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# Development and Experimental Validation of a Master Interface with Vibrotactile Feedback for Robotic Telesurgery

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*Abstract*— **This work wants to investigate the efficacy of a vibro-tactile feedback to convey a haptic perception to the surgeon in a teleoperated robotic system for surgery. To this purpose, vibrotactile actuators have been embedded in the end-effector of the master interface of a tele-operated robotic system made of the haptic joystick Novint Falcon and the Kuka Light Weight Robot III. Vibrotactile feedback can be used to support the surgeon during the surgical procedure, guiding him/her during the intervention, and to train unskilled surgeons with simulators. The development and the experimental validation of the master interface with the vibrotactile feedback is presented in this paper. The system has been validated on 12 subjects, who were requested to control the movement of a sphere along a desired path in a virtual environment. Results have been compared with the three cases of absence of feedback, visual feedback and combined vibrotactile and visual feedback. The obtained results demonstrate that a vibrotactile feedback can improve in a statistically significant manner the accuracy of the procedure with respect to the absence of feedback.**

## I. INTRODUCTION

Robot-assisted telesurgery is a field of Minimally Invasive Robotic Surgery (MIRS) based on tele-operated robotic systems. In tele-operated (or master-slave) approach, a slave robot is remotely controlled by the surgeon through a haptic interface (representing the master system). This means that the surgeon (who is physically separated from the patient) controls movements of the slave robot that interact with patient's tissues. Robotic telesurgery can solve a number of problems encountered in conventional laparoscopic surgery, such as the reduced dexterity during intervention, the lack of haptic feedback for the surgeon, the reduced hand-eye coordination, the pivoting effect caused by the incision point.

The use of haptic interfaces in telesurgery has a twofold purpose: the haptic interface sends position data to the slave system and provides the surgeon with haptic feedback during the robotic surgery. Haptic feedback is aimed at providing the user with kinesthetic and/or tactile sensations representing the interaction with patient's tissues. Although beneficial for the surgeon, commercially available MIRS systems (e.g. the Da Vinci Surgical System by Intuitive Surgical, Inc.), do not provide the surgeon with haptic feedback.

Providing a kinesthetic feedback requires accurately measuring the interaction forces and torques between the instrument and the tissue on the slave side. No sensors able to provide both forces and torques while fulfilling the requirements of sterilizability, biocompatibility and miniaturization have been released on market yet [1]. An alternative approach consists of using Virtual Fixtures [2] for guiding users towards a predefined target [3]-[6], or at preventing them from penetrating in undesired regions [6]-[9].

On the other hand, the realization of a tactile feedback poses the delicate issue at master-side of conveying the surgeon with effective cutaneous stimuli. Various systems have been developed in the literature in different application fields to provide a subject with a comprehensive tactile feedback. These systems relies on different types of actuation [10]-[11] with pros and cons: piezoelectric actuators, shape memory alloys, vibrotactile actuators, rheological fluids or, else, pneumatic actuators.

This work wants to investigate the efficacy of a vibro-tactile feedback to convey a haptic perception to the surgeon in a teleoperated robotic system for MIS. The effectiveness of vibrotactile clues has been already tested in MIS by stimulating different areas of the skin, e.g. the sole of the foot and the wrist in needle-insertion task [12]-[13], or the abdomen in Computer-Aided Surgery (CAS), to guide the surgeon towards a target [14].

Embedding the vibrotactile actuators in the end-effector of the master interface of a tele-operated robotic system represents an alternative approach that is studied in this work to provide the surgeons with a feedback on the task he/she is performing. It can be regarded as a type of sensory substitution or augmentation (e.g. as a substitution or a support to the kinesthetic feedback) during surgical procedures as well as surgeon training. It relies on the assumption that receiving a spatial indication directly from the object that is moved (thus soliciting the same body part that generates the movement) can be more immediate and effective than receiving the same information on another location of the body.

Therefore, this work presents the development and the experimental validation of a low cost vibrotactile module to be embedded in the master side of a teleoperated robotic system for MIS. By modulating vibration amplitude, it is possible to provide the user with a vibrotactile feedback aimed at guiding the surgical instrument towards a target or at preventing collisions and dangerous positions of the laparoscopic instrument.

