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Improving Transparency in Passive Teleoperation by Combining Cutaneous and Kinesthetic Force Feedback

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***Abstract*— A novel idea for improving transparency of teleoperation systems with force feedback is presented. This approach is based on the idea of *sensory subtraction* presented in [12], and consists of providing the operator with independently controlled kinesthetic and cutaneous feedback to improve the realism of haptic rendering of the remote environment (i.e., transparency), while preserving stability. More specifically, cutaneous force feedback is employed to recover transparency when a lack of kinesthetic feedback has to be enforced to keep the teleoperation loop stable. The viability of this approach is demonstrated with two experiments of teleoperated needle insertion. Results showed improved performance with respect to common control techniques not employing the proposed cutaneous compensation.**

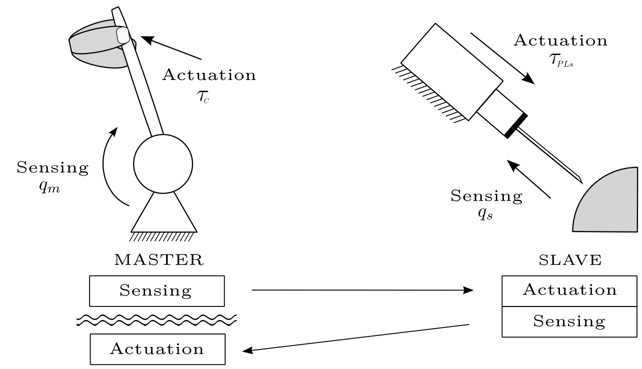

Fig. 1: Teleoperation system employing cutaneous feedback only. The force feedback is applied to the fingertips of the operator and does *not* affect the position of the end-effector of the master device, thus opening the haptic loop and making it intrinsically stable.

I. INTRODUCTION

Teleoperation systems are employed to sense and mechanically manipulate objects at a distance. They are composed of a slave robot which interacts with a given environment according to the commands of a master system, commonly operated by a human. In order to achieve a good illusion of telepresence, the slave robot should efficiently mimic the user's actions and provide him or her with reliable information about the remote environment [1].

Achieving a good illusion of telepresence relies on situational awareness. The system needs to make the human operator aware of the state of the slave system. This is achieved through different types of information which flow from the remote environment to the human operator. They are usually a combination of visual, auditory and haptic stimuli. In this paper, we consider the problem of efficiently providing haptic stimuli, since this has an important role in enhancing the performance in terms of completion time of a given task [2], [3], accuracy [3], peak [4], [5] and mean force [5].

The major goals while designing teleoperation systems are stability and transparency. Researchers have proposed a great variety of transparency- and stability-optimized bilateral controllers [6], [7] and it has always been a big challenge to find a good trade-off between these two objectives. In this respect, passivity [8] 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 [9], Energy Bounding Algorithm [10] and Passive Set Position Modulation [11]. In [7], a dual-layer controller structure is presented. On the one hand, a transparency layer is in charge of computing the ideal forces to be actuated at both the master and the slave, regardless of passivity constraints. On the other hand, a passivity layer modulates such forces when this is necessary to avoid violations of the passivity condition, thus guaranteeing stability at the price of a temporary loss of transparency.

A further possible approach, aimed at achieving stability and transparency on the master side, consists of avoiding the usage of any actuators for kinesthetic feedback and providing alternative forms of feedback using *sensory substitution* techniques. In this case, since no kinesthetic feedback is given, the haptic loop becomes intrinsically stable [12]. Force feedback is substituted with other forms of stimuli such as vibrotactile [13], auditory, and/or visual feedback [14]. Along this line, a technique focusing on enhancing transparency while preserving the intrinsic stability of the system has been presented in [12]. In that paper, the authors substituted haptic, i.e. kinesthetic and cutaneous, force feedback with cutaneous feedback only, and showed that higher transparency levels were obtained compared to other conventional sensory substitution techniques (i.e., visual feedback). This is due to the fact that cutaneous stimuli are perceived where the user expects them and provide the operator with a direct and co-located perception of the contact force. The authors named this tecnhique *sensory subtraction* [12]. However, even if this approach has been efficiently employed in complex

