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Cutaneous device for teleoperated needle insertion

Claudio Pacchierotti, Francesco Chinello and Domenico Prattichizzo

Abstract— **A new device providing cutaneous feedback is presented. Two motors are used to flex two mobile platforms, applying a normal force to the user's thumb and index finger pads. The cutaneous device substitutes the typical kinesthetic and cutaneous feedback, usually provided by grounded haptic interfaces, with the cutaneous component only. The main advantage of this approach is that it does not suffer from typical stability issues and it can be considered intrinsically safe when used in a teleoperation system.**

The proposed technique can be casted in a sensory substitution framework but there are relevant differences which are worth underlining. Its main advantage, with respect to classic sensory substitution techniques which employ visual and/or auditory feedback, is that the substitution occurs at the cutaneous level and the feedback is applied directly on the finger pads, i.e. exactly where the force feedback is expected by the operator. A teleoperated needle insertion application is considered, in order to evaluate the effectiveness of the device.

I. Introduction

The use of robot-assisted surgery can significantly enhance surgeons' accuracy and dexterity [1], however it is not common to find commercially-available devices implementing haptic feedback. One of the few examples is the DLR MiroSurge [2] or the Hansen Medical Sensei robotic catheter system [3].

To render a realistic representation of the remote environment, haptic displays use active input devices, such as electric motors, to generate the forces fed back to the operator. Stability and transparency of such systems can be significantly affected by communication latency, reducing their applicability and effectiveness in case of stiff remote environments [4], [5]. This limitation can be alleviated by designing proper control systems [6], [7], [8] but these approaches do not address an intrinsic issue affecting the haptic loop design: in case of serious failure of the haptic device's actuators, the teleoperation loop can experience problems that cannot be managed by control and may cause an abrupt change in the behaviour of the remote robot. This is a serious problem in surgical robotics as, for example, in needle insertion tasks.

A way to address this issue is to act on the hardware design, substituting master actuation with passive components such as brakes [9]. However, passive input devices have rendering limitations and may lead to large steady-state errors in teleoperation tasks [10]. Another interesting approach is to remove the actuator from the haptic device and replace haptic feedback with other forms of feedback, such as vibrotactile, auditory, and/or visual feedback [11], [12]. This approach is referred as sensory substitution. When employing this technique, the haptic device could be substituted with a device able to track the position of the operator's hand, without any active component, since haptic feedback is missing. Using sensory substitution techniques in medical surgery dramatically reduces the risk of producing uncontrollable displacement of the robotic tool and, consequently, it increases the safety of the overall teleoperation loop [1].

C. Pacchierotti, F. Chinello and D. Prattichizzo are with the Department of Information Engineering, University of Siena, Via Roma, 56, 53100 Siena, Italy.

C. Pacchierotti and D. Prattichizzo are also with the Department of Advanced Robotics, Istituto Italiano di Tecnologia, via Morego, 30, 16163 Genova, Italy.

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pacchierotti, chinello, prattichizzo@dii.unisi.it

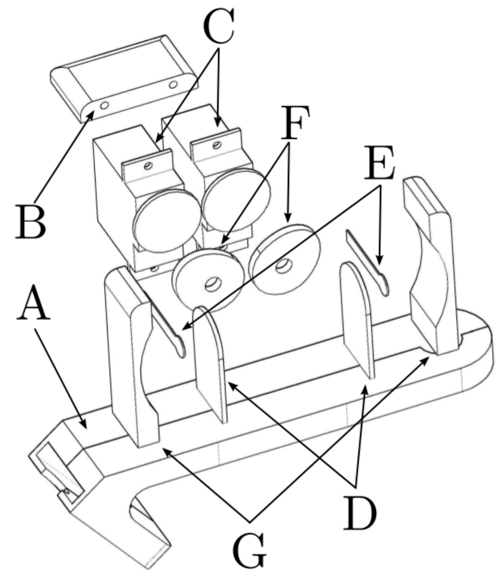


Fig. 1. CAD rendering of the handle prototype. Part A is fixed to the haptic device end-effector while parts B and F permit to use the torque of the motors (C) to flex the two platforms (D). Two sensors (E) are in charge of registering the actual force applied by the device while platforms G support the fingers.