The development of a vibrotactile module has the advantage that force sensorization of the slave robot is not required. Additionally, the vibrotactile feedback allows relieving the visual perception channel, which might be saturated during a surgical procedure, and has lower reaction time than the visual modality. Time reaction for the touch sense is much

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Fig. 1. Novint Falcon haptic manipulator.

lower than for the other senses, except for the auditive one [15].

The developed vibrotactile module has been integrated in the haptic joystick Novint Falcon (Fig. 1) used as master console of the tele-operated system made of the Novint Falcon and the Kuka Light Weight Robot III [2]. The module has been experimentally tested on 12 subjects who were requested to move a virtual object along a desired path. A comparative analysis in four different experimental conditions has been performed: absence of feedback, with vibrotactile feedback, with visual feedback, and with both vibrotactile and visual feedback.

The paper is structured as follows. Section II describes the proposed vibrotactile feedback module, illustrating the design requirements and the development of the prototype. Section III presents the experimental setup and protocol, and reports the validation results. Finally, conclusions and future developments are reported in Section IV.

## II. A VIBROTACTILE FEEDBACK MODULE FOR HAPTIC INTERFACES

### A. Design requirements

In the design of a vibrotactile feedback module it is essential to analyze neurophysiological mechanisms and constraints, which are directly related to the stimulated receptor system.

Tactile sensitivity in human hand (and hairless skin in general) is modulated by four different types of mechanoreceptors. Mechanoreceptors involved in the perception of vibrating stimuli are Pacinian corpuscles, fast-adapting receptors (i.e. FA II) very sensible to stimulations with fast transient and high frequency components. The highest sensitivity to vibration in humans is at a frequency of 200÷300 Hz [20].

Starting from the psychophysics relations between the magnitude of the vibrating stimulus, the perceived intensity and the sensation it evokes, it is possible to extract three main requirements to address to stimulate the FA II receptors on fingertips. They are:

- *Vibrotactile sensitivity* and *adaptation.* The detection threshold of a sinusoidal displacement of the skin depends on many factors, such as frequency and amplitude of the stimulus, end-effector shape, contact area, contact force, skin temperature, subject age. The relation between the detection threshold and the frequency of the stimulation has already been tested with a spherical handle (contact area mean value: 1097 $mm^2$) [17]. The results show a standard U-shaped curve with a minimum around 200 Hz.
  However, for the adaptation mechanism, the stimulation of the Pacinian corpuscles has a deleterious effect on the long-term perception of vibrotactile actuators. Moreover, the threshold amplitude for vibrotactile stimulation increases after a strong conditioning stimulus (i.e. stimuli that last more than 7 minutes) [21]. Therefore, the prolonged use of vibrotactile actuators in surgical robotics has to be carefully evaluated [10].
- *Response time* of vibrotactile actuators. Latency between an event and the perception of the vibrotactile stimulus can degrade the quality of the feedback. It has been shown that latency periods have an impact on user error rates when time response exceed 25 ms, but the user has a perception of the presence of a latency only over 50 ms of delay [22]-[23].
- Maximization of the *perception* of the stimulation. Tangential and normal displacements of the skin produce different tactile sensations. It is shown that normal stimulation is more effective than tangential stimulation on the fingertip (naked skin) [24].

### B. Prototype development

To address the design requirements, rotary electromagnetic actuators with respect to linear ones have been selected.

In rotary actuators an offset mass is typically coupled to the shaft of a DC motor (ERM motor), while in linear actuators a coil is wrapped around a ferromagnetic material (solenoid) or a permanent magnet (voice-coil actuator) [16].

In ERM motors the input signal controls both amplitude and frequency of the vibrations. In linear actuators the AC input signal allows controlling these two parameters separately. Although ERM motors cannot create a wide range of sensations, these small-sized and cheap actuators operate in a broad band of frequency and allow high spatial resolution, especially when their vibration frequency is around 250 Hz. Additionally, because of the small size, they can be stably located in the end effector of the master interface and allow producing a normal stimulation on the fingertip. On the other hand, solenoids and voice-coil actuators are generally more expensive and bulkier than ERM motors, work at a single resonant frequency and are sensitive to dissipative phenomena.

Therefore the choice of ERM motors is the result of a compromise between bulkiness and vibration effