Multi–Contact Bilateral Telemanipulation using Wearable Haptics

Leonardo Meli[1], Gionata Salvietti[1,2], Guido Gioioso[1], Monica Malvezzi[1,2], and Domenico Prattichizzo[1,2]

Abstract— **Bilateral telemanipulation refers to frameworks in which a human operator manipulates a master robotic interface and a slave robotic device emulates the behavior of the master, while haptic feedback is provided to the operator. For multi-contact bilateral teleoperation we intend master and slave systems that can establish multiple contact points with the user and with the environment. A paradigmatic example can be a multi-fingered robotic hand teleoperated by the human hand. Two of the most critical issues in this context are: (i) how to provide haptic feedback on multiple points of the human hand; (ii) how to solve the correspondence problem between the human hand and the robotic slave device. In this work, we propose finger-worn devices able to apply a three dimensional vector of force at a specific contact point to solve the multi-contact feedback problem. For the correspondence problem, we propose an object-based mapping procedure. The approach is based on two virtual objects, defined both at the master and slave sides, to capture the human hand motion and to compute the related force feedback. The proposed approach has been tested in a telemanipulation framework where the master side was composed of a Leap Motion sensor used to track the hand plus three wearable haptic devices, while a robotic hand/arm system performed a manipulation task as slave.**

I. Introduction

Bilateral telemanipulation deals with the possibility of extending remotely human manipulation capabilities [1]. A telemanipulator is a complex system which includes a master and a slave device, interconnected by a communication channel. The overall system is interfaced with a human operator at the master side, and with the environment at the slave side. Both master and slave devices have their own local control system, with a very large variety of complexity and sophistication levels, which allow the execution of desired tasks [2]. A great research effort has been focused on stability issues due to the delay introduced by the communication channel [3, 4] and on guaranteeing the transparency of the whole teleoperation loop [5, 6]. Most of the systems presented in the above mentioned works consider the possibility of establishing a single contact point with the remote environment as well as a single interaction point with the user. Although single-master/single-slave architectures can deal with several operations (e.g., screwing/unscrewing, soldering, etc.), complex teleoperation tasks, as well as emergent network-based applications, require a more sophisticated architectures where master and/or slave are systems establishing multiple contacts with the operator and/or with the environment [7]. Bilateral telemanipulation scenarios where the human hand is in correspondence with a multi-fingered robotic hand as slave end-effector is a classical example of multi-contact interaction. While human hand tracking can be achieved using datagloves [8] or by means of vision systems [9], providing force feedback on all the fingers still represents a challenge. Commonly used 3-DoFs haptic interfaces cannot provide more than two interaction points due to their overall size and workspace limitations [10]. Glove-type haptic displays, such as the CyberGrasp (CyberGlove Systems LLC, San Jose, CA, USA) can provide forces to all five fingers of the hand simultaneously [11]. However, the mechanics of these displays, including wires and bulky transmission systems, is usually rather complex and it compromises the overall system wearability and portability. A promising solution is represented by wearable displays able to apply cutaneous signals to the finger pad, such as the device presented by Prattichizzo et al. [12]. It was a 3-DoFs parallel mechanism: the static part was located on the dorsal part of the finger, while the mobile platform was in contact with the finger pulp. Three motors, by controlling the length of three cables, moved the platform towards the user's fingertip and re-angle it to simulate contacts with arbitrarily oriented surfaces. The wearability of cutaneous devices was gained at the expense of kinesthetic feedback. In [13] such devices have been used in a virtual telemanipulation framework where the hand was tracked with a RGB-D camera and the slave was represented by a virtual model of the human hand. Frisoli et al. [14] presented a wearable haptic device capable of providing both kinesthetic and cutaneous cues informative of shape geometry at the contact point.

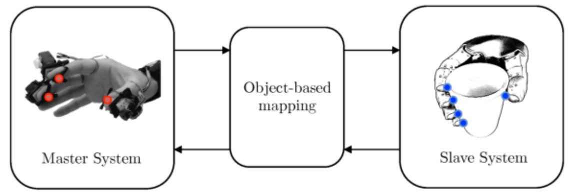


Fig. 1: General bilateral telemanipulation framework. The kinematics of master and slave, as well as the number of contact points, may differ in the considered approach.

In this paper, we take inspiration from the master architecture presented in [13] and we considered a multi-contact master for telemanipulation where the human hand motion is

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007- 2013 under grant agreement 601165 of the project WEARHAP.