We introduce here a new cutaneous device which is able to feed back forces along one direction. This paper extends the results presented in [13], where the authors employed two wearable cutaneous devices to render contact forces for an industrial application and in [14], where the authors developed a wearable cutaneous device for interaction with virtual objects.

In this paper we present a new device, designed to be safer and more precise. Moreover it can be easily mounted as an extension of grounded haptic interfaces, as shown in Fig. 2. This new device shows better performance, uses two motors

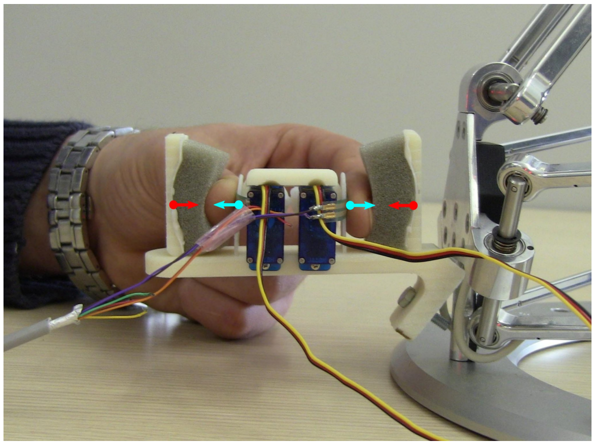


Fig. 2. The cutaneous device mounted on the Omega 3 end-effector. The motors flex the platforms, applying a force to the thumb or to the index finger (cyan arrows). Each force is balanced by a force supported by the structure of the device on the back of the each finger (red arrows).

and largely improves the safety of the teleoperation. In fact the devices used in [13], [14] had to be worn on the fingertips and then fastened to the finger. Nothing has to be worn while using the proposed tool. This can greatly improve the safety of surgical teleoperations, making the surgeon ready to leave the man-machine master interface without any impairment to operate directly on the patient (e.g., in case of failure of the robotic system). The device has been validated in a medical application, in particular in the case of needle insertion in soft tissue, as a special case of one degree of freedom (DoF) haptic interaction task.

The rest of the paper is organized as follows: the device is presented in Sec. II along with its working principles and the control system design. The teleoperated needle insertion application is described in Sec. III along with the experimental results. Sec. IV addresses concluding remarks and perspectives of the work.

II. Device for 1 DoF cutaneous feedback

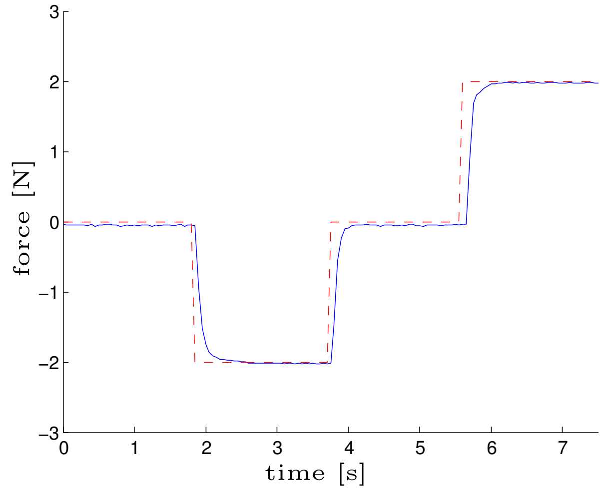
The sketch of the proposed device and an assembled prototype are reported, respectively, in Fig. 1 and Fig. 2.

A. Device hardware and control

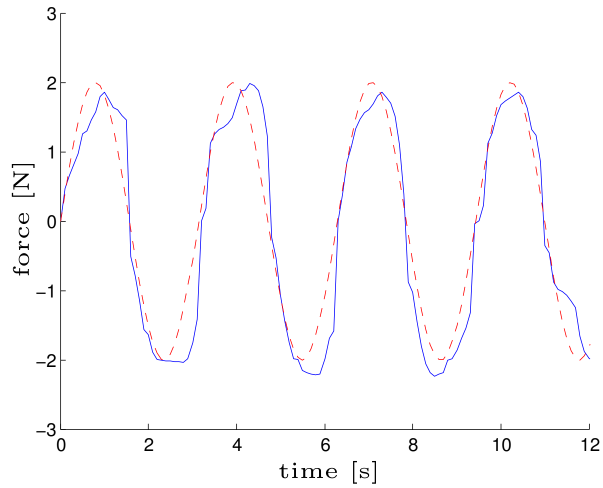
The device consists of a static part (named A in Fig. 1), rigidly connected to the haptic interface end-effector, and two platforms (D).

