Using a Fingertip Tactile Device to Substitute Kinesthetic Feedback in Haptic Interaction

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Abstract. A prototype of a joystick where the kinesthetic feedback is substituted by tactile feedback is proposed. Tactile feedback is provided by a wearable device able to apply vertical stress to the fingertip in contact with the joystick. To test the device, rigid wall rendering is considered. Preliminary experiments show that the sensation of touching a virtual wall using the force feedback provided by the electric motor of the joystick is nearly indistinguishable from the sensation felt by the user using the tactile display only. The proposed device does not suffer from typical stability issues of teleoperation systems and is intrinsically safe.

Keywords: tactile display, force rendering, stability.

1 Introduction

Haptic feedback is fundamental for the human operator to perform complex tasks safely. For instance, studies on manual minimally invasive surgery (MIS) have linked the lack of significant haptic feedback in MIS to increased intraoperative injury [1]. To obtain a realistic representation of the remote environment, haptic interfaces, of the impedance type, available today use active input devices as motors to generate forces on the operator's hand. However, stability and transparency of such systems can be significantly affected by communication latency, reducing their applicability and effectiveness in case of stiff remote environments [2,3]. This limitation can be alleviated by implementing proper control systems [4,3], or by substituting master actuation with passive components such as brakes [5]. However, passive input devices have rendering limitations and may lead to large steady-state errors in teleoperation tasks. A more recent approach consists of using motors and brakes together, with the aim of obtaining a safer teleoperation while preserving system transparency [6]. Another interesting way of achieving stability is sensory substitution, which consists of replacing kinesthetic feedback with other forms of feedback such as auditory and/or visual feedback [7,8] or vibrotactile feedback [9]. Passive devices and sensory substitution approaches are particularly interesting, as the risk of producing motion of the master device due to active actuation is dramatically reduced.

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We propose here a novel approach in which a non-actuated master handle is used in combination with a wearable tactile feedback device. In this system, the slave device can track the position of the human hand, as in conventional teleoperation systems, while the contact force between the hand and the handle is substituted by a normal force produced at fingertips by a tactile device. It is worth noting that, differently from other examples of sensory substitution as in [9], where a vibrotactile force is produced on the bottom surface of the foot, in our system the tactile force, fed back to the user, is similar, in terms of application area and intensity, to the one perceived by interacting with an active handle. It will be shown in the experiment section that the absence of active actuation of the handle makes the system very safe to operate, even in the presence of large transmission delays.

2 The Tactile Device Substituting Kinesthetic Feedback

Inspired by the recent work on tactile feedback developed in [10,11], we propose an innovative combination of tactile force feedback and a handle able to track the position of the human hand. The prototype is shown in Fig. 1 where a joystick is held by the subject hand wearing a tactile device applying normal forces at the index fingertip. The joystick is thought of as a device with no actuation: the only force feedback at the user's hand is provided by the tactile device. Indeed, in Sec. 3 joystick motors will be used to compare results with conventional haptic rendering techniques. The joystick employed in this study was first used for testing a teleoperation scheme to enhance stability of heavy duty machines [12].

The idea behind tactile substitution is that the role of kinesthetic force feedback generated with proper actuation of the joystick can be partially replaced by a local tactile action: a normal stress at the fingertip generated by a simple mechanism consisting of two motors and a belt wrapping the fingertip as in Fig. 1. Note that this device has been designed to generate also tangential stress [11] but here only vertical stress is taken into account.

It will be shown in the experiment that there is no relevant degradation of performances in haptic interaction tasks, like touching virtual walls, when using the vertical stress instead of the kinesthetic force feedback. The substitution idea is supported also by recent findings in [10] where the authors use a single point kinesthesia model to simulate complex contact interaction with objects through multiple points.

3 Experiments

Preliminary experiments have been performed. The experimental setup consists of the device shown in Fig. 1, simulating a haptic interaction along 1–Dof. The simulator for the virtual environment was developed in Matlab. Communication between simulator, joystick and tactile display was realized using the UDP protocol over a local network.Control update rate was set to 1000 Hz.

Regarding haptic rendering, the joystick position is linked to a point (x_h) moving in a 1-DoF virtual environment, with a virtual wall in $x_{\text{wall}} = 52$mm. A spring ($K = 3$N/mm) is used to model the contact force F according to the god-object model [13]. Note that

Fig. 1. Shot of the prototype, including the joystick and the tactile device (left). Scheme of the tactile device: two motors allow to generate a stress normal to fingertip (right).

the measured variable is joystick angle θ, while the linear displacement is computed as $x_h = L\theta$ with $L = 1.5$mm/deg.

Five participants (5 males, age range 23–30 years) took part in the trials, all of them were right-handed. Two of them had previous experience with haptic interfaces and perception experiments. None of the participants reported any deficiencies in perception abilities. We asked the subjects to control the joystick with their right hand using the thumb and the index fingers only (Fig. 1), and to stop when they touched the virtual wall (starting point: $x_h = 0$ for all trials).

3.1 Experiment 1: Comparison of the Feedback Modalities

Kinesthetic and tactile feedback were considered alternatively. Force feedback was either applied by the motor of the joystick (in the case of kinesthetic feedback) or it was produced by the motors of the tactile display, rolling up the belt to provide a normal stress at the fingertip of the index finger (in the case of tactile feedback)[1]. Visual feedback, which consisted in showing a moving box and a wall on a computer screen, was either used or switched off.