[1]Department of Information Engineering and Mathematics, University of Siena, Siena, Italy, {meli, salviettigio, gioioso, malvezzi, prattichizzo}@diism.unisi.it.

[2]Department of Advanced Robotics, Istituto Italiano di Tecnologia, Genova, Italy,

tracked using a Leap Motion IR camera (Leap Motion, Inc, San Francisco, CA, USA) and the forces are displayed on the fingertips using wearable thimbles. Cutaneous feedback provides the user with a reliable sensation of telepresence, as the cutaneous force feedback is perceived where it is expected (i.e., the fingertip) and provides the operator with a direct and co-located perception of the contact force, even though kinesthesia is missing. The advantages of this master system is twofold. Firstly, the master workspace is not limited by the workspace of the devices thanks to their extreme wearability and portability. This furthermore enables the simultaneous stimulation of several interaction points on the human hand. Secondly, the teleoperation system is intrinsically stable [15]. In fact, an interesting approach to stabilize telemanipulation loops consists in using sensory substitution techniques, such as vibrotactile [16], auditory or visual channels [17] to provide feedback at the master side. Similar to sensory substitution, in [15] the authors presented a novel feedback technique named "sensory subtraction", as it subtracts the destabilizing kinesthetic part of the full haptic interaction to leave only cutaneous cues, thus making the teleoperation system stable.

Another important issue to be addressed in case of multi-contact master and slave devices concerns the correspondence problem between the human hand and the slave device, that typically have dissimilar kinematic structures. In this work, we introduce a mapping algorithm able to abstract from the number of interaction/contact points defined at the master/slave sides, and that can compute the force feedback also when the master system includes wearable devices. We have defined as *forward mapping* the steps necessary to reproduce on the slave side the user motion captured on the master side, while *backward mapping* deals with the algorithm that computes the correct forces to be displayed back to the user, starting from the signals acquired at the slave side. The idea is pictorially represented in Fig. 1. The teleoperation framework introduced in this work can also deal with slave devices different from a robotic hand. Systems like the one presented in [18], where a swarm of UAVs was used to cooperatively grasp an object, could implement the same mapping strategy to transfer the human hand motion to some robot formation parameters and to feed back to the user information about the forces applied on the slave side. Differently from [19, 20], the virtual object used here lacks a defined shape, but it is instead defined by the interaction/contact points.

The rest of the paper is organized as it follows. In Section II the object-based mapping is described. Section III deals with the description of the experimental setup and ends with some preliminary results on a peg in a hole task. Finally, in Section IV conclusion and future work are outlined.

II. Teleoperation framework

A. Forward mapping

The issues in transferring the motion of the human hand onto robotic systems have been investigated with different approaches [19]. In this paper, we take advantage of a virtual object to abstract from the kinematics of master and slave. This object-based mapping has been pioneered in telemanipulation by Griffin et al. [21]. The main idea is to use a virtual object to translate the motion of the human hand in the variation of some object parameters, such as the position of the center and the radius of a circle. In [19] and [22] the object-based mapping has been extended to 3-D cases and to an arbitrary number of reference points necessary to define the virtual objects. One of the main advantages of object-based mappings is that the definition of virtual objects permits to generalize to an arbitrary number of contact points that can be different in the human and robotic hands, as well as to remove the constraints on the position of contact points. The forward mapping is based on the definition of a series of reference points, both on the human and the robotic hand (see Fig. 2a). The reference points on the human hand are necessary to evaluate the transformation produced by the hand motion and they are the points where the force feedback is rendered. These points are referred to as *interaction points*. The *contact points* on the robotic hand are necessary to define the virtual object on the slave side. A configuration variation on the human hand causes a transformation of the position of the interaction points, which can be generally represented by a six-dimensional displacement and/or a non rigid deformation. In this paper, we assume that this transformation can be represented as a linear transformation, estimated from the displacement of the reference points. The same linear transformation is then imposed to the robotic hand reference points and the hand joint displacement is consequently defined by solving its inverse kinematics. A linear transformation matrix can be decomposed to separately reproduce the contribution in terms of internal forces [23], which are paramount for grasp control, and in terms of the rigid body motion imposed by the hand on the manipulated object [24]. In the following, we will briefly report the main procedure equations.