Two servo motors (C), connected to the pulleys (F), make the platforms (C) flex backward and forward, applying a normal force to the thumb and to the index (cyan arrows in Fig. 2). The parts of the device which are behind the finger pads and in contact with the back of the fingers (G) are in charge of balancing the force applied by the device at the fingertips (red arrows in Fig. 2).

Two piezoresistive force sensors are fixed to the surface of the platforms, those in contact with the finger pads. The aim is to measure the actual force applied at the fingertip, in order to implement a closed loop force control strategy. The sensors employed in the prototype have a diameter of 5mm and a thickness of 0.3mm, making them very transparent to



(a) Step response



(b) Variable force signal reference

Fig. 3. The dashed red line and the blue line represent, respectively, the signal reference and the response of the system. When the force is negative (positive) the thumb (index) finger pad is stretched.

the user and easily embeddable in the device. The actuators used for the device prototype are two HS-55 MicroLite Servo motors [15].

To properly use the cutaneous device, the operator has to insert the thumb and the index finger in the device, as shown in Fig. 2.

The device is controlled by a micro-controller At-Mega 328, installed on an Arduino UNO board, which commands the motors via PWM and reads the force sensors analogue signals. The force applied by the two mobile platforms to the user's fingertips is regulated by a PD controller.

In order to check the device accuracy in applying a desired force to the fingertips, two different tests were performed. Fig. 3(a) shows the step response of the system. The estimated forces reach the reference value with a settling time of about 0.25s and an error in the stationary phase lower than 2%. Fig. 3(b) analyses the behaviour of the device when following a sinusoidal force reference signal with a period of 2s and an amplitude of 2N. Note that when the force generated is positive the force is applied to the index finger and when the force value is negative the force is applied to the thumb (see Fig. 2).

B. Working principle

The normal force applied by the device to the user's finger pads (cyan arrows in Fig. 2) is balanced by the force supported by the structure of the device on the back of the finger (red arrows in Fig. 2). The support force is distributed on a larger contact surface so that the local pressure is much lower and the contact is perceived *only* on the finger pad and not on the back side of the finger. This idea was inspired by the *gravity grabber* presented by K. Minamizawa *et al.* in [16], where a wearable haptic display was employed to simulate weight sensations of virtual objects.

III. Experiments

The scenario considered is a teleoperated needle insertion along one direction [17], [18].

Two different experiments have been performed. In the first one a needle insertion in soft tissue has been simulated while in the second experiment a robot, equipped with a needle, and a real object have been used. In both cases the master side consists of the proposed device fixed to the Omega 3 end-effector (Force Dimension, CH) as shown in Fig. 2. The motion of the Omega 3 is constrained along the z-axis by means of three rigid clamps fixed to the parallel structure of the haptic device.

The human operator puts the fingers in the device as shown in Fig. 2. The sensory substitution approach consists of substituting the force feedback, usually provided by the haptic device, as follows: if the force is directed towards the negative direction of the z-axis, a pressure is applied to the index finger pad and, alternatively, if the force is directed towards the opposite direction, a pressure is applied to the thumb pad (see Fig. 2).

The position of the haptic device end-effector (i.e., the position of the cutaneous device proposed) is linked with the position of the needle. The operator holds the tool as in Fig. 2 and steers the needle by moving the end-effector along the z-axis of the haptic device.

The force feedback employed during the trials was either haptic feedback (i.e., cutaneous and kinesthetic feedback) provided by the Omega 3 haptic device (task H) *or* cutaneous feedback only provided by the proposed cutaneous device (task C). In tasks H the motors of the cutaneous device are turned off while in tasks C the motors of the haptic device are the ones to be turned off. In both cases the Omega 3 haptic device is used to track the position of the operator's hand.

A. Experiment in a virtual environment

This first experiment aimed at showing that there is no relevant degradation of performance in haptic interaction tasks when a normal force is fed back to the user's finger pads using the proposed cutaneous device in substitution of the force feedback generated by a grounded haptic interface.

