

# Toward a General Bilateral Teleoperation Framework Between Dissimilar Kinematic Structures

Gionata Salvietti<sup>1</sup>, Leonardo Meli<sup>1,2</sup>, Guido Gioioso<sup>1,2</sup>, Domenico Prattichizzo<sup>1,2</sup>

<sup>1</sup>Dept. of Advanced Robotics, Istituto Italiano di Tecnologia, Via Morego 30, 16163 Genoa, Italy

<sup>2</sup>Dept. of Information Engineering and Mathematics, University of Siena, Via Roma 56, 53100, Siena, Italy

**Abstract** – In bilateral telemanipulation scenarios the human hand/arm is usually put in correspondence with a robotic hand/arm system. The kinematic structure of the human hand and of the robotic hand are typically different requiring algorithm to map human motion on the robot workspace. At the same time, the force measured at the robotic side cannot usually be displayed in the same point on the human hand/arm system. In this work we propose a bilateral mapping algorithm able to mitigate differences in master-slave kinematic structures. The algorithm is based on the use of a virtual object which allows to work on the task space abstracting from the joints space. The proposed approach has been tested with an experimental setup consisting of two single-point haptic interfaces as master devices and a robotic hand system as slave.

## I. INTRODUCTION

In a bilateral telemanipulation scenario a human operator is able to physically interact with a remote environment. In many cases, the remote environment cannot be accessed directly by the operator for safety reasons, e.g., radiations, or for space reasons as, for instance, in pipe inspection and repair. However, tasks like transport loads, seal leakages, open-close valves, drill, cut, etc., require human intelligence excluding in the immediate future a fully autonomous robotic technology. Several solutions have been proposed to solve bilateral telemanipulation in a wide range of scenarios [1]. Tasks are usually performed by a mechanical manipulator (slave) remotely controlled by a human operator provided with a force reflecting interfaces (master). Kinematic structures of master and slave devices are typically different [2]. To solve this issue there are two possible ways: remove the kinematic differences by designing a specular master-slave system or introduce a control layer able to overcome kinematic dissimilarities. Although the first solution seems so solve quickly the problem, in most of the applications constraining the design of the slave robot to the human ergonomics is very limiting. Moreover the complexity of the whole system increases

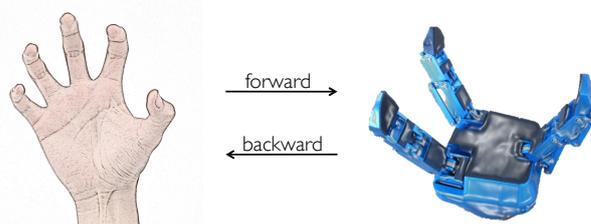


Fig. 1. General idea of the telemanipulation framework. A virtual object is used to map human hand motion (forward mapping) and to compute the force feedback (backward mapping).

when complex grippers or robotic hands are considered as slave devices and a force feedback is required on the human hand fingers. In [3], for instance, a shared control framework is presented where an instrumented glove (Immersion CyberGlove) is exploited as master interface and a two fingered gripper is used as slave device. In [4] the authors present a two-fingered haptic device to teleoperate a five-fingered robotic hand.

In our opinion, there is a need of an universal kinematic interface, independent from the device structures. This will allow an operator to practice on a single master and teleoperate different slaves reducing the training time and the complexity of the adaptation to a new slave devices. This simplification comes at the cost of a complex control framework able to hide the real kinematic structure and to compute the correct force feedback. However, while different solutions have been proposed to map human hand configurations onto robotic hand with dissimilar kinematics [5, 6, 7, 8], there are few studies on how to compute the correct force feedback.

In this work we present a telemanipulation framework that can deal with kinematic asymmetries between master and slave structures, where a new approach for force feedback computation is considered. The main idea is to define

a virtual object on both the master and the slave sides and to impose a correspondence between the twist/wrench applied on these objects. Such correspondence provides basic building blocks to translate human hand motions into movements of a robotic hand, as well as to compute the correct force to be rendered by the haptic devices. We believe that the proposed approach is a first step toward the realization of a general framework to overcome the discrepancies between human and robot kinematics and dynamics. The definition of a virtual object on the master allows not only to abstract over the kinematics of the master, but also to use the mathematics of robotic grasping [9] to evaluate the feedback forces. For the sake of simplicity, in this work we focus only on in-hand manipulation assuming the real object on the slave side already grasped. We tested our approach using two Omega.3 haptic devices by Force Dimension [10] as master device and a robotic DLR-HIT II Hand [11] as slave device.