Let $\{W_m\}$ be an inertial reference frame attached to the master sub-system. Similarly, consider $\{W_s\}$ an inertial reference frame, adopted to describe the slave motion. Let the vector $p^m_{j,c} \in \Re^3$ represent the coordinates of the j-th interaction point, expressed in $\{W_m\}$, when the master is in a given configuration $\mathcal{C}^m$, with $j = 1, \cdots, n^m$, where n^m is the number of interaction points on the master. Let us define a vector $p^m_c \in \Re^{3n^m}$ as the collections of the coordinates of all these points. A set of n^s contact points can be defined on the slave: when the slave is in a certain configuration $\mathcal{C}^s$, their coordinates, expressed in $\{W_s\}$, are indicated with $p^s_{l,c}$, with $l = 1, \cdots, n^s$ and are collected in a vector $p^s_c \in \Re^{3n^s}$. Note that, in general, $n^m \neq n^s$, and n^m and n^s are not a priori related. Let us assume that the position of the reference points over time can be tracked. In the following, we will denote by $\hat{a} \in \Re^4$ the augmented representation of a generic vector a, adopted to write affine transformations, i.e., $\hat{a} = [a^{\mathrm{T}} \;\; 1]^{\mathrm{T}}$. The mapping procedure proposed to evaluate the reference displacements for the slave system on the basis of the master ones is based on the assumption that the configuration variation of the contact points from $\hat{p}_i^m$ to $\hat{p}_f^m$ can be represented as a linear transformation, i.e., for each point p_j^m, the following linear equation can be written

$$\hat{p}_{j,f}^m = T\hat{p}_{j,i}^m, \tag{1}$$

where $T \in \Re^{4\times4}$ is a linear transformation. Given $\hat{p}_i^m$ and $\hat{p}_f^m$, it can be evaluated by solving a linear system [25, 26].

The transformation matrix T defined in Eq. (1) can be decomposed as $T = T_{def}T_{rb}$, where T_{def} represents the non–rigid part of the transformation, and T_{rb} is a rigid–body transformation [26]. This decomposition can be used in the forward mapping procedure, to reproduce separately at the slave side the contribution of the internal force and the contribution of rigid body motion. According to this decomposition of T, the motion of the contact points on the master system can be decomposed in two parts as

$$\hat{p}_{j,rb}^m = T_{rb}\hat{p}_{j,i}^m, \quad \hat{p}_{j,f}^m = T_{def}\hat{p}_{j,rb}^m,$$

where $\hat{p}_{j,rb}^m$ is the configuration that the point would reach if we consider only the rigid body part of the transformation. We can therefore introduce two displacements

$$\Delta p_j^m = p_{j,f}^m - p_{j,i}^m = \Delta p_{j,rb}^m + \Delta p_{j,def}^m, \tag{2}$$

where $\Delta p_{j,rb}^m = p_{j,rb}^m - p_{j,i}^m$, $\Delta p_{j,def}^m = p_{j,f}^m - p_{j,rb}^m$. This decomposition of the displacement of the contact points will be useful in the backward mapping to map the internal contact forces of the slave system to the master one.

The main idea behind the proposed approach is that the homogeneous matrix T computed on the master is used to update the position of the contact points on the slave. Assume that in the initial reference configuration, the coordinates of the contact points on the slave are $p_{l,i}^s$, collected in the vector p_i^s. The final configuration of these points, according to the previously defined linear transformation, can be evaluated as the composition of two motions

$$\hat{p}_{l,f}^s = T_{def}T_{rb}\hat{p}_{l,i}^s. \tag{3}$$

The l-th contact point after the rigid transformation defined by matrix T_{rb} can be denoted by $p_{l,rb}^s \in \Re^3$, leading to the following relation

$$\hat{p}_{l,f}^s = T_{def}\hat{p}_{l,rb}^s. \tag{4}$$

Collecting all the $p_{l,rb}^s$ in the vector $p_{rb}^s \in \Re^{3n^s}$ and all the final points $p_{l,f}^s$ in the vector $p_f^s \in \Re^{3n^s}$, we can define the displacements $\Delta p_{rb}^s \in \Re^{3n^s}$ and $\Delta p_f^s \in \Re^{3n^s}$ as

$$\Delta p_{rb}^s = p_{rb}^s - p_i^s \qquad \Delta p_f^s = p_f^s - p_{rb}^s.$$

B. Backward mapping

In the following, we describe how to evaluate the forces to be rendered by each master wearable device starting from the contact forces measured on the slave side. The backward mapping is the key concept of the proposed bilateral teleoperation framework between different kinematic structures.

