Sensory subtraction with cutaneous feedback to ensure safety in bimanual robot-assisted surgery

Leonardo Meli, Claudio Pacchierotti, and Domenico Prattichizzo

Abstract— **In this paper we present a novel approach to force feedback in robot-assisted surgery. Haptic stimuli, consisting of both kinesthetic and cutaneous components, are substituted with cutaneous feedback only. This new approach to sensory substitution in haptics is called *sensory subtraction*, since it can be thought as the subtraction between the complete haptic interaction and its kinesthetic component. In order to evaluate the feasibility of the proposed technique, we carried out a bimanual teleoperation experiment, wherein we compared the performance of our sensory subtraction approach with that of (1) complete haptic feedback, (2) visual feedback, and (3) auditory feedback. Results assess the proposed method as a viable solution to substitute haptic feedback in complex teleoperation scenarios. Moreover, as any other sensory substitution technique, this approach allows to overcome any stability issue affecting the haptic loop.**

I. Introduction

Haptic force is widely considered to be a valuable navigation tool during teleoperated surgical procedures [1], [2]. However, the kinesthetic part of the haptic interaction can lead to undesired oscillations of the system, which may be unsafe for both the clinician and the patient being operated. Stability of haptic systems can be in fact significantly affected by communication latency in the teleoperation loop, hard contacts, stiff control settings, and many other destabilizing factors that dramatically reduce the effectiveness of haptic force feedback in teleoperation [3]. For this reason, feedback approaches that disregard kinesthetic feedback are lately gaining great interest.

A popular non-kinesthetic approach to provide information about forces exerted at the slave side is *sensory substitution*. It consists of substituting kinesthetic force with alternative forms of feedback, such as vibrotactile [4], auditory, and/or visual feedback [5]. 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 [3]. Similarly to sensory substitution, Prattichizzo *et al.* [3] presented a feedback approach that substituted haptic force feedback with cutaneous feedback only. Results showed higher transparency levels than that obtained compared to other conventional sensory substitution techniques. The authors named this technique *sensory subtraction*, since the force provided (i.e., cutaneous stimuli only) can be thought as a subtraction between the complete haptic interaction, consisting of cutaneous and kinesthetic components [6], and the kinesthetic part of it.

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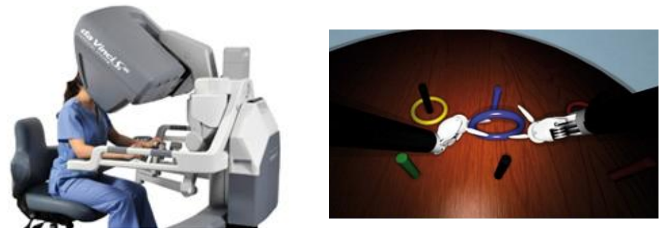


Fig. 1. The da Vinci Skills Simulator (Intuitive Surgical, USA, and Mimic Technologies, USA) contains a variety of scenarios (right) designed to give surgeons the opportunity to improve their proficiency with the da Vinci console controls (left).

In this paper we exploited the idea of sensory subtraction in a challenging medical scenario: a bimanual 7 degrees-of-freedom (DoF) teleoperation task, very similar to the *Peg Board* module of the da Vinci Skills Simulator (see Fig. I). Performance were compared while providing (1) complete haptic force feedback through a couple of haptic interfaces, (2) cutaneous force feedback through four cutaneous devices, i.e. the sensory subtraction approach, (3) visual and (4) audio feedback in substitution of force feedback, which are two popular sensory substitution techniques.

II. Fingertip skin deformation devices

Cutaneous stimuli, sensed by skin pressure receptors, are useful to perceive local properties of the objects such as shape, edges, embossing and recessed features. This is possible, mainly, thanks to a direct measure of intensity and direction of contact forces, and to the encoding of the force spatial distribution over the fingertip. Conversely, kinesthesia provides the user with information about the relative position of neighbouring parts of the body, principally by means of sensory organs in muscles and joints.

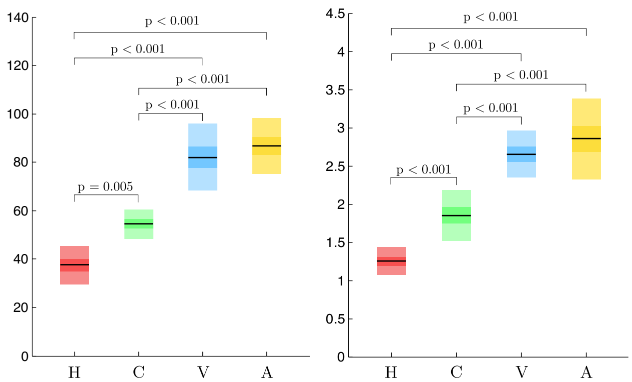
In this work we employ a wearable fingertip deformation device, which consists of two platforms: one fixed to the back of the finger and one in contact with the fingertip, connected by three cables. Three small electrical motors, equipped with position encoders, control the length of the cables, thus being able to tilt and move the platform towards or away from the fingertip. As a consequence, a 3-D force can be displayed to the users fingertip. The force to be provided was estimated according to a mathematical model of the fingertip [7], which considers a linear relationship between resultant wrench at the fingertip and devices platform displacement. More information about these devices can be found in [8].

III. Experimental evaluation

The sensory subtraction technique has been evaluated in two bimanual peg board experiments, with and without delay in the haptic loop.