The paper is organized as it follows. Section II deals with the description of how the motions of the master devices are mapped onto the slave one and how the force feedback is computed. In Section III the setup used to validate the approach is outlined, while in Section IV the experimental results are presented and discussed. Finally Section V addresses concluding remarks and future work. An extended version of this work has been presented in [12].

## II. TELEMANIPULATION FRAMEWORK

In this section we describe how the proposed telemanipulation framework can be used abstracting from master and slave kinematics. We refer to *forward mapping* to indicate all the passages necessary to reproduce the motion captured in the master side in the slave side. All the procedures needed to map forces measured on the slave side onto the master side are referred as *backward mapping*.

In this paper we do not discuss about the passivity layer which is designed using well known techniques, based on passivity [13].

### A. Forward mapping

In this work, we considered the total manipulation effects on a virtual object instead of the single contribution of each finger. This solution allows to generalize the algorithm to different contact points number and positions without focusing on the kinematic of master and slave sides. Let  $\{N_m\}$  indicate the reference frame set on the base of one device and let  $p_{1,m}$  and  $p_{2,m}$  represent the position of the two device end-effectors, both computed with respect to  $\{N_m\}$  as showed in Fig. 2a. The virtual object is obtained considering the line connecting the two fingertips as pictorially represented in Fig. 2b. Let us indicate with

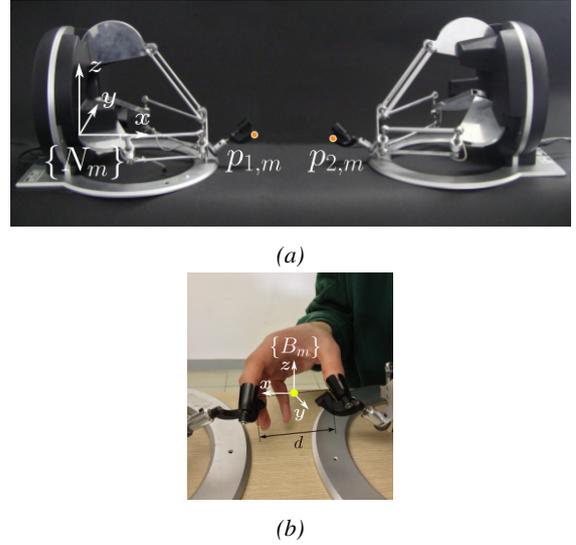


Fig. 2. The master sub-system setup. (a) two Omega.3 haptic devices. Both  $p_{1,m}$  and  $p_{2,m}$  are expressed with respect to the same reference frame  $\{N_m\}$ . (b) virtual object with its own reference frame  $\{B_m\}$ .

$d_m$  the distance between the two fingertips, i.e.

$$d_m = \|p_{2,m} - p_{1,m}\|.$$

The virtual object idea can be extended to an arbitrary number of reference points by considering for instance a sphere as virtual object [5]. In that case the virtual object can be defined for instance as the minimum volume sphere containing the reference points, and the role of  $d_m$  is played by the sphere diameter. All the following considerations can be easily extended to the virtual sphere formulation.

Let  $\{B_m\}$  represent a reference frame of the virtual object (see Fig. 2b).  $o_m \in \mathbb{R}^3$  denotes the position of  $\{B_m\}$  origin with respect to  $\{N_m\}$ . In the proposed work, the object center  $o_m$  is considered as the mid-point between the two haptic device end-effectors and its coordinates can be computed as

$$o_m = \frac{1}{2} (p_{1,m} + p_{2,m}).$$

Consider also  $\phi_m \in R^3$  a vector describing the relative orientation between the frames (e.g. Euler angles). Let furthermore  $u_m = [o_m^T \ \phi_m^T]^T \in \mathbb{R}^6$  collects information on position and orientation between the above mentioned frames.

Starting from an equilibrium configuration and considering a small change of the hand posture it is possible to evaluate the corresponding object displacement  $\Delta u_m$  as

$$\Delta u_m = (G_m^T)^\# \Delta p_m + N_{G^T} \psi,$$

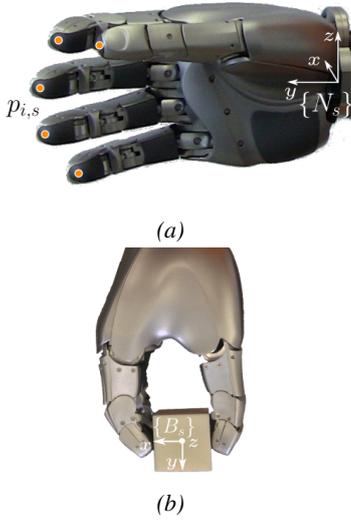


Fig. 3. The slave sub-system setup. (a) a DLR HIT II Hand with its own reference frame  $\{N_s\}$ . (b) real cube with its own reference frame  $\{B_s\}$ .