Assume that the slave system grasps an object through n^s contact points. Assume also that the contact points are known and tracked. We propose to use a virtual object to evaluate the manipulation effects and to abstract from the kinematics of the master and slave devices. Let us define $\lambda^s \in \Re^{3n^s}$ as the collection of forces $\lambda_l^s \in \Re^3$ with $l = 1, \ldots, n^s$ measured at the contact points on the slave. Such forces can be directly measured or estimated starting from the torques τ measured at the joints of the robotic hand [24].

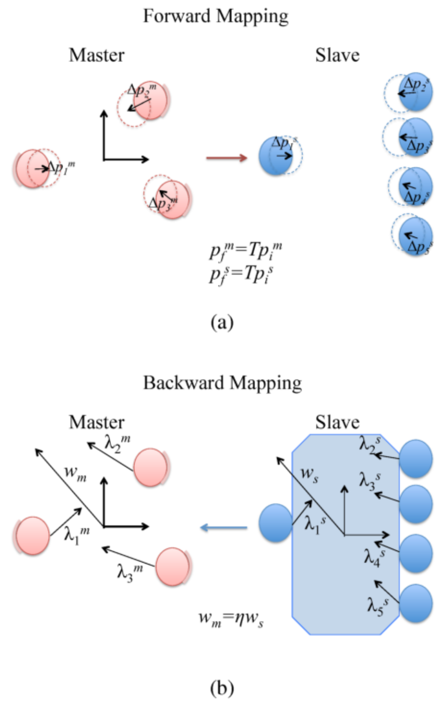


Fig. 2: Forward and backward mapping principles.

The wrench acting at the slave side, $w_s \in \Re^6$, can be estimated as

$$w_s = G_s\, \lambda^s, \tag{5}$$

where $G_s \in \Re^{6\times3n^s}$ is the grasp matrix evaluated for the contact points on the slave system. Let us define *internal forces* as all the forces that represent all the possible solutions of Eq. 5, when no external actions are applied. Internal forces play a key role in grasp control: in force-closure grasps, a convenient control of internal forces guarantees that the whole vector of contact forces complies with contact friction constraints notwithstanding disturbances acting on the manipulated object [27]. Thus, we can furthermore decompose the λ^s contact forces in external and internal forces, i.e., $\lambda^s = \lambda_e^s + \lambda_i^s$, where $\lambda_e^s = G_s^{\#}G_s\lambda^s$ is the projection of λ^s vector onto the image of G_s (external forces) and $\lambda_i^s = (I - G_s^{\#}G_s)\lambda^s$ is the projection of λ^s vector onto $\mathcal{N}(G_s)$ (internal forces).

The definition of a virtual object on both the master and slave systems allows us to assume the following relation: the total wrench w_s acting on the object grasped by the slave system is also acting on the virtual object defined for the master, possibly scaled. Consequently, we assume

$$w_m = \eta w_s, \tag{6}$$

where $w_m \in \Re^6$ is the wrench acting on the virtual object at the master side (see Fig. 2b), while η is a coefficient representing a scaling factor, which takes into account possible workspace discrepancies and maximum force constraints of the actuators on the master system. This equation can be rewritten, in terms of contact forces, as

$$G_m \, \lambda^m \quad = \quad \eta \, G_s \, \lambda^s , \tag{7}$$

where $G_m \in \Re^{6 \times 3 n_c^m}$ is the grasp matrix defined for the master system and $\lambda^m \in \Re^{3 n_c^m}$ is the collection of the forces $\lambda_j^m \in \Re^3$ with $j = 1, \ldots, n^m$ to be actuated at the master side. Vector λ^m in Eq. (7) can be computed as

$$\lambda^m \quad = \quad \lambda_e^m + \lambda_i^m , \tag{8}$$

where the particular non–homogeneous solution, i.e., the set of contact forces whose resulting wrench is w_m, referred to as external forces, is given by

$$\lambda_e^m \quad = \quad \eta \, G_m^{\#} \, G_s \, \lambda^s , \tag{9}$$

while the general solution of the homogeneous problem, i.e., the internal forces, are evaluated as

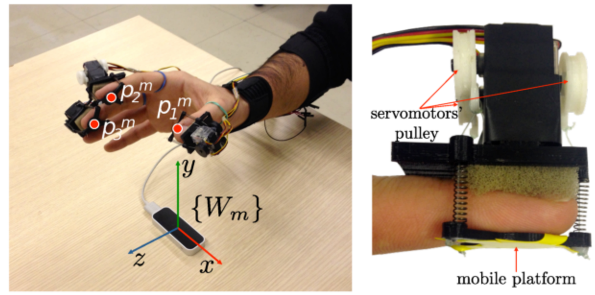
$$\lambda_i^m \quad = \quad N_{Gm} \, \zeta \; , \tag{10}$$

where N_{Gm} is a matrix whose columns form a basis for the nullspace of G_m and $\zeta \in \Re^m$ is a vector parametrizing the homogeneous part of the solution. Although the non–homogeneous part of the solution, Eq. (9), is straightforward, how to choose the homogeneous part, Eq. (10) represents an issue, since the solution is, in general, not unique and it is necessary to determine the direction where it is more convenient to render the forces.