The task consisted in inserting the needle into a soft tissue and stopping the motion of the hand as soon as a virtual stiff constraint was perceived. The stiff constraint played the role of a virtual fixture, i.e. a software function used in assistive robotic systems to regulate the motion of surgical implements. The motion of the surgical tool, the needle in our case, is still controlled by the surgeon, but the system constantly monitors its motion and takes some actions if the surgical tool fails to follow a predetermined procedure [19]. In this paper we consider an example of a forbidden-region virtual fixture. It is in charge of preventing the needle from entering a specific region of the workspace. This is a common scenario for biopsies, deep brain stimulation and functional neurosurgery [20], [21].

(a) no contact between the needle and the tissue

(b) the needle penetrates the tissue

Fig. 4. The virtual environment is composed of the needle (white), driven by the operator, the deformable tissue (cyan), and the stiff constraint. The position of the needle in the virtual environment is linked to the position of the haptic device end-effector.

A virtual environment simulating a needle insertion in soft tissue has been employed. The model used to simulate the phases of tissue needle insertion is described in [22]. Our aim is not the design of an accurate tissue simulator, as, for example, in [23] and [24], but the validation of the proposed cutaneous force feedback device. If the operator steers the needle towards the unsafe area delimited by the stiff constraint, a force is fed back to the operator in order to avoid the penetration of the needle in the forbidden area:

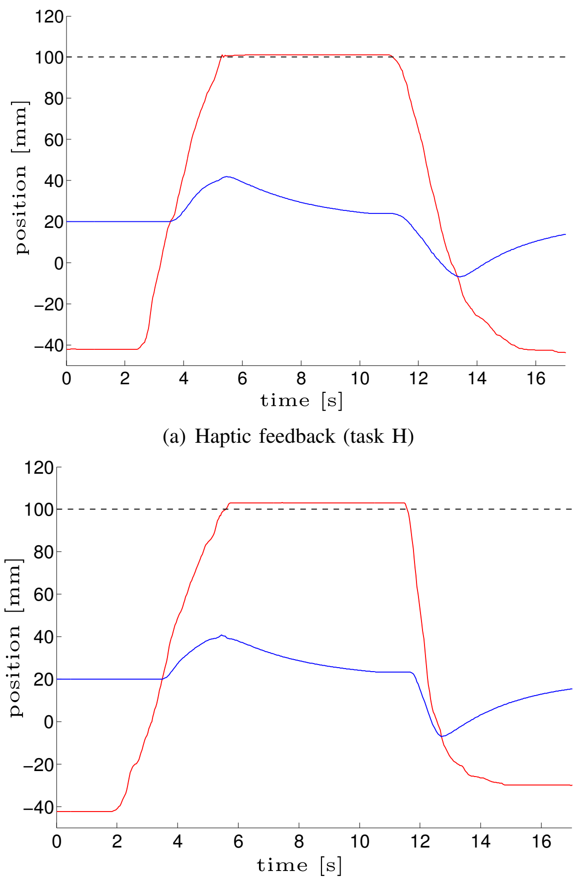
$$F_{vf} = -K_{vf}\ (z_n - \bar{z}_{vf}),$$

where K_{vf} = 2N/mm, z_n represents the position of the haptic device end-effector and $\bar{z}_{vf}$ the position of the stiff constraint.

The operator was able to see the part of the needle out of the tissue and the tissue surface, while the position of the stiff constraint and the part of the needle inside the tissue were not visible (see Fig. 4).

The haptic device measures the position of the operator's hand, sends it to the controller and then the virtual environment computes the force feedback and tissue dynamics. The controller then sends these forces back to the user through either the haptic interface or the cutaneous device.

