Sensory subtraction via cutaneous feedback: a novel technique to improve the transparency of robotic surgery

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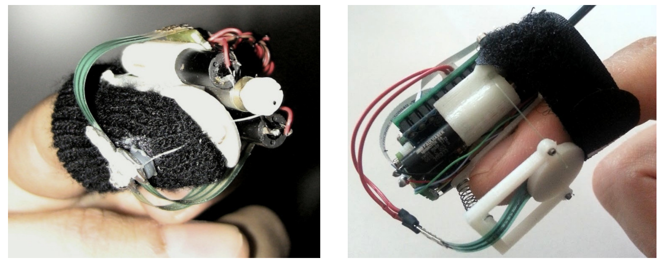
***Abstract*— In this paper we present a novel technique to force feedback in robot-assisted surgery. It consists of substituting haptic force, composed by kinesthetic and cutaneous components, with cutaneous stimuli only. The force generated can be thus thought as a subtraction between the complete haptic interaction, cutaneous and kinesthetic, and the kinesthetic part of it. For this reason, we refer to this approach as *sensory subtraction* and not sensory substitution. Sensory subtraction, first introduced in [1], aims at improving the performance of conventional force feedback techniques in teleoperation while guaranteeing the same stability properties. In this work we recall the idea of sensory subtraction in teleoperation, together with its evaluation in two paradigmatic surgical teleoperation scenarios.**



(a) Chinello *et al.* in [17]. (b) Pacchierotti *et al.* in [18].

Fig. 1: Two of the custom cutaneous devices employed in sensory subtraction.

I. INTRODUCTION

Achieving a good illusion of telepresence in robotic teleoperation is a matter of technology. If the teleoperator transmits sufficient information to the user, displayed in a sufficiently articulated way, the illusion of telepresence can be compelling [2], [3]. The primary tool to achieve this objective is providing a *transparent* implementation of the teleoperation system. Transparency can be defined as the correspondence between the master and slave positions and forces [4], or as the match between the impedance of the environment and the one perceived by the operator [5]. A compelling illusion of telepresence can be achieved through different types of information, which flow from the remote scenario to the human operator. Haptic force feedback is one piece of this information flow and it has been proved to play an important role in enhancing teleoperation performance in terms of task completion time [6], [7], [8], accuracy [7], [1], peak [9], [10], and mean exerted force [10], [8].

However, employing haptic force feedback may affect the *stability* of teleoperation systems. For this reason, researchers have proposed a great variety of stability bilateral controllers [11], [12] and it has always been a big challenge to find a good trade-off between stability and transparency. In this respect, passivity [13] has been exploited as the main tool for providing a sufficient condition for stable teleoperation in several controller design approaches, such as Time Domain Passivity Control [14], Energy Bounding Algorithm [15] and Passive Set Position Modulation [16]. However, control techniques guarantee the stability of the system at the price of a temporary loss of transparency, which could lead to degraded performance.

Another interesting approach to provide information about forces exerted at the slave side consists in completely avoiding the usage of actuators on the master device, and then providing alternative forms of feedback using *sensory substitution* techniques. In this case, since no kinesthetic force is fed back to the operator, the haptic loop becomes intrinsically stable and no bilateral controller is thus needed [1]. Force feedback is then substituted with other forms of stimuli, such as vibrotactile [19], auditory, and/or visual feedback [20]. However, these stimuli are clearly very different from the ones being substituted (e.g. a beep sound instead of force feedback) and they thus show worse performance than that achieved employing unaltered haptic force feedback.

In this paper we present a novel approach to force feedback in robotic teleoperation. It consists of substituting haptic force feedback, composed by kinesthetic and cutaneous components, with cutaneous feedback only, provided by custom cutaneous devices. It aims at outperforming conventional sensory substitution techniques while guaranteeing the same stability properties. Cutaneous stimuli does not in fact affect the stability of the system, since the contact force is applied directly to the user's skin and does not affect the position of the master device end-effector, thus opening the haptic loop [1], [21]. However, with respect to popular sensory substitution techniques, the stimuli provided are much more similar to the one being substituted [1], [18]. Moreover, cutaneous feedback will be exerted exactly where it is expected to be (e.g., the fingertips), providing the operator with a direct and co-located perception of the contact force.