where  $p_m = [p_{1,m}^T \ p_{2,m}^T]^T \in \mathbb{R}^6$  groups the two reference points on the master side,  $G_m$  represents the *grasp matrix* as described in [9],  $N_{G^T}$  is a matrix whose columns form a basis of the nullspace of  $G^T$  and the vector  $\psi$  parametrizes the homogeneous solution.

Consider now the robotic hand on the slave side grasping an object using  $nc_s$  contact points, and let us indicate with  $p_s \in \mathbb{R}^{3nc_s}$  the resulting contact point location vector, expressed with respect to the reference frame  $\{N_s\}$  depicted in Fig. 3a.

A second virtual object is considered for the robotic hand. It is defined by the fingertips position involved in the grasp of the real object. The virtual object center  $o_s$  is considered as the mean position between the contact points,

$$o_s = \frac{1}{nc_s} \sum_{i=1}^{nc_s} p_{i,s} .$$

We assumed to determine the same grasping matrix for the real and the virtual objects in the slave sub-system.

The final target of the forward mapping is to move the manipulated object accordingly to the virtual object defined on the master side, while guaranteeing the stability of the grasp in the slave sub-system. We considered a generic motion on the master side as a composition of a rigid body motion and a deformation of the virtual object, that can be related to an internal force contribution. The master rigid body motion is mapped on the slave one, while the internal force variation applied by the master sub-system is projected on the slave subspace of controllable internal forces. Therefore the motion decoupling allows to independently control both the component variations.

The rigid body contribution to the motion of the reference points on the slave side, can be computed as

$$\Delta p_{s,RB} = J \Gamma_{qc} \Gamma_{uc}^\# \Delta u_m , \quad (1)$$

where  $J$  is the Jacobian matrix of the slave device as defined in [9]. Details on the computation of  $\Gamma$  matrix can be found in [14].

To deal with different initial positions of haptic device end-effectors we introduced a scaling factor

$$s_f = \frac{1}{nc_s \|d\|} \sum_{i=1}^{nc_s} \|p_{i,s} - o_s\| , \quad (2)$$

computed at the beginning of the telemanipulation task.

Concerning the internal forces, the contribution in terms of reference point displacement can be obtained as

$$\Delta p_{s,IF} = K^{-1} E_v \hat{y} \Delta d_m s_f , \quad (3)$$

where  $K \in \mathbb{R}^{3nc_s \times 3nc_s}$  is the contact points stiffness matrix,  $E_v$  is a matrix whose columns form a basis for the subspace  $\mathcal{R}(P N_V)$ ,  $N_V$  is a matrix whose columns form a basis for the subspace nullspace of  $V$ ,  $\hat{y}$  is evaluated as  $\hat{y} = (E_v)^\# n$ , and  $n \in \mathbb{R}^{3 \times nc_s}$  is the vector of the normals to the contact surface. Details on the definition of matrix  $P$  and  $V$  can be found on [14]. This part of the solution depends on the system compliance, defined through the stiffness matrix  $K$ , that takes into account both the contact and the joint compliance. More details can be found in [15]. The projection on the  $\mathcal{R}(P N_V)$  subspace avoids to move the object while the internal forces are modified, as detailed in [16]. The displacements defined in eq. (1) and (3) are related to the reference contact points. It is worth to observe that if the grasp of a real object is considered, the reference points ideally can move inside the object, while the real contact points lie on the surface. The penetration of the reference points inside the object is proportional to the contact force, according to the compliant model described in [14].

Combining eq. (1) and (3), we get the displacement of the reference points on the slave side

$$\Delta p_s = J \Gamma_q \Gamma_{uc}^\# \Delta u_m + K^{-1} E_v \hat{y} \Delta d_m .$$

Finally, the displacement of the robotic hand joints  $\Delta q_s$  is computed as

$$\Delta q_s = J^\# \Delta p_s .$$

### B. Backward mapping

The target of the backward mapping is to display to the user the wrench acting on the real object at the slave side. This part of the teleoperation framework does not consider the specific kinematics of the master and slave, but it focuses only on the effects imposed by the manipulated object.