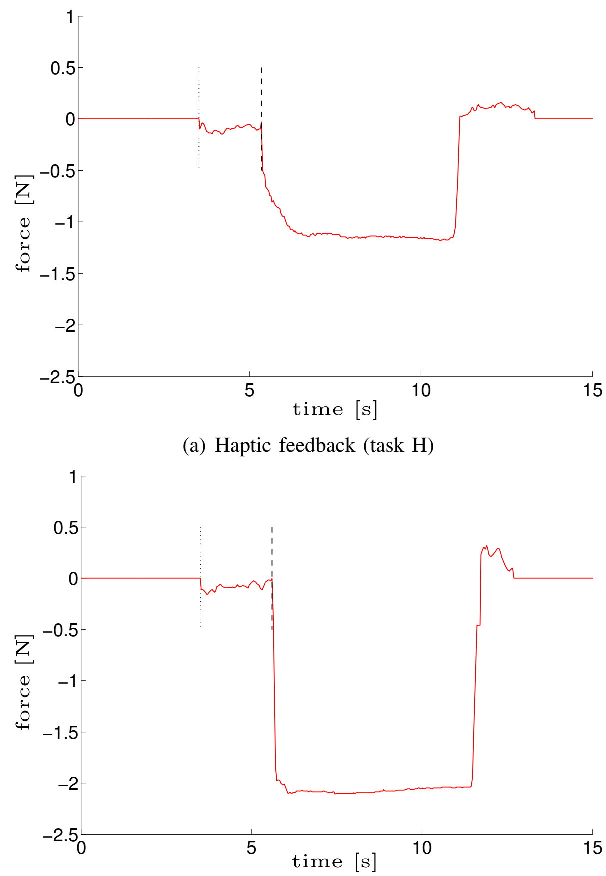
Seven participants (5 males, 2 female, age range 20–26) took part to the experiment, all of whom were right-handed. Four of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in the perception abilities. Each participant made six repetitions



(a) Haptic feedback (task H)

(b) Cutaneous only feedback (task C)

Fig. 5. Experiment in a simulated environment. Needle position versus time, expressed in [mm], is shown in red. The blue line represents the position of the tissue surface while the dashed black line represents the position of the virtual fixture surface.



(a) Haptic feedback (task H)

(b) Cutaneous only feedback (task C)

Fig. 6. Experiment in a simulated environment. Force measured at the needle tip versus time, expressed in [N], is shown in red. The dotted black line represents the instant the needle enters the soft tissue and the dashed black line represents the instant the needle collides with the virtual fixture surface.

of the needle insertion task, with three randomized trials for each feedback modality: haptic feedback (task H) and cutaneous feedback (task C), as already discussed in Sec. III.

Fig. 5 and Fig. 6 respectively show the needle position and the force measured at the needle tip versus time, for a representative run, while using haptic feedback (task H) or cutaneous feedback (task C). Fig. 7 shows the mean penetration depth $\bar{p}$ into the stiff constraint. The collected data of each task passed the Shapiro-Wilk normality test. Then a parametric two-tailed paired t-test was performed in order to evaluate the statistical significance of the differences between tasks (i.e., between the two feedback modalities). The p-values found reveal statistically significant difference between the groups.

The results of this experiment indicate that haptic feedback (task H) produced better peformances with respect to cutaneous feedback only (task C). However all the subjects were able to perceive the presence of the stiff constraint while using the cutaneous device and stop the motion of the hand right after having penetrated into the forbidden area. We believe that this is a price worth paying, in terms of performance, in order to get a great improvement in the stability of the teleoperation loop, as will be shown

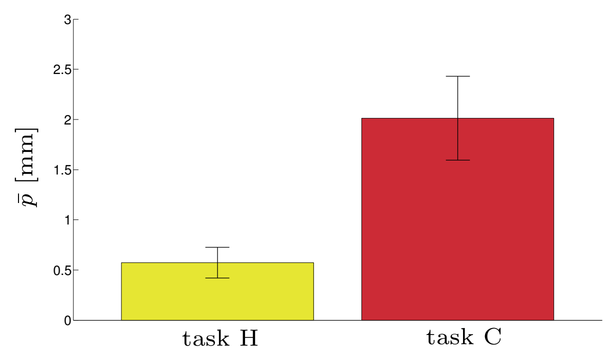
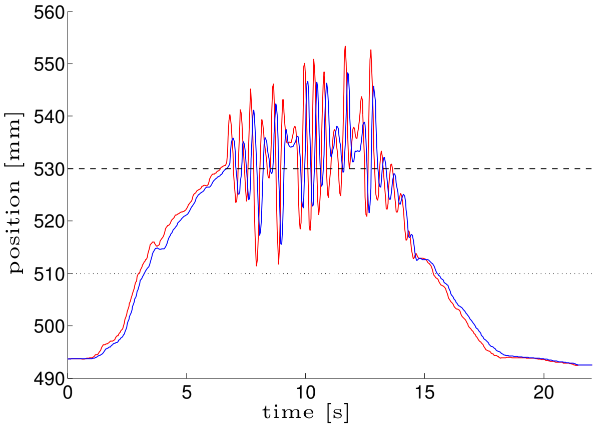