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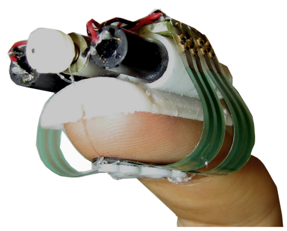


Fig. 2: The 3-DoFs wearable haptic display prototype. The motors, acting on the length of three wires, provide the requested force to the user's fingertip.

teleoperation scenarios, it usually provides the user with less transparency than that achieved using kinesthetic force feedback [15], [16].

In this paper, an approach based on the combination of kinesthetic and cutaneous feedback is proposed. The idea is to compute force feedback on the master side according to the technique in [7] and actuate it via a kinesthetic device as long as the passivity condition is not violated. As the passivity layer detects a violation and the kinesthetic device is thus unable to provide the required feedback, a cutaneous actuator conveys a suitable amount of force, thus recovering transparency. The control law in [7] is chosen here for illustrative purposes, although the proposed approach can be used on top of several other time domain control algorithms. This method yields a teleoperation system that is stable as the chosen control technique guarantees but with improved realism, since cutaneous feedback conveys the information that cannot be provided through the kinesthetic channel.

We present experimental validation of the proposed idea in a benchmark teleoperation scenario. Task performance is compared while employing kinesthetic feedback only, cutaneous feedback only and the mixed approach described in this work.

II. Cutaneous force feedback

Cutaneous sensations are produced 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, thanks to a direct measure of the intensity and direction of the contact forces [17]. On the other hand, kinesthesia provides the user with information about the relative position of neighbouring parts of the body, by means of sensory organs in muscles and joints [18].

Cutaneous feedback has been widely employed in the past years, due to the richness of information conveyed by cutaneous stimuli [17] and the appealing opportunity of developing haptic devices which are portable, wearable and inexpensive [19], [18], [20]. Moreover, employing cutaneous stimuli to provide force feedback in a teleoperation system makes this system intrinsically stable, since the force fed back is applied directly to the user's skin and does not affect the position of the end-effector of the master device, thus opening the haptic loop [12] (see Fig. 1). This is why cutaneous feedback has been efficiently employed in different teleoperation scenarios [12], [19], [15] and will be employed here to enhance the transparency of common teleoperation systems without affecting their stability.

The cutaneous haptic device used in this work is a wearable 3-DoF device, presented in [20] and shown in Fig. 2. It consists of two main parts: the first one is placed on the back 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. The two parts are connected by three cables. The motors, by controlling the lengths 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. The direction and amount of the force reflected to the user is changed by properly controlling the cable lengths. Three piezoresistive force sensors are placed near the platform vertices, in contact with the finger, in order to measure the components of the force applied to the fingertips. Further information about the device can be found in [20].

Note that, since the experiments described in Sec. V consist of 1-DoF telemanipulation tasks, the wearable devices are used as 1-DoF cutaneous devices (the three cables are pulled together), so that only forces in the sagittal plane of the finger are actuated, roughly normal to the longitudinal axis of the distal phalanx.

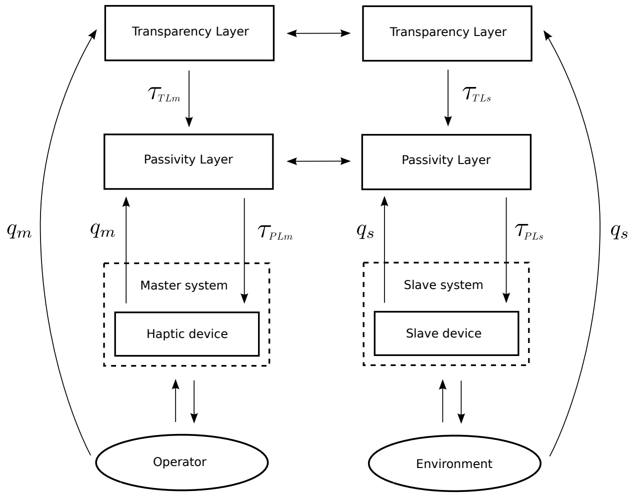
III. Control strategy for kinesthetic feedback

A passive implementation of a bilateral controller ensures stable behaviour of the system even in the presence of factors that could, otherwise, destabilize it. Although passivity is only a sufficient condition for stability, this is often considered an elegant solution to prevent unstable behaviour [21].