In this paper, we propose a novel approach to backward map the internal forces from the slave to the master system that strongly depends on the voluntary action of the human at the master side. According to the displacement decomposition in Eq. (2), the motion of the master contact points can be represented as a combination of a rigid body part and a non–rigid one, representing a sort of deformation of the virtual object. According to a quasi static model it is possible to verify that, assuming that the master hand is grasping a virtual object with a compliance at the contacts described by matrix $K_v \in \Re^{3n^m \times 3n^m}$, symmetric and positive definite, the contact force variation induced by the non–rigid part of the displacement $\Delta p_{def}^m = [\Delta p_{1,def}^{m\mathrm{T}}, \cdots, \Delta p_{n^m}^{m\mathrm{T}}]^{\mathrm{T}} \in \Re^{3n^m}$ of the interaction points leads to a variation of the virtual contact forces

$$\Delta\lambda_{v,i}^m = \left(I - G_{m,K}^{\#} G_m \right) K_v \Delta p_{def}^m , \tag{11}$$

where $G_{m,K}^{\#} = G_m^{\mathrm{T}} (G_m K_v G_m^{\mathrm{T}})^{-1}$ is the K_v–weighted pseudoinverse of G_m. It is possible to verify that $\lambda_{v,i}^m \in \mathcal{N}(G_m)$, i.e., they are internal forces and therefore do not influence the equivalent wrench w_m. Eq. (11) transforms a motion of the user's fingertips in a virtual contact force, through the stiffness matrix K_v. In a real grasp, this matrix would represent the contact stiffness between the object and the fingers of the hand. In our teleoperation scenario, Eq. (11) is only used to determine the direction on which feedback the internal forces measured at the slave side.



(a) (b)

Fig. 3: (a) Master subsystem. The Leap Motion tracks the human hand. Three wearable haptic devices are used for cutaneous feedback. p_1^m , p_2^m and p_3^m indicate the position of the interaction points in the $\{W_m\}$ reference frame. (b) The cutaneous device. Three servo-motors control the length of three wires in order to tilt the mobile platform according to the forces to be rendered.

In the following we will compute the rendered internal force on the master as a function of the measured internal force on the slave. The direction of the variation of the rendered internal forces $\Delta\lambda_i^m$ on the master is computed normalizing Eq. (11), while the magnitude of $\Delta\lambda_i^m$ is computed as the sum of the norms of internal forces measured at slave side divided by the number of interaction points at the master side. Summarizing, internal forces rendered at master side are achieved as

$$\Delta\lambda_i^m = \frac{\Delta\lambda_{v,i}^m}{\|\Delta\lambda_{v,i}^m\|} \frac{1}{n^m} \sum_{l=1}^{n^s} \|\lambda_{i,l}^s\|. \tag{12}$$

III. Experiments

A. Experimental setup

The proposed framework has been tested in a peg in hole task carried out with a bilateral telemanipulation system. The master system used in the experiments is reported in Fig. 3a. It consists of a Leap Motion sensor and three wearable cutaneous devices placed in the thumb, index, and medium fingers. The Leap Motion is a compact device for hand gesture recognition guaranteeing a position tracking of the fingers with sub-millimeter accuracy. The sensor is based on three infrared light emitters and two IR cameras [28]. The accuracy in the detection of each fingertip position is approximately 0.01 mm, with a frame rate of up to 300 fps. The field of view of this tracker is up to 150 degrees, which gives to the user the opportunity to move his/her hand freely in a large workspace. The SDK supplied by the manufacturer delivers information about Cartesian space of fingertips, hand palm position, and rotation of the hand. All delivered positions are relative to the Leap Motion's center point, which lies between the two IR cameras. This point has been thus chosen has the origin of the master reference system $\{W_m\}$.