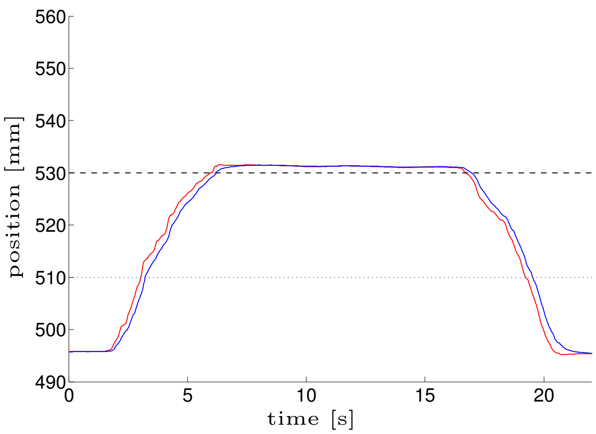
Fig. 7. Experiment in a simulated environment. Mean penetration depth $\bar{p}$ into the stiff constraint, expressed in [mm], during tests with the haptic (task H) and cutaneous feedback (task C).

in Sec. III-B. It is worth underlying that larger penetration depth into the virtual fixture corresponds to higher forces fed back by the virtual environment (applied by either the haptic device or the cutaneous actuator), according to the stiff element chosen for the virtual surface.

During the experiment, the motors of the cutaneous display never reached its saturation limits.

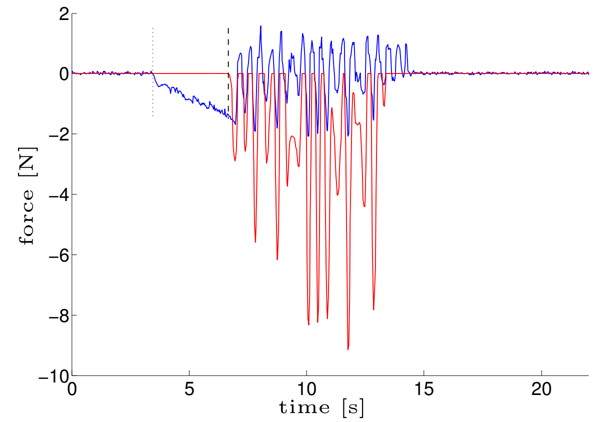


(a) Haptic feedback (task H)

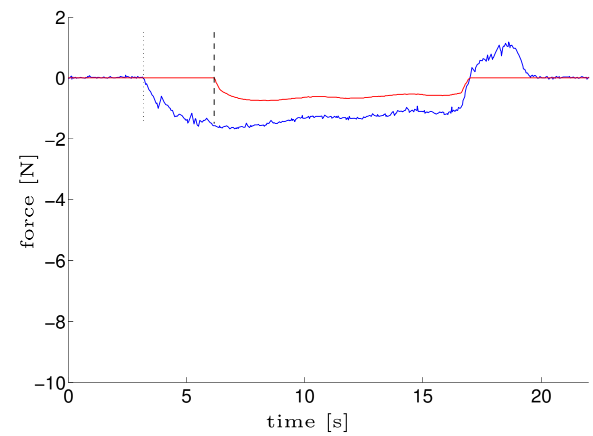


(b) Cutaneous only feedback (task C)

Fig. 8. Experiment in a real world scenario. Needle and haptic interface positions, expressed in [mm], are respectively shown in blue and red. The dotted black line represents the position of the object being penetrated while the dashed black line represents the position of the virtual fixture.



(a) Haptic feedback (task H)



(b) Cutaneous only feedback (task C)

Fig. 9. Experiment in a real world scenario. Force measured at the needle tip and force generated by the virtual fixture model, expressed in [N], are shown, respectively, in blue and red. The dotted black line represents the instant the needle penetrate the object and the dashed black line represents the instant the needle collides with the virtual fixture surface.

B. Experiment in a real world scenario

The main advantage of cutaneous feedback is that it makes the haptic loop intrinsically stable, no matter what happens in the external environment. To support this argument a new experiment was carried out, in which the same protocol of the experiment described in Sec. III-A was used. A needle insertion task with the same feedback modalities was proposed in a real scenario.