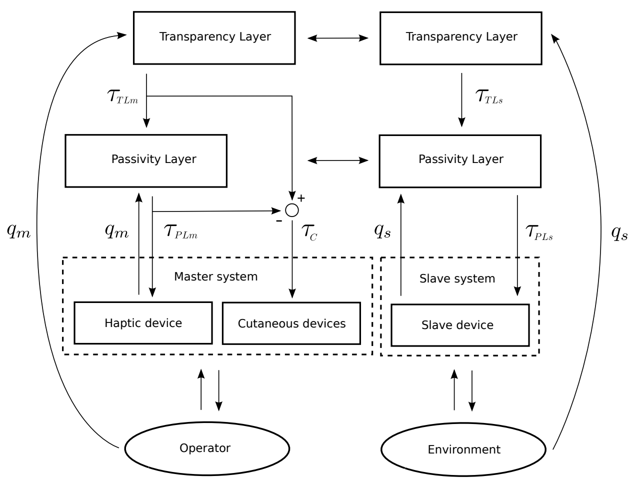
In this paper we integrate our method with the passivity-based two-layer approach presented in [7], although other control techniques can be used. In [7], the authors propose a control algorithm which is able to guarantee stable behaviour of bilateral telemanipulation systems in the presence of time-varying destabilizing factors, such as hard contacts, relaxed user grasps, stiff control settings, and/or communication delays. The control architecture is split into two separate layers. The hierarchical top layer, named *Transparency Layer*, aims at achieving the desired transparency, while the lower layer, named *Passivity Layer*, ensures the passivity of the system (see Fig. 3a). Separate communication channels connect the layers at the slave and master levels so that information related to exchanged energy is separated from information about the desired behaviour.

Let q_m and q_s be the displacements of the master and the slave systems, respectively[1]. The Transparency Layer is in charge of displaying the desired behaviour to obtain transparency by computing the torques τ_{TL*} to be applied to the operator/environment. The Passivity Layer is in charge of checking how the action planned by the Transparency Layer influences the energy balance of the system. If the passivity condition is not violated, the planned actions τ_{TL*} can be directly applied to the system. However, if loss of passivity is detected, a scaled control action τ_{PL*} is applied to preserve stability, resulting in a loss of transparency.

[1]For homogeneity, we are going to stick with the same notation used in [7].



(a) Original approach presented in [7].



(b) Combined kinesthetic and cutaneous feedback.

Fig. 3: Our approach modifies the control strategy in [7] by adding the opportunity of providing cutaneous feedback when the required force cannot be conveyed using kinesthesia.

IV. Mixed cutaneous-kinesthetic feedback

We can now introduce our idea with respect to the control strategy discussed above. When the Passivity Layer forces the system to alter the kinesthetic feedback given to the user, the amount of force which gets subtracted is provided through the cutaneous channel. This is possible since kinesthetic and cutaneous feedback can be controlled independently using the devices described in Sec. II. In this way, we attempt to recover a certain amount of transparency at the master side.

With reference to Fig. 3b, let τ_{TLm} be the desired (ideal) control action at the master side, as computed by the Transparency Layer, and τ_{PLm} the action which is actually applied to the user by the Passivity Layer [2].

[2]To be more precise, the action applied is given by $\tau_{PLm} + \tau_{TLCm}$, where τ_{TLCm} is an additional term used to extract small amounts of energy from the user, when necessary. Since we are not going to modify this part of the algorithm, we can safely disregard the presence of τ_{TLCm} in our discussion. However, in the experimental evaluation in Sec. V, the algorithm is correctly implemented.