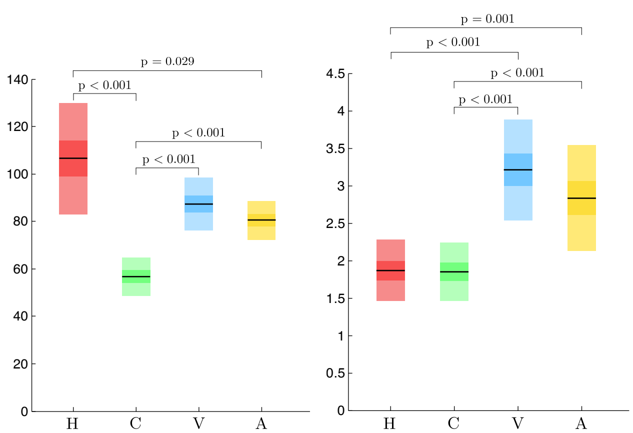
(a) (b)

Fig. 2. Experimental setup. (a) General overview of the setup. (b) Detail of one hand wearing the cutaneous devices.



(a) Completion time (b) Contact forces

Fig. 3. Bimanual peg board experiment. Means of the completion time and contact forces are represented by the thicker black lines for the haptic (H), cutaneous (C), visual (V) and auditive (A) modalities, while the lighter and darker color tones represent the SD and the SEM respectively. p-values of post-hoc group comparisons are reported when a statistically significant difference is present (confidence interval of 95%).



(a) Completion time (b) Contact forces

Fig. 4. Bimanual peg board experiment with a communication delay of 20 ms between master and slave systems. Means of the completion time and contact forces are represented by the thicker black lines for the haptic (H), cutaneous (C), visual (V) and auditive (A) modalities. p-values of post-hoc group comparisons are reported when a statistically significant difference is present (confidence interval of 95%).

A. *Peg Board Experiment*

The master system was composed of two Omega 7 haptic interfaces and four cutaneous devices. The slave system was composed of two virtual surgical pliers, directly controlled by the master interfaces. Operators were able to both move and rotate the pliers in the remote scenario and control their gripping forces. The virtual environment consisted of four rings, two green and two red, and two pegs fixed to the ground, one green and one red. The experimental setup is shown in Fig. 2.

Ten participants took part to the experiment. The task consisted of lifting, one by one, the rings 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 this experiment can be download at http://goo.gl/0b9eZ6. Subjects were asked to accomplish the task as quickly as possible. Each participant made sixteen trials of the aforementioned peg board task, with four randomized repetitions of each force feedback condition considered:

- complete haptic force feedback provided by the Omega 7 haptic interfaces (condition H),
- cutaneous force feedback provided by the fingertip skin deformation devices presented in Sec. II (condition C), i.e. the sensory subtraction approach,
- visual feedback in substitution of force feedback, provided by changing color brightness of the ring being grasped (condition V),
- auditory feedback in substitution of force feedback, provided by changing the repetition frequency of a stereo beep tone (condition A).

In all the considered conditions the Omega 7 devices were in charge of controlling the movements of the surgical pliers by tracking position and orientation of the operator's hands. In conditions C, V and A the Omega 7 interfaces did not provide any force feedback.

In order to evaluate the performance of the considered feedback conditions, we recorded the completion time needed to accomplish the task and the forces generated by the contact between the pliers (see Fig. 3). Data resulting from different trials of the same feedback condition, performed by the same subject, were averaged before comparison with other conditions' data. Means were analysed using an ANOVA test and a pairwise comparisons test. The investigation revealed no statistically significant difference between the visual and auditory conditions (V and A) in both the considered metrics, while it revealed a statistically significant difference between all the other conditions.

B. Peg board experiment with communication delay

The second experiment considered the same task, performed by the same ten subjects, with the same experimental setup and feedback conditions. However, this time we introduced a communication delay of 20 ms in the teleoperation loop. A video of this experiment, focusing on the unstable behaviour of the haptic modality, can be download at http://goo.gl/Q9h300. In order to evaluate the performance of the considered feedback conditions, we considered the same metrics as before and we processed the data in the same way (see Fig. 4).

The investigation revealed no statistically significant difference between the visual and auditory conditions (V and A) for both the metrics, no significant difference between cutaneous and haptic conditions (C and H) for what regards the gripping force, and no significant difference between visual and haptic modality (V and H) for what regards completion time. It then revealed a statistically significant difference between the modalities in all the other cases.

IV. Discussion

We analysed four feedback modalities in two different experimental scenarios. Subjects in the first experiment (no delay), while receiving haptic force feedback (H), showed better performance than while receiving any other form of stimuli (C, V, or A). Moreover, sensory subtraction (C) yielded to significant better results than employing auditory or visual feedback in substitution of haptic feedback (A and V). These considerations are valid for both the considered metrics: completion time, and grip force.

In order to validate the stability properties of sensory subtraction, we carried out an additional experiment, in which we introduced a communication delay of 20 ms between the master and slave systems. Users showed a similar behaviour with respect to the one experienced in the first experiment, while using the sensory subtraction and substitution modalities proposed, but a high degradation of performance was registered when the haptic force feedback was provided. Such an unstable behaviour is well-known in the literature and was here reported to point out the intrinsic stability of the sensory subtraction approach. We can hence state that the sensory subtraction is a reliable replacement for the haptic feedback force in teleoperation, in particular when safety is paramount, e.g. robotic surgery.

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