In Fig. 3b one of the cutaneous devices used in the master system is shown. It consists of a static part placed

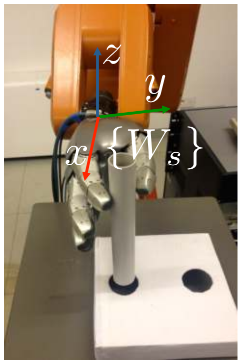


Fig. 4: Slave subsystem. A DLR-HIT Hand II is the end-effector of a 6 DoFs robotic arm, the KUKA KR3 robot.

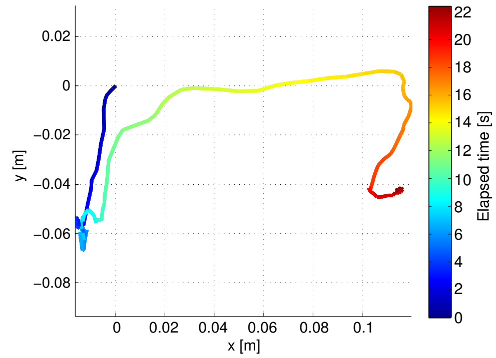


Fig. 5: Trajectories of the centroid of the two contact points on the slave projected on the $z - y$ plane. The color bar on the right shows elapsed time throughout the carried out task.

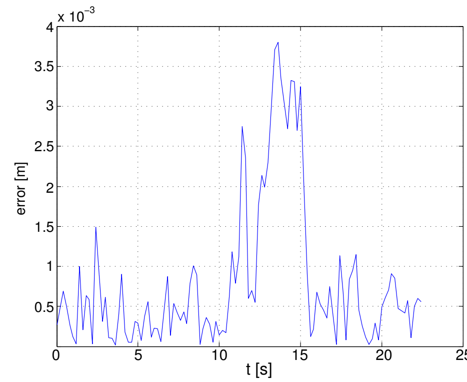


Fig. 6: Error between trajectories of the centroid of the three interaction points for the master and the trajectory of the centroid of the two contact points on the slave.

over the finger nail and a mobile platform able to apply the requested stimuli to the fingertip's volar surface. Three springs, placed between the mobile platform and the static part, keep the platform horizontally aligned with the rest of the device. Three servo-motors control the length of the three wires connecting the mobile platform vertices to the static platform, allowing to apply the requested force at the user's fingertip. The device structure, design and control are described in [29]. The actuators used for the device prototype are three HS-5035HD Digital Ultra Nano servos. The mechanical supports for the actuators and the mobile platform are made using acrylonitrile butadiene styrene, called ABSPlusTM (Stratasys Inc., USA). The total weight of the whole device, including actuators, springs, wires, and the mechanical support is about 40g. The force applied by the device to the user's finger pad is balanced by a force supported by the structure of the device on the back of the finger. This structure has a larger contact surface with respect to the mobile platform so that the local pressure is much lower and the contact is mainly perceived on the finger pad and not on the back side of the finger. Both devices are able to render cutaneous stimuli and most of the kinesthetic feedback is missing.

A DLR-HIT Hand II mounted on a KUKA KR3 arm form the hand/arm system at the slave side. Only index and thumb fingers are actively used during the task to highlight the capability of the mapping framework to deal with different contact/interaction points at master and slave level. The peg position is computed with respect to the reference frame $\{W_s\}$, placed on the wrist of the arm, as shown in Fig. 4. The system is managed by a GNU/Linux machine, equipped with a real-time scheduler. It communicates via UDP/IP with the controller of the robotic hand and via Eth.RSIXML with the telemanipulator. The cutaneous devices are PWM controlled with an Arduino Mega 2560 Board and are connected to the GNU/Linux machine via USB.

B. *Experimental results*

The task consists in picking a peg from a hole in a support base and place it in another one (see Fig. 4). The peg is a cylinder with diameter 3 cm and height 20 cm. The support base, whose height is 3.5 cm, has two holes of 4 cm in diameter. Fig. 5 shows the trajectories of the centroid of the two contact points on the slave. Fig. 6 shows the error between trajectories of the centroid of the three interaction points for the master and the trajectory of the centroid of the two contact points on the slave. The plot of the error shows that during the task the error in terms of position is less than 4 mm. Fig. 7 shows the magnitude of the internal forces acting on the slave side and rendered on the master side during the peg in hole task. The total amount of forces is measured through the torque sensors placed at the robotic fingers joints. Internal forces at the slave side increase when the contact with the peg is achieved. When inserting the peg inside the second hole, the user tends to squeeze more the object in order to be more precise and avoid the loss of grasp due to undesired contacts with the punctured board.