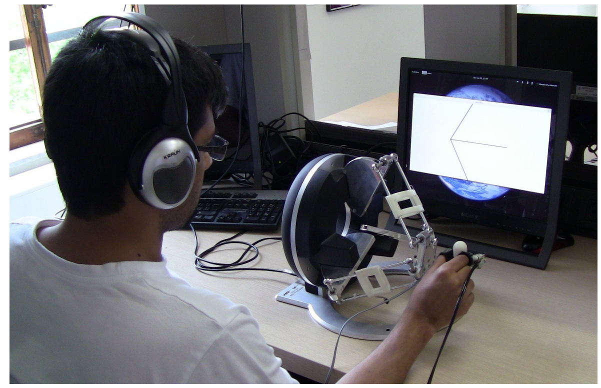


Fig. 4: Experimental setup. The operator wears two cutaneous devices. The motion of the haptic device is constrained along one direction and the position of its end-effector is linked with the position of the needle.

If, at a given time instant k,

$$\tau_{TLm}(k) = \tau_{PLm}(k),$$

then the control action planned by the Transparency Layer is being fully actuated through the kinesthetic channel. Otherwise, the Passivity Layer is acting in order to preserve the passivity of the system and loss of transparency occurs.

As already discussed, our idea consists of compensating for this loss of transparency by adding additional cutaneous force feedback. At any time instant k, the amount of force to be provided via the cutaneous device is computed as

$$\tau_C(k) = \tau_{TLm}(k) - \tau_{PLm}(k),$$

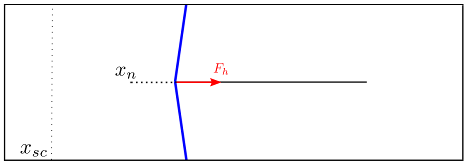
i.e., the force that is currently being cut off by the Passivity Layer. In this way, the system attempts to provide the operator with the full force feedback action computed by the Transparency Layer.

V. Experimental results

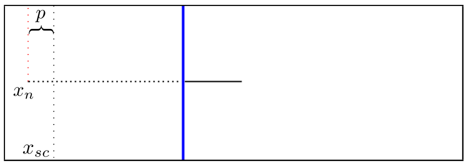
In order to demonstrate the viability and the performance of our approach, two experiments have been carried out. The scenario considered is a simulated teleoperated needle insertion in soft tissue, along one direction [22].

The master side consists of a special handle fixed to the end-effector of a commercial haptic device (Omega 3 by Force Dimension), as shown in Fig. 4. The motion of the haptic device is constrained along one direction by means of three rigid clamps fixed to the parallel structure of the haptic device. The operator wears two cutaneous devices on one hand, one on the thumb and one on the index finger, and grabs the handle (see again Fig. 4). The position of the haptic device end-effector (i.e., the position of the user's fingers) is linked with the position of the needle.

The task consists of inserting the needle into a soft tissue and stopping the motion of the hand as soon as a virtual stiff constraint is perceived, trying to overrun it as little as possible. The stiff constraint plays the role of an active constraint, 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 controlled by the surgeon, but the system constantly monitors



(a) needle penetrating the soft tissue



(b) needle penetrating the stiff constraint

Fig. 5: The virtual environment is composed of the needle (black), driven by the operator, the deformable tissue (blue), and the stiff constraint (dashed). The position of the needle x_n is linked to the position of the haptic device end-effector, the position of the stiff constraint is fixed to x_{sc}, and p represents the penetration of the needle inside the stiff constraint.

its motion and takes action if the surgical tool fails to follow a predetermined procedure [23]. In this experiment, we consider an example of a forbidden-region active constraint, which is in charge of preventing the needle from entering a specific region of the workspace.

A virtual environment simulating needle insertion has been implemented, whose model is described in [12] (see Fig. 5).