Let define  $\tau \in \mathbb{R}^{n_q}$  as the vector of the torques measured at the joints. It is possible to compute the forces at the contact points as [9],

$$\lambda_s = (J^T)^\# \tau + N_{J^T} \chi, \quad (4)$$

where  $N_{J^T}$  is a matrix whose columns form a basis of the nullspace of  $J^T$ , and the vector  $\chi$  parametrizes the homogeneous solution. The generic contact force  $\lambda_{str} = N_{J^T} \chi$  represents a set of contact forces that satisfies the condition  $J^T \lambda_{str} = 0$ . In the literature, such contact forces are referred as structural forces [9].

The corresponding wrench acting on the slave side can be estimated as

$$w_s = G_s \lambda_s,$$

where  $G_s$  is the grasp matrix evaluated for the slave hand grasp.

By imposing that the wrench to be rendered on the master virtual object  $w_m$  is the same applied at the slave side  $w_s$ , the arising forces to be rendered by the haptic interfaces  $\lambda_m \in \mathbb{R}^{3n_{cm}}$  are

$$\lambda_m = G_m^\# G_s \lambda_s + N_{G_m} \xi,$$

where  $N_{G_m} \in \mathbb{R}^{3n_{cm} \times h}$  is a matrix whose columns form a basis for the nullspace of  $G_m$  and  $\xi \in \mathbb{R}^h$  is a vector parametrizing the homogeneous part of the solution.  $\xi$  can be selected considering the human hand skills in terms of joint torques and muscle activity as proposed in [17]. In this work  $N_{G_m} \in \mathbb{R}^{6 \times 1}$  and  $\xi \in \mathbb{R}$  since only two contact points are taken into account. We then evaluated  $\xi$  as

$$\|N_{G_m} \xi\| = \|(I - G_s^\# G_s) \lambda_s\|.$$

The term  $\|(I - G_s^\# G_s) \lambda_s\|$  represents an estimation of the total amount of forces exerted on the real grasped object.

### III. EXPERIMENTAL SETUP

The proposed algorithm has been validated with a teleoperation system composed of two Omega.3 haptic devices on the master side and a DLR-HIT Hand II on the slave side. Each haptic interface has a thimble instead of the default end-effector to easily fit thumb and index fingertip respectively (see Fig. 2a). Since only in-hand manipulation was considered, the operator was asked to keep its wrist firm during the tasks execution.

The position of the right interface is strictly related with the one on the left, since only a reference frame for the master side is used as introduced in Sec. II. A preliminary calibration test is thus necessary to place the devices in the correct positions.

In the experiments, the robotic hand grasps a plastic cube with a side of 3 cm, whose position was computed with respect to  $\{B_s\}$  as shown in Fig. 3b.

The system is managed by a GNU/Linux machine, equipped with a real-time kernel. Both the haptic interfaces use their own embedded controllers connected through USB, while the controller of the DLR-HIT Hand II is implemented on a QNX machine and it communicates via UDP/IP protocol.

A multi-thread software is built to deal with the different sampling rates of each controller. A refresh rate  $f_m$  for the Omegas of approximately 750 Hz ensures that the operator's fingers are tracked with accuracy. We set the refresh frequency of the slave sub-system  $f_s$  thread at around 200 Hz. This is due mostly to the the robotic hand motors bandwidth. The difference in terms of sampling rate between the threads is exploited to manage possible force spikes on the master side. The force signals read from the robotic hand were smoothly applied to the human fingertips during the  $\lfloor \frac{f_m}{f_s} \rfloor$  extra loops on the master sub-system. In the same way, the position of the virtual object received by the robotic hand was evaluated as the mean between the positions tracked. No tactile sensors are considered. The forces exerted at the fingertip are computed evaluating the hand Jacobian and the read motor torques. Similarly, the position of the fingertips are computed through forward kinematics based on the joint position read from the encoders available in the robotic hand. We always assume a precision grasp where the contact points are placed at the fingertips during manipulation.

### IV. RESULTS

In order to validate the performances of the proposed framework, five male subjects, age range 24 – 30, all right-handed, took part to two experiments. Two of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their perception abilities. The participants were asked to wear the thimbles, one on the thumb and one on the index finger.