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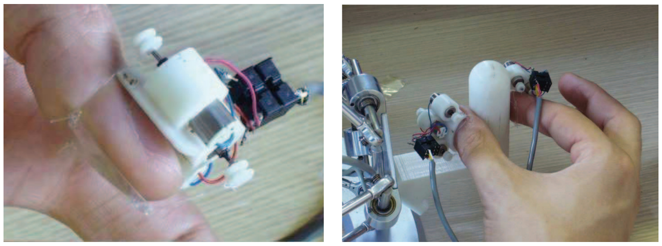
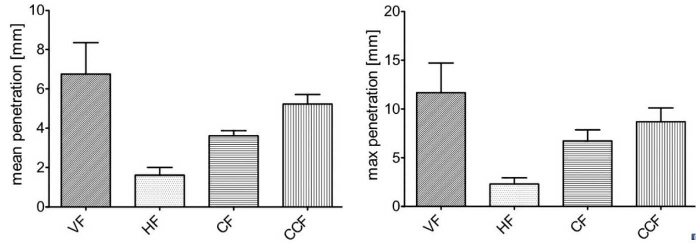


(a) Cutaneous device (b) Handle of the Omega 3

Fig. 2: Experimental setup of [1]. Users had to wear four cutaneous devices, one on the thumb and one on the index finger of each hand.



(a) Average penetration (b) Maximum penetration

Fig. 3: Experiment of sensory subtraction in [1]. Average and maximum penetration beyond the stiff constraint (mean and std), for the visual (VF), haptic (HF) and cutaneous feedback conditions (CF, CCF). A null value of this metric indicated the best accuracy in reaching the target depth. The sensory subtraction approach is employed in condition CF.

On the other hand, with the aim of improving transparency, this approach can be also combined with popular control techniques able to provide kinesthesia while guaranteeing stability. As the control algorithm detects a violation of its stability conditions, and the kinesthetic device is thus unable to provide the required feedback, the cutaneous devices convey a suitable amount of force, thus (partially) recovering transparency. For instance, we can provide as much kinesthetic force as the stability controller permits and then provide the rest via cutaneous feedback [21].

Sensory subtraction is thus similar to sensory substitution, since we *substitute* haptic force with cutaneous stimuli. However, since haptic force provided by popular grounded haptic interface is composed by kinesthetic and cutaneous components [18], we like to refer to this technique as *sensory subtraction*: kinesthetic force can be considered as *subtracted* from the complete haptic interaction, thus resulting in cutaneous force only. This idea was first introduced by Prattichizzo *et al.* in [1] and then further validated in different teleoperation scenarios [8], [21], [22], [23], [24]. In this work we are going to present the sensory subtraction idea and provide a comprehensive view of the scenarios where it has been employed, focusing on its application in the field of robot-assisted surgery.

II. SENSORY SUBTRACTION: THE CUTANEOUS AND KINESTHETIC COMPONENTS

Most of the well-known haptic devices for single-point contact interaction, such as the Omega (Force Dimension, Switzerland) or the Phantom (Sensable group, USA), provide kinesthetic force feedback to the users [25]. However, these devices *also* provide cutaneous stimuli to the fingertips if we assume that the interaction with the remote environment is mediated by a stylus, a ball, or any other tool mounted on the haptic interface [1], [18]. Cutaneous stimuli are sensed by pressure receptors in the skin and they are useful to recognize the local properties of objects such as shape, edges, embossings and recessed features. This is possible, principally, thanks to a direct measure of intensity and direction of contact forces and to the encoding of the force spatial distribution over the fingertip [26], [27]. On the other hand, kinesthetic feedback provides humans with information about the position and velocity of neighboring body parts, as well as the applied force and torque, mainly by means of receptors in the skin, muscles and joints [28], [25].

Sensory subtraction consists in substituting this haptic force with cutaneous stimuli only, provided by custom cutaneous devices. The first device developed for this purpose was the 3-DoF wearable cutaneous interface presented in [17] and shown in Fig. 1a. It consists of two main parts: the first one is placed on the dorsal side of the finger and supports three small electrical motors; the other one is a mobile platform in contact with the volar skin surface of the fingertip. These two parts are connected by three cables. The motors, by controlling the length of the cables, are able to move the platform towards the user's fingertip. As a result, a force is generated, simulating the contact of the fingertip with an arbitrary surface. Three force sensors are placed near to the platform vertices, in contact with the finger, so that they measured the three components of the cutaneous force applied to the fingertip. A second device was presented in [18]. It is similar to the one mentioned above but showed higher accuracy. It consists again of two platforms connected by three cables. Three small electrical motors, equipped with position encoders, control the length of the cables, thus being able to move the platform towards the fingertip. One force sensor is placed at the platform's centre, in contact with the finger, so that it can measure the component of the cutaneous force perpendicular to the volar skin surface of the fingertip (see Fig. 1b). Employing a cutaneous device instead of a grounded haptic interface to provide force feedback makes the idea of sensory subtraction possible: we disregard haptic force feedback in favour of cutaneous stimuli only.