The operator remotely steering the needle feels a resistive force while penetrating the tissue, due to its visco-elastic properties, and an opposing force while trying to pull the needle out. In real scenarios, these forces are either measured by force sensors or estimated from other parameters. A spring ($K_t = 2$ N/m) and a damper ($B_t = 5$ N s/m) are used to model the contact force F_t between the needle and the tissue, while a spring ($K_{sc} = 2$ N/mm) is used to model the contact force F_{sc} between the needle and the stiff constraint. For the sake of simplicity we assume that the mass of the tissue ($M_t = 1$ kg) is concentrated at the contact point. The viscous coefficient of the body beneath the tissue is $V_t = 0.7$ N s/m. As for the haptic rendering, the interaction is designed according to the god-object model [24] and the position of the Omega handle is linked to the needle position x_n moving in the virtual environment. The tissue position changes according to the interaction with the needle, which is able to penetrate the surface only when the exerted force F_h is larger than a predetermined threshold ($F_p = 0.1$ N).

It is thus possible to discriminate four different operating conditions for the needle-tissue interaction model here presented:

- no contact,
- contact without penetration,
- penetration within the safe area (see Fig. 5a),
- penetration and contact with the stiff constraint (see Fig. 5b).

In the first case, since the needle is out of the tissue, the model is designed to feed back no force to the operator and the surface of the tissue tends to return to its predetermined initial position. When the needle touches the tissue, but the force F_h is not yet sufficient to penetrate it, the tissue surface is deformed by the movement of the needle. As soon as $F_h > F_p$, the needle penetrates the surface. If the operator steers the needle towards the unsafe workspace area delimited by the stiff constraint located at x_{sc}, a force is fed back to the operator in order to act against penetration of the needle in the forbidden area:

$$F_{sc} = -K_{sc}\,(x_n - x_{sc}).$$

The operator visually perceives the part of the needle outside the tissue and the tissue surface, while the position of the stiff constraint and the part of the needle inside the tissue are not visible (see again Fig. 4 and 5). According to the environment model, the controller computes the forces to be actuated by the haptic interface and the cutaneous devices, as described in Sec. IV.

Nine participants (7 males, 2 females, age range 23 – 29) took part in the experiment, all of whom were right-handed. Six of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their perception abilities. Each participant made eighteen repetitions of the needle insertion task, with six randomized trials for each of the following feedback modalities:

- both kinesthetic and cutaneous feedback (i.e., the approach proposed here, task KC),
- cutaneous feedback only (i.e., the approach employed in [12], [19], [15], task C),
- kinesthetic feedback only, computed according to the unmodified algorithm presented in [7] (task K).

Since the goal of the task is to avoid overrunning the stiff constraint, it is natural to consider, as a measure of transparency (i.e., of correct perception of the remote environment), the penetration $\bar{p}$ inside the stiff constraint itself, averaged over the six repetitions of each experiment.

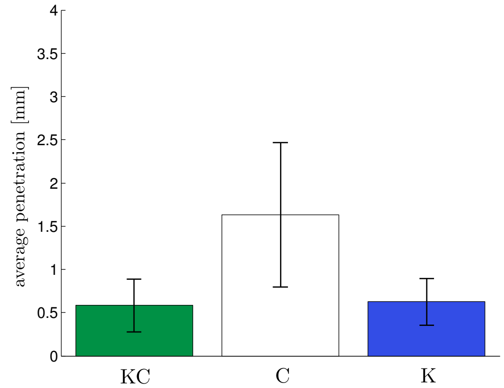
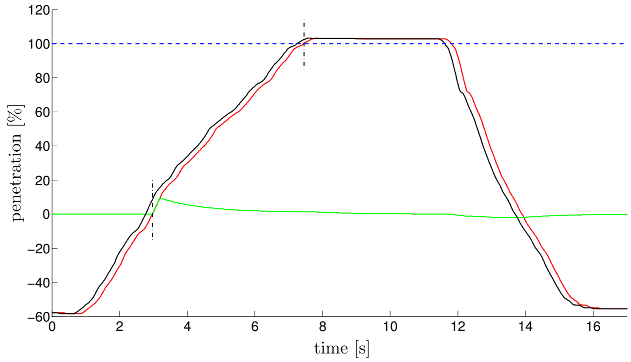


