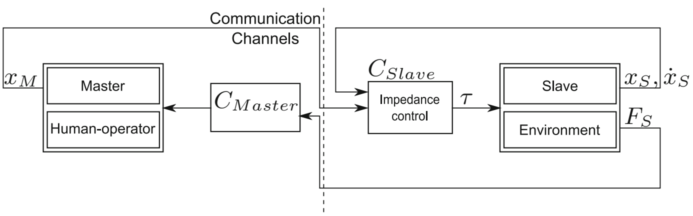

Fig. 1. Block-diagram of impedance control within a telemanipulation system

Fig. 1 shows the basic elements of a telemanipulation system (Human-Operator, Master, Communication, Slave and Environment) [3]. C_{Slave} is the

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controller on the slave, where x_m, x_s, and $\dot{x}_s$ represent the desired position, current position and velocity of the slave robot, respectively. The output τ stands for the motors' torques applied to the robot motors. The two main factors in controlling telemanipulation system are stability and transparency. If a force occurs on the slave, measured by force sensors, then reflected back to the master, this is referred to as bilateral control of the teleoperator [2, 3]. Reflection of forces allows the human operator to rely on both his/her haptic and visual senses. A delay in the communication channels can lead to instability of the system, which can be solved using many methods e.g. wave variables [6].

2 Basic Concepts

2.1 Cartesian Impedance Control

Given two homogeneous matrices $\boldsymbol{H}_t^0$ and $\boldsymbol{H}_v^0$ describing the current and the desired poses of a robot's Tool center point (TCP), the cartesian impedance controller for a 6-DOF robot is physically described by a spatial multidimensional spring with symmetric stiffness matrix $\boldsymbol{K} \in R^{6\times 6}$ connected between both poses and attempts to match them along with a spatial multidimensional damper. The wrench W_s exerted on the robot caused by the spatial spring is given as [4]:

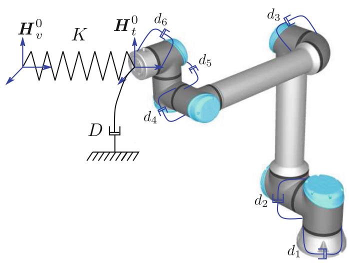

Fig. 2. Cartesian impedance control: compliance is added via a spatial multidimensional spring $\boldsymbol{K} \in \boldsymbol{R}^{6\times 6}$ and damping is introduced either via a spatial multidimensional damper $\boldsymbol{D} \in \boldsymbol{R}^{6\times 6}$ or space dampers d_i connected to each joint.

$$\boldsymbol{W}_s = \begin{pmatrix} \boldsymbol{m}_s \\ \boldsymbol{f}_s \end{pmatrix} = \begin{pmatrix} \boldsymbol{K}_o & \boldsymbol{K}_c \\ \boldsymbol{K}_c^T & \boldsymbol{K}_t \end{pmatrix} \cdot \begin{pmatrix} \delta\boldsymbol{\theta}_t^v \\ \delta\boldsymbol{p}_t^v \end{pmatrix}$$

Where $\delta\boldsymbol{\theta}_t^v$ and $\delta\boldsymbol{p}_t^v$ are infinitesimal twists in vector form and $\boldsymbol{K}_t$, $\boldsymbol{K}_o$, and $\boldsymbol{K}_c$, are the symmetric translational, rotational and coupling stiffness matrices, which represent the spatial compliance. Starting with $\boldsymbol{W}_s$ and using the related equations in [4], the wrench can be calculated and transformed in the base frame $\boldsymbol{W}_s^0$. Adding a damper can be done using the same procedure or as follows:

$$\boldsymbol{W}_{sd}^0 = \begin{pmatrix} \boldsymbol{m}^0 \\ \boldsymbol{f}^0 \end{pmatrix}_{sd} = \boldsymbol{W}_s^0 - \begin{pmatrix} \boldsymbol{D}_o & 0 \\ 0 & \boldsymbol{D}_t \end{pmatrix} \left(\boldsymbol{v}_o \boldsymbol{v}_t\right) \quad (1)$$

where the indices $\boldsymbol{s}$ and $\boldsymbol{sd}$ represent spring and (spring + damper), $\boldsymbol{D}_t$ and $\boldsymbol{D}_o$ are the translational and the rotational damping matrices, with $\boldsymbol{D}_i = d_i\boldsymbol{I}_3$. Finally, $\boldsymbol{v}_t$ and $\boldsymbol{v}_o$ are the translational and rotational velocities of the TCP, respectively.

2.2 Telemanipulation System Using Cartesian Impedance Control

The controller presented in the previous section was implemented for both robots, master and slave, within the Kinesthetic Force Feedback (*KFF*) architecture to build a telemanipulation system. According to [5, 7], in this architecture the position of the master is transmitted to the slave, and the environment force acting on the slave is sent back to the master, that is passed to the operator as a feedback force. A block diagram of this architecture can be seen in Fig. 1.

3 Experiments

Two *UR10e* robots were used Fig. 2. The forces measured on the slave were filtered using a Kalman filter Fig. 3b before being reflected as feedback force to the master. The *forcemode* function provided by the robot was used, that accept wrench directly without the need to determine the motors' torques $\boldsymbol{\tau}$. On the master side, the filtered force was used as wrench for the cartesian impedance controller, that's why no wrench was calculated and the controller was used for the hand guidance and force feedback. In the evaluation a cartesian trajectory planning Fig. 3a, with the gains $\boldsymbol{K}_t = 3000\boldsymbol{I}_3[\frac{N}{m}]$, $\boldsymbol{K}_o = 50\boldsymbol{I}_3[\frac{N}{rad}]$, $\boldsymbol{K}_c = 0_3$, $\boldsymbol{D}_t = 50\boldsymbol{I}_3[\frac{Ns}{m}]$ and $\boldsymbol{D}_o = 5\boldsymbol{I}_3[Ns/rad]$ are used. One can see that the delay is between both sides is less than 200 ms.

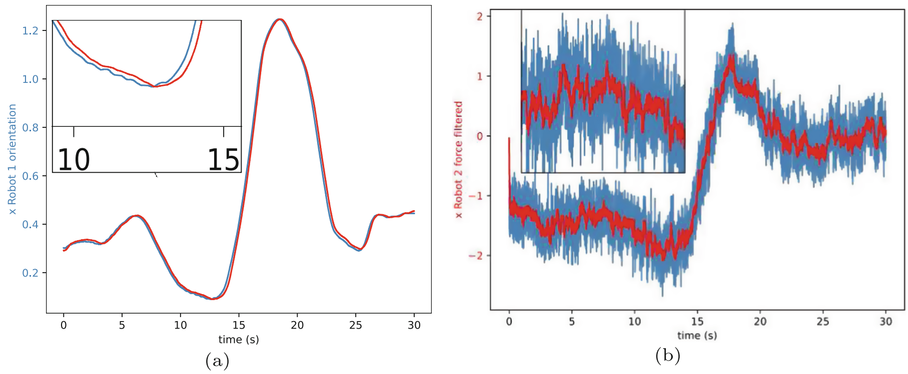

Fig. 3. (a): the Orientation of the Master (blue) and Slave (red) Robots on the X-axis. (b): force measured (blue) and filtered using a Kalman filter (red)

4 Summary

The performance of cartesian impedance control in telemanipulation systems was studied, where a delay of less than 200 ms, and stability in contact was achieved. Optimizating the performance can be made with, for example, adding Shared Compliance Control, that can improve the stability, dealing with time delays and perception. Also, the effect of using a higher accuracy external F/T sensor to be discussed instead of internal force sensor used.

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