More information about the role of kinesthetic and cutaneous sensory channels in sensory subtraction can be found in [18]. Features and limitations of this kind of cutaneous devices are discussed in [17].

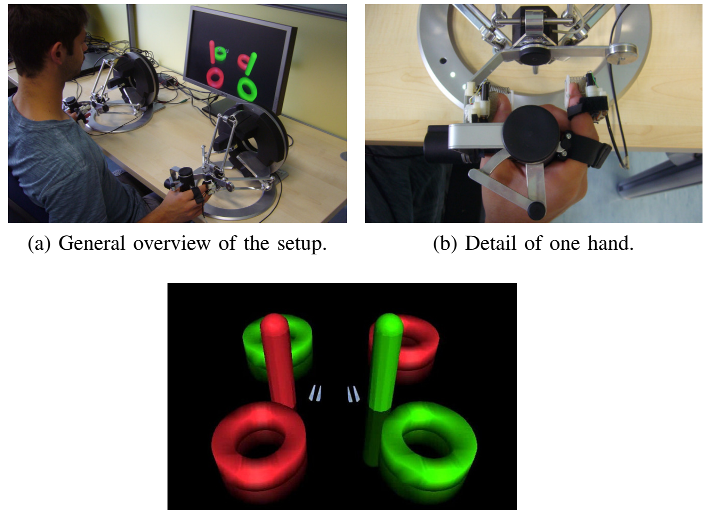
III. SENSORY SUBTRACTION IN MEDICAL TELEOPERATION

The idea of sensory subtraction has been effectively employed in many teleoperation scenarios, achieving high performance while guaranteeing stability. Prattichizzo *et al.* [1] used it in a teleoperated needle insertion task along one direction. They used four cutaneous devices, similar to the one presented in [17] (see Fig. 2a), and a commercial haptic device. The operator wore two devices on one hand, one on the thumb and one on the index finger, and grabbed the handle of the grounded interface as shown in Fig. 2b. Two additional cutaneous devices were worn on the thumb and index finger of the contralateral hand. The haptic device was an Omega 3 by Force Dimension, to which three clamps were applied to reduce the degrees of freedom from three to one. Moreover, a plastic handle was attached to its end-effector to allow the operator to easily grab the device with two fingers. During the experiments the hardware was operated in two different conditions. In the first one the force feedback was provided by the Omega, while the wearable devices were switched off. In the second condition the sensory subtraction technique was implemented. The Omega 3 was used only to track the motion of the hand and did not apply any active force to the operator. At the same time, the cutaneous devices were used to reproduce the cutaneous sensation associated to the manipulation task being simulated. Moreover, to investigate the role of feedback localization with respect to the hand involved in the task, either the devices on the active hand or those worn on the contralateral hand were alternatively activated.

The task consisted in inserting a simulated needle into a soft tissue and stopping the motion as soon as a stiff constraint was perceived. A video of the experiment can be found at http://goo.gl/hfy24. The average penetration inside the constraint provided a measure of accuracy in reaching the target depth. Prattichizzo *et al.* compared task performance while providing (1) complete haptic feedback through the Omega 3 (HF), (2) cutaneous feedback through the cutaneous devices, applied to the hand holding the handle (CF), (3) cutaneous feedback through the cutaneous devices, applied to the contralateral handle (CCF), and (4) visual feedback in substitution of force feedback through a horizontal bar (VF), which is a popular sensory substitution technique [20].

Results reported in [1] are shown in Fig. 3. Figures 3a and 3b report, respectively, the average and maximum penetrations beyond the stiff constraint for each feedback condition. A null value of these metrics indicate no overshoot in reaching the target depth and, therefore, maximum accuracy. Results show that the sensory subtraction condition (CF) outperformed visual substitution of force feedback, but it performed worse than complete haptic feedback. This behaviour was, however, largely expected, since cutaneous force is just a subset of the complete haptic feedback provided by grounded interfaces. However, Prattichizzo *et al.* tested the idea only for a simple one degree-of-freedom (DoF) task.