The experimental setup is reported in Fig. 10 and consisted of the 6 DoFs manipulator KUKA KR3 teleoperated by an Omega 3 haptic interface. A needle and a force sensor, able to measure the force at the base of the needle, were fixed to the robot end-effector. The motion of the manipulator was controlled using the haptic device.

The haptic interface controller runs at a rate of 1KHz which is higher than the TCP/IP KUKA maximum frequency of 83 Hz, resulting in a haptic interface-to-robot command delay. It is worth noting that the instability problem of the haptic loop in the presence of time delays can be solved with advanced controls, as the wave variable transformation [25], [8]. Nonetheless, with the aim of emphasizing the intrinsic stability of cutaneous feedback, this method was not used in the experiment.

The sensory substitution approach here used makes the haptic loop intrinsically stable. The instability behaviour of the haptic device, induced in this experiment with a communication delay, is a case of study for generic stability issues in teleoperation.

We asked a single subject to insert the needle in an object made of expanded polystyrene (EPS) and then stop the motion of the hand when the stiff constraint was perceived. Fig. 8 shows the position of the needle fixed to the remote robot's end-effector and the operator's hand position versus time, while Fig. 9 shows the force measured at the needle base and the force generated by the virtual fixture model versus time. This result shows that haptic feedback (task H) can bring the haptic loop near to instability, as significant oscillations of the probe position occurred, whereas cutaneous feedback (task C) allows a stable contact with the virtual fixture surface. The same behaviour is expected in every case of serious failure of the haptic device's actuators, which can cause an abrupt change in the behaviour of the remote robot.

IV. Conclusions and future works

A new device able to provide cutaneous feedback has been presented. The actuation used for the cutaneous display re-

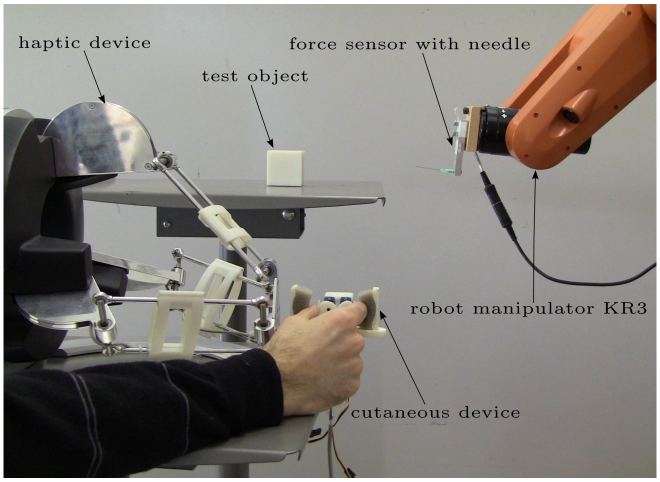


Fig. 10. The experimental setup. The haptic device, with the proposed device mounted on, controls the motion of the manipulator. The force measured at the needle tip by a sensor is fed back to the operator either by the motors of the Omega 3 or by the motors of the cutaneous device.

quires less power and it is less bulky than the one required to generate haptic feedback, with a direct effect on simplifying mechanical design and reducing costs.

Experiments have shown that cutaneous feedback at the fingertips may be effectively used in the proposed scenario to substitute complete haptic feedback (i.e. cutaneous and kinesthetic feedback).

The main advantage of using the fingertip cutaneous display instead of the complete haptic feedback is that the stability of the haptic loop is intrinsically guaranteed. This can be very convenient for critical applications, such as robot-assisted surgery. The main drawback of this novel approach is that, in spite of a practically indistinguishable perception of touching a virtual wall, the realism of the interaction certainly improves with kinesthetic feedback. Moreover, it is worth underlining that, to exploit this idea in medical applications like robotic surgery, we need to prove that applying cutaneous feedback to the fingertips of the operator will not distract him/her from the surgical task.

To improve the performance and the accuracy of the control of the device we are considering to introduce a position sensor in addition to the two force sensors. Furthermore, work is in progress to validate the device with more subjects and more tests. We also want to compare other sensory substitution techniques existing in literature with the proposed cutaneous device performance.

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