In the first experiment we validated the forward mapping. The subjects were asked to move the real cube on the robotic hand acting on the two haptic interface at the master side. The cube was grasped with the fingertips of thumb, index and middle finger. To emphasize the effectiveness of the rigid body motion contribution on the forward mapping procedure, the rendering of the internal forces was disabled. In this way, independently from how much the subject squeezed the virtual object on the master side, the initial internal force value of the slave side was kept. Six virtual walls were introduced in order to avoid users to reach the boundaries of the robotic hand workspace, where joint singularities were experienced. This approach limits the workspace of the master devices, however since an in-hand manipulation was considered, these limitations did not significantly affected the experiments. Fig. 4 shows the trajectories of the virtual object and the real cube, considering for both  $[0 \ 0 \ 0]^T$  as the

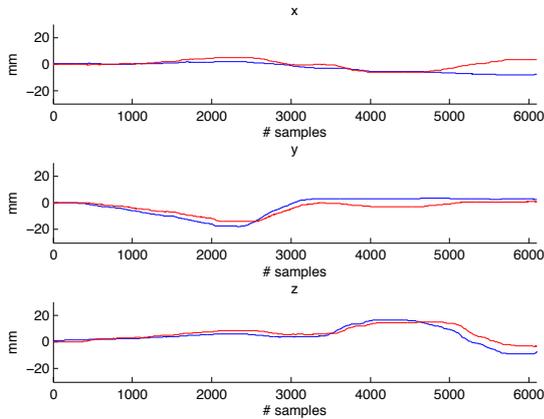


Fig. 4. Experiments for forward mapping validation. Trajectories of the virtual object on the master side (blue) and the cube in slave sub-system (red).

initial position. The position of the real cube is computed considering the position of the contact points.

In the second experiment, the backward mapping was validated. The subjects were asked to squeeze the object grasped by the robotic hand acting on the master devices. Fig. 5 reports the sum of the absolute value of forces applied on the user fingertips with respect to distance between the thimbles  $d$ . The results of two subjects are reported. Forces on the slave side were evaluated using torque sensors available on the three robotic hand fingers involved in the grasp and rendered using the Omegas at the master side. Note that backward mapping procedure hide to the user the fact that three forces exerted at three contact points on the slave side are rendered by two forces applied at two contact points on the master side. The different slopes of the interpolation lines are related to the scaling factor considered (eq. (2)), since the two users started from two different initial positions. The bigger is the scaling factor, the higher is the force provided to the users with respect to specific value of  $d$ .

## V. CONCLUSION AND FUTURE WORK

In this paper we proposed a possible telemanipulation framework that can deal with kinematic asymmetries between master and slave structures. This work represents a first step toward the realization of a universal master side that can be interfaced with different slave devices without requiring a new training period for the operator. One of the main issues to solve to achieve such result is the computation of force feedback. We proposed an object-based approach where the forces are computed by imposing the same wrench estimated on the real grasped object on a vir-

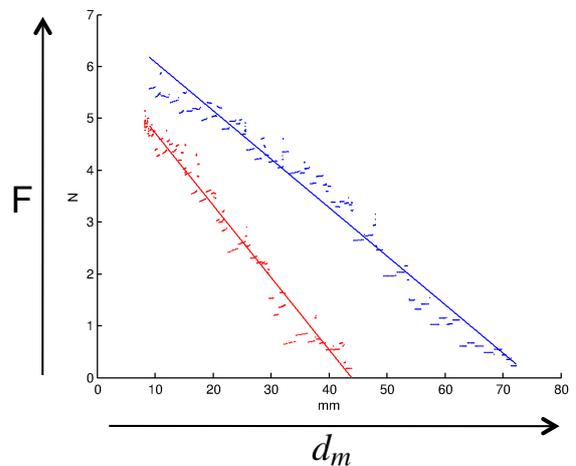


Fig. 5. Sum of the absolute value of the forces belonging to  $\mathcal{N}_G$  perceived by two users with respect to the norm of the distance between the haptic device end-effectors  $d$ . Different colors belong to different subjects. Raw data represented by dots are fitted with a linear interpolation to emphasize the proportion of the variables analyzed.

tual object defined on the master side. This solution focuses on the effects on the manipulated object and consents to abstract from the device kinematics. Two manipulation experiments have been proposed to validate the approach. We considered the object on the slave side already grasped by the robotic hand. This assumption was useful to easily define the Grasp matrix for the real grasped object. A grasp approaching phase may be considered as an extension of the algorithm proposed.

As future work, we are testing different models of robotic hands in the slave side, with particular emphasis on non-anthropomorphic structures. Moreover, we are planning to substitute the grounded haptic interface used in the proposed setup with more light and wearable devices that can be directly worn on the fingertips like those proposed in [18].

## VI. ACKNOWLEDGMENT

Authors are grateful to Prof. Monica Malvezzi for her suggestions during the definition of the mapping framework.

## VII. \*

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