A video showing an experiment can be downloaded from http://tinyurl.com/IROS16-teleop-leap

IV. Conclusion

In this paper, we presented a telemanipulation framework where the master system consisted of three wearable cutaneous device plus a Leap Motion for the human hand tracking. The force feedback has been computed by imposing the same wrench, estimated on the real grasped object, on a virtual object defined on the master side. This approach

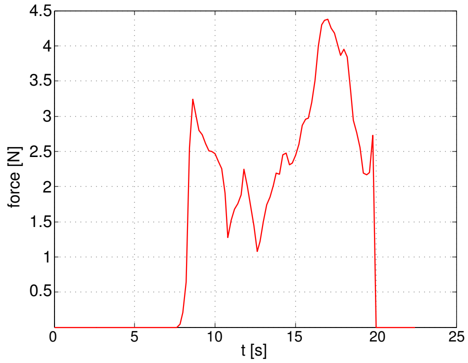


Fig. 7: Magnitude of the internal forces acting at the slave side and rendered at the master side during the peg in hole task.

focuses on the effects of the manipulation on the grasped object, real for the slave and virtual for the master, and permits to abstract from the device kinematics and explicitly take into account the case of multiple contacts with the objects. The system has been evaluated on an experimental setup with three interaction points for the master and two contact points with the real object on the slave side. Although the thimbles resulted highly wearable and allowed to increase the master workspace, there are still some issues in the hand tracking. In fact, during experiments we faced some problems due to the Leap Motion tracking system. We are currently working on further reducing the size of the haptic devices. We are also testing the setup with a higher number of subjects to further evaluate the ease of use of the system and the improvement offered by the haptic feedback. As future work, we are planning to extend the framework to robots cooperatively grasping an object. We are also testing different models of robotic hands at the slave side, with particular emphasis on non–anthropomorphic structures.

References

[1] P. F. Hokayem and M. W. Spong, "Bilateral teleoperation: An historical survey," *Automatica*, vol. 42, no. 12, pp. 2035–2057, 2006.

[2] C. Melchiorri, "Robotic telemanipulation systems: an overview on control aspects," in *Proc. 7th IFAC Symp. on Robot Control*, 2003, pp. 707–716.

[3] P. Arcara and C. Melchiorri, "Control schemes for teleoperation with time delay: A comparative study," *Robotics and Autonomous Systems*, vol. 38, no. 1, pp. 49–64, 2002.

[4] K. Hashtrudi-Zaad and S. E. Salcudean, "Analysis of control architectures for teleoperation systems with impedance/admittance master and slave manipulators," *The International Journal of Robotics Research*, vol. 20, no. 6, pp. 419–445, 2001.

[5] R. Cortesão, J. Park, and O. Khatib, "Real-time adaptive control for haptic telemanipulation with kalman active observers," *IEEE Transactions on Robotics*, vol. 22, no. 5, pp. 987–999, 2006.

[6] M. Franken, S. Stramigioli, S. Misra, C. Secchi, and A. Macchelli, "Bilateral telemanipulation with time delays: A two-layer approach combining passivity and transparency," *IEEE Transactions on Robotics*, vol. 27, no. 4, pp. 741–756, 2011.

[7] F. Barbagli, K. Salisbury, and D. Prattichizzo, "Dynamic local models for stable multi-contact haptic interaction with deformable objects," in *Proc. IEEE Int. Symp. in Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2003, pp. 109–116.

[8] N. Y. Lii, Z. Chen, M. A. Roa, A. Maier, B. Pleintinger, and C. Borst, "Toward a task space framework for gesture commanded telemanipulation," in *Proc. IEEE Int. Symp. in Robot and Human Interactive Communication*, 2012, pp. 925–932.

[9] I. Oikonomidis, N. Kyriazis, and A. A. Argyros, "Efficient model-based 3d tracking of hand articulations using kinect." in *Proc. British Machine Vision Conference*, vol. 1, no. 2, 2011, p. 3.

[10] Q. Z. Ang, B. Horan, and S. Nahavandi, "Multipoint haptic mediator interface for robotic teleoperation," *IEEE Systems Journal*, no. 99, pp. 1–12, 2013.

[11] A. Kron and G. Schmidt, "Multi-fingered tactile feedback from virtual and remote environments," in *Proc. IEEE Int. Symp. in Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2003, pp. 16–23.