Each participant made four different tests, whose order was randomly generated for each subject:

- kinesthetic feedback w/ visual feedback, no tactile feedback (task A)
- kinesthetic feedback w/o visual feedback, no tactile feedback (task B)
- tactile feedback w/ visual feedback, no kinesthetic feedback (task C)
- tactile feedback w/o visual feedback, no kinesthetic feedback (task D)

The mean and the maximum values of contact force were estimated from penetration depth $F = K(x_h - x_{\text{wall}})$, for each subject and for each trial. Fig. 2 shows the means and standard deviations of measured mean (left) and maximum (right) contact forces. Comparison between tasks suggests that kinesthetic feedback (A-B) exhibits better performances than tactile feedback (C-D) with or without visual feedback in terms of both maximum and mean contact forces. Note that larger contact forces correspond to larger penetration depth of the virtual wall according to the elastic coefficient K. Nonetheless,

[1] Due to the specific tactile device used, the normal stress was discretized into 4 levels.

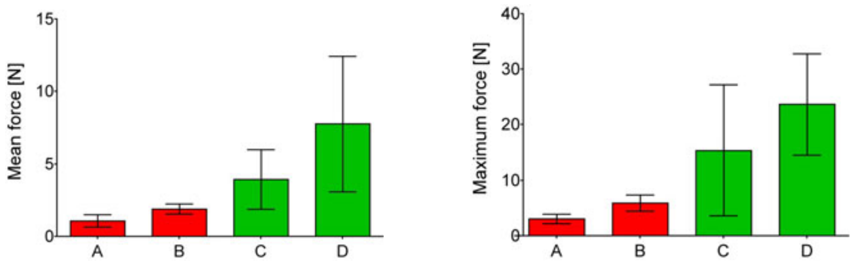

Fig. 2. Mean (left) and maximum (right) contact forces, expressed in [N], during tasks A, B, C ad D. Each bar represents the average of all participants for a single task. Red bars indicate kinesthetic feedback, green bars indicate tactile feedback.

the results observed in tasks C and D suggest that all subjects were able to perceive the presence of the wall and to reach a stable contact position within the wall thanks to tactile feedback only. It is worth noting that the larger contact forces observed when tactile feedback was used may be partly due to the delay of the tactile actuators and in particular to the dynamics of the belt [10,11].

3.2 Experiment 2: Stability with Time Delay

As already pointed out, the main advantage of tactile feedback is not that it is more realistic than kinesthetic feedback, but that it makes the haptic loop intrinsically safe, showing no instability behaviors neither in presence of delays. In Fig. 3, we report probe position $x_h(t)$ versus time for two representative runs in presence of transmission delays. We asked the subject to touch the wall three times. The experiment was performed with kinesthetic feedback (left) and with tactile feedback (right), with no visual feedback. In both cases, a delay of 100ms was introduced in the haptic loop[2]. Fig. 3 clearly shows

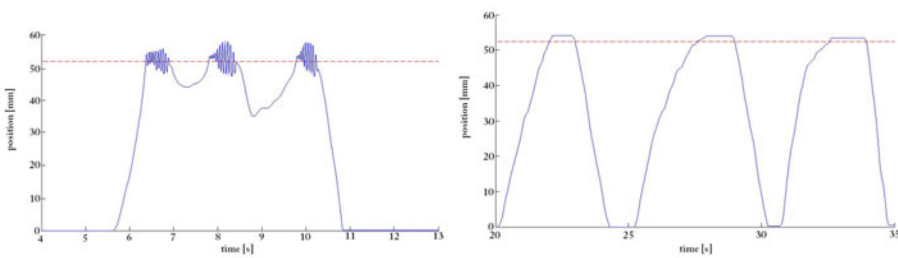

Fig. 3. Joystick probe position $x_h(t)$ expressed in [mm] using kinesthetic feedback (left) and tactile feedback (right), with a network delay of 0.1s in the haptic loop. Dotted red lines represent the position of the virtual wall.

[2] Instability of haptic feedback in the presence of time delay can be fixed with wave variable transformation [14]. Nonetheless, with the aim of emphasizing the intrinsic stability of tactile feedback, this method was not used in the trials.

that kinesthetic feedback can bring the haptic loop near to instability, as significant oscillations of the probe x_h position occurred, whereas tactile feedback allows for stable contact with the wall despite the presence of transmission delays.

4 Conclusion

Preliminary experiments with a joystick have shown that tactile feedback at the fingertips may be effectively used to substitute kinesthesia in haptic displays.

The main advantage of using fingertip tactile displays instead of kinesthetic feedback given by the joystick is that the stability of the haptic loop is intrinsically guaranteed. This can be very convenient for critical applications like robotic surgery or hazardous environment robotics. Note also that actuation for tactile displays usually requires less power and is less bulky than that required to generate kinesthetic feedback, with a direct effect on simplifying mechanical design and cost reduction.

The main drawback is that, in spite of a practically indistinguishable sensation of touching a virtual wall, the realism of the interaction certainly improves with kinesthetic feedback. Moreover, it is worth underlying that, to exploit this idea in medical applications like robotic surgery, we need to prove that applying tactile feedback to the fingertips of the operator would not distract him/her from the surgical task. On the other hand, it must be noticed that the fingertip, and the hand in general, is exactly the place where kinesthetic feedback is expected.

Another possible drawback with the tactile feedback option, as proposed in the paper, is that it could put higher stresses on tissues with respect to traditional haptic interaction, unless the tactile device is properly tuned.

While preliminary experiments validate the approach, further analysis is required for a complete evaluation of the proposed concept. We are building new tactile displays with better dynamic performances in order to design and conduct additional psychophysical experiments to assess other relevant parameters, like for instance the JND for stiffness perception.

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