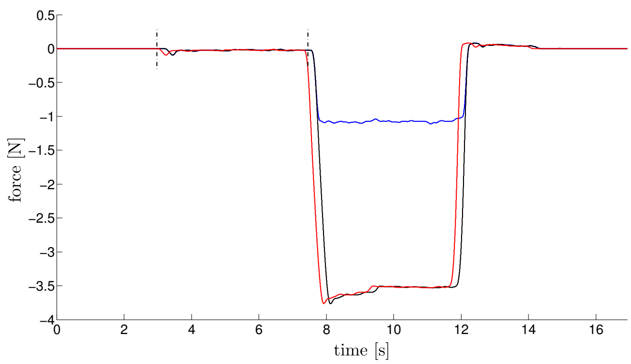
Fig. 6: Experiment #1. Average penetration beyond the stiff constraint for the three feedback modalities: kinesthetic and cutaneous (KC), cutaneous only (C) and kinesthetic only (K).

A. *Experiment #1*

In the first experiment the virtual environment is simulated at a sampling time $T_s = 1$ ms, with no transmission delay. In this case, it turns out that the virtual environment can almost always be rendered passively using the algorithm in [7] and, therefore, the Passivity Layer does not alter the action planned by the Transparency Layer significantly. For

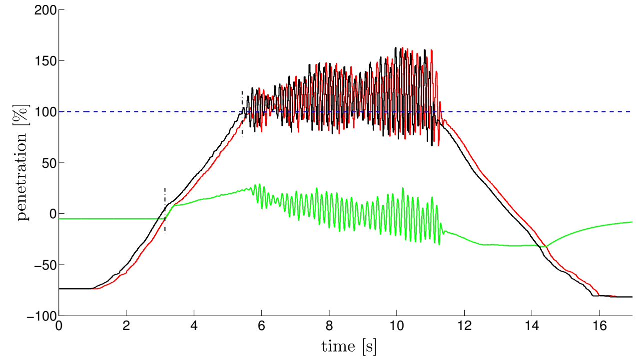


(a) Position of the master handle (black), needle in the remote environment (red), stiff constraint (blue), and tissue (green).

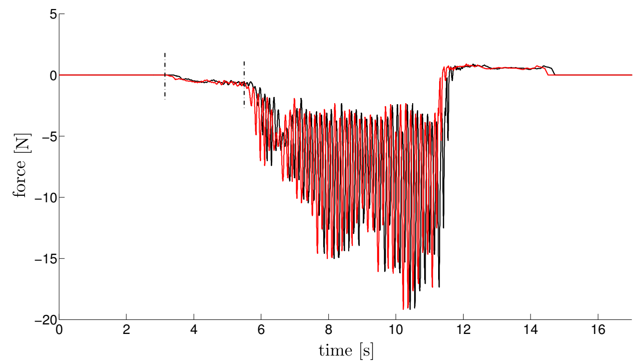


(b) Desired force exerted at the needle's tip (τ_{TLs}, red), at the the master handle (τ_{TLs}, black) and force actually applied to the user (τ_{PLm}, blue).

Fig. 7: Experiment #2. Position of the needle, desired and exerted force vs time, for a representative run, with a 0.2 s network delay in the haptic loop. Black vertical lines represent the instants when the depicted trajectory enters the tissue (left) and the stiff constraint (right).



(a) Position of the master handle (black), needle in the remote environment (red), stiff constraint (blue), and tissue (green).



(b) Force exerted at the needle's tip (red) and at the the master handle (black).

Fig. 8: Experiment #2. Position of the needle and force exerted versus time, for a representative run with a 0.2 s network delay in the haptic loop and the desired force τ_{TL_s} fully rendered via the kinesthetic channel (Passivity Layer bypassed). Unstable behaviour arises.

this reason, the actual force provided to the user is (almost) the same as the desired one, i.e. $\tau_{PLm} = \tau_{TLm}$.