[12] D. Prattichizzo, F. Chinello, C. Pacchierotti, and M. Malvezzi, "Towards wearability in fingertip haptics: a 3-dof wearable device for cutaneous force feedback," *IEEE Transactions on Haptics*, vol. 6, no. 4, pp. 506–516, 2013.

[13] L. Meli, S. Scheggi, C. Pacchierotti, and D. Prattichizzo, "Wearable haptics and hand tracking via an rgb-d camera for immersive tactile experiences," in *Proc. ACM Int. Conf. on Computer graphics and interactive techniques*, 2014.

[14] A. Frisoli, M. Solazzi, F. Salsedo, and M. Bergamasco, "A fingertip haptic display for improving curvature discrimination," *Presence: Teleoperators and Virtual Environments*, vol. 17, no. 6, pp. 550–561, 2008.

[15] D. Prattichizzo, C. Pacchierotti, and G. Rosati, "Cutaneous force feedback as a sensory subtraction technique in haptics," *IEEE Transactions on Haptics*, 2012.

[16] M. J. Massimino and T. B. Sheridan, "Sensory substitution for force feedback in teleoperation," *Presence: Teleoperators and Virtual Environments*, vol. 2, no. 4, pp. 344–352, 1993.

[17] M. Kitagawa, D. Dokko, A. M. Okamura, and D. D. Yuh, "Effect of sensory substitution on suture-manipulation forces for robotic surgical systems," *The Journal of thoracic and cardiovascular surgery*, vol. 129, no. 1, pp. 151–158, 2005.

[18] G. Gioioso, A. Franchi, G. Salvietti, S. Scheggi, and D. Prattichizzo, "The flying hand: A formation of uavs for cooperative aerial telemanipulation," in *Proc. IEEE Int. Conf. on Robotics and Automation*, 2014, pp. 4335–4341.

[19] G. Gioioso, G. Salvietti, M. Malvezzi, and D. Prattichizzo, "Mapping synergies from human to robotic hands with dissimilar kinematics: an approach in the object domain," *IEEE Trans. on Robotics*, vol. 29, no. 4, pp. 825–837, August 2013.

[20] G. Salvietti, L. Meli, G. Gioioso, M. Malvezzi, and D. Prattichizzo, "Object-based bilateral telemanipulation between dissimilar kinematic structures," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, 2013, pp. 5451–5456.

[21] W. B. Griffin, R. P. Findley, M. L. Turner, and M. R. Cutkosky, "Calibration and mapping of a human hand for dexterous telemanipulation," in *ASME IMECE 2000 Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems*, 2000, pp. 1–8.

[22] G. Gioioso, G. Salvietti, M. Malvezzi, and D. Prattichizzo, "An object-based approach to map human hand synergies onto robotic hands with dissimilar kinematics," in *Robotics: Science and Systems VIII*. The MIT Press, 2012.

[23] A. Bicchi, "On the closure properties of robotic grasping," *International Journal of Robotics Research*, vol. 14, no. 4, pp. 319–334, 1995.

[24] D. Prattichizzo and J. Trinkle, "Grasping," in *Handbook on Robotics*, B. Siciliano and O. Kathib, Eds. Springer, 2008, pp. 671–700.

[25] R. W. Ogden, *Non-linear elastic deformations*. Courier Corporation, 1997.

[26] G. Salvietti, M. Malvezzi, G. Gioioso, and D. Prattichizzo, "On the use of homogeneous transformations to map human hand movements onto robotic hands," in *Proc. IEEE Int. Conf. on Robotics and Automation*, 2014.

[27] D. Prattichizzo, M. Malvezzi, M. Gabiccini, and A. Bicchi, "On motion and force controllability of precision grasps with hands actuated by soft synergies," *IEEE Transactions on Robotics*, vol. 29, no. 6, pp. 1440–1456, 2013.

[28] F. Weichert, D. Bachmann, B. Rudak, and D. Fisseler, "Analysis of the accuracy and robustness of the leap motion controller," *Sensors*, vol. 13, no. 5, pp. 6380–6393, 2013.

[29] C. Pacchierotti, F. Chinello, M. Malvezzi, L. Meli, and D. Prattichizzo, "Two finger grasping simulation with cutaneous and kinesthetic force feedback," in *Haptics: Perception, Devices, Mobility, and Communication*, ser. Lecture Notes in Computer Science, P. Isokoski and J. Springare, Eds. Springer, 2012, vol. 7282, pp. 373–382.