For this reason, Meli *et al.* [23] decided to evaluate the sensory subtraction idea in a more challenging teleoperation scenario, considering a 7-DoF bimanual teleoperation task similar to the Peg Board experiment of the da Vinci Skills Simulator. Fig. 4 shows the experimental setup. The master system was composed of two Omega 7 haptic interfaces and four cutaneous devices. The cutaneous devices are similar to the ones presented in Sec. II and were worn as shown in Fig. 4b, i.e. on the thumb and index finger of both hands.



(a) General overview of the setup.

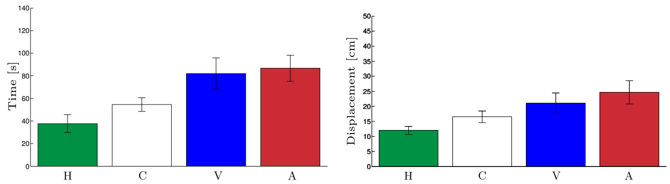
(b) Detail of one hand.

(c) Virtual environment.

Fig. 4: Experimental setup. Users had to wear four cutaneous devices, one on the thumb and one on the index finger of both hands, and teleoperate two pairs of surgical pliers using a couple of Omega 7 haptic interfaces.

The slave system was composed of two virtual surgical pliers, directly controlled by the master interfaces. The pliers accurately resembled fingers' motion on the Omega devices. Users were able to move and rotate the pliers in the 3-D space and control their gripping force. The virtual environment consisted of four rings, two green and two red, and two pegs, one green and one red (see Fig. 4c). The rings weighed 30 g and had a minor radius of 3 cm, a major radius of 5 cm, and a height of 1 cm. The pegs were fixed to the ground and had a base diameter of 4 cm and a height of 10 cm. A spring $k_0 = 40$ N/m was used to model the contact force between the proxies and the objects, according to the god-object model [29]. The virtual environment was built using CHAI 3D, an open-source set of C++ libraries for computer haptics and interactive real-time simulation. The task consisted of lifting, one by one, the rings from the ground with one pair of pliers, handing them to the other pair and inserting them into the peg of the corresponding color. An insertion was considered valid only when the ring was inserted in the correct peg. The task started when the user grasped a ring for the very first time and ended when all the rings were inserted into the pegs. A video of the experiment can be download at http://goo.gl/Wc6WYB. Meli *et al.* compared task performance while providing (1) complete haptic feedback through the two Omega 7 (H), (2) cutaneous feedback through the cutaneous devices (C), (3) visual feedback in substitution of force feedback, provided by changing color brightness of the ring being grasped (V), and (4) auditory feedback in substitution of force feedback, provided by changing the repetition frequency of a stereo beep tone (A). The time needed to complete the task and the forces generated by the contact between the pliers and the rings provided a measure of performance.

Results reported in [23] are shown in Fig. 5. Fig. 5a shows the average task completion time, while Fig. 5b shows the



(a) Completion time (b) Rings' displacement

Fig. 5: 7-DoF bimanual peg board experiment. Completion time and contact forces for the haptic (H), cutaneous (C), visual (V) and auditive (A) conditions. Lower values of this metrics indicate higher performances in completing the given peg board task.

average grip forces generated between the two pairs of pliers and the rings along the direction of actuation of the Omega's gripper, i.e. the one perpendicular to the object surface. Sensory subtraction led to improved performance with respect to providing no force feedback at all and with respect to the considered sensory substitution techniques. However, as in the experiment presented in [1], cutaneous feedback showed worse performance with respect to providing complete haptic force feedback.

IV. CONCLUSIONS

This work presents the idea of sensory subtraction, a novel approach to force feedback in bilateral teleoperation systems. It consists of substituting haptic feedback with cutaneous feedback. We call this approach *sensory subtraction*, in contrast to *sensory substitution*, as it subtracts the kinesthetic part from the complete haptic interaction to leave only the cutaneous cues. Sensory subtraction was first introduced in [1] and later evaluated in several different scenarios [8], [21], [22], [23], [24]. The main advantage of this approach is that it makes the teleoperation system intrinsically stable. However, it still performs worse than providing complete haptic feedback through grounded haptic interfaces. For this reason, we are now developing new approaches to combine the idea of sensory subtraction with common force reflection techniques, in order to provide additional kinesthetic force and enhance transparency [21].

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