Fig. 6 shows the average penetrations beyond the stiff constraint for each feedback modality (means and standard deviations are plotted). All column data passed the D'Agostino-Pearson omnibus K2 normality test. Comparison of the means among the feedback modalities was tested using one-way, repeated measures analysis of variance (ANOVA). The means of average penetration differed significantly among the feedback modalities. Post-hoc analyses (Bonferroni's multiple comparison test) revealed a statistically significant difference between task K and KC, and task C. As already seen in [12], [19], kinesthetic feedback led to better performance than employing cutaneous feedback only. However, even with cutaneous feedback only, all the subjects were able to feel the presence of the stiff constraint and stop the motion of the hand as requested. As expected, tasks K and KC behave very similarly in this case, as the cutaneous channel is almost never activated there.

B. Experiment #2

In this second scenario, we simulated a 0.2 s communication delay between the master system and the virtual environment. The same nine subjects were asked to complete again the eighteen repetitions of the same needle insertion task, with six randomized trials for each feedback modality. The average penetration inside the stiff constraint was again analysed.

Fig. 7 shows the positions of the needle (red line), of the stiff constraint (dashed blue line) and of the tissue (green line) versus time for a representative run of the experiment. In this case, the passivity layer is cutting the kinesthetic feedback while the operator is in contact with the stiff constraint, and cutaneous compensation is active. Note that a stable rendering of this virtual environment via only kinesthetic feedback would not even be possible. Indeed, if the desired force τ_{TL_s} is fully actuated through the kinesthetic channel (i.e., the passivity layer is bypassed), unstable behaviour arises, as it is clear from the experiment run depicted in Fig. 8. Fig. 9 shows the average penetrations beyond the stiff constraint for each feedback modality. All column data passed the D'Agostino-Pearson omnibus K2 normality test. Comparison of the means among the feedback modalities was again tested using one-way, repeated measures analysis of variance (ANOVA). In this case, the average penetration differs among all three feedback modalities. Post-hoc analysis reveals statistically significant differences.

Tasks employing kinesthetic feedback (KC and K) led again to better performance than employing cutaneous feedback only, as expected. In this case, however, task KC

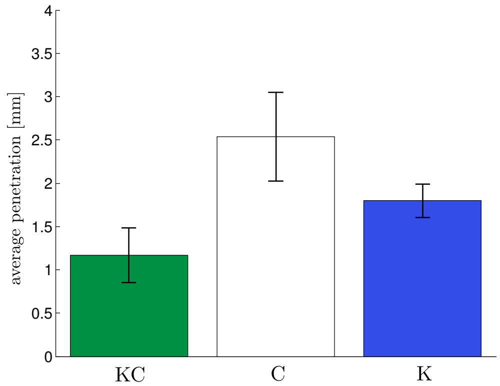


Fig. 9: Experiment #2. Average penetration beyond the stiff constraint, for the three feedback modalities.

performed better than task K: the average penetration for task KC was 33.14% lower than for task K. This result shows the performance improvement in terms of transparency introduced by our approach with respect to the use of only kinesthetic feedback computed according to the algorithm in [7]. Moreover, the time needed to complete the given tasks was recorded as well and no statistical difference was found between the average values for the three conditions. Therefore, providing force feedback through a cutaneous channel in combination with kinesthesia can be considered a viable technique for improving the transparency of telemanipulation systems.

VI. Conclusions

The use of combined cutaneous and kinesthetic force feedback has been illustrated as a viable mean to improve the transparency of teleoperation systems at the master side while guaranteeing stability. This approach can be integrated into existing control strategies for passive teleoperation. Two experiments of simulated needle insertion have been carried out in order to evaluate the performance of the proposed method. Results show a significant improvement in terms of transparency compared to the use of either cutaneous or kinesthetic feedback alone.

Work is in progress to design new cutaneous displays with better dynamic performance and wearability in order to improve the results hereby registered. The validation of the proposed approach on top of other control strategies as well as the design of ad-hoc controllers for optimal exploitation of cutaneous feedback are the subject of current research. Moreover, new experiments aiming at evaluating system's performance while interacting with a real environment will be performed in the next future. Finally, work is in progress to validate the approach with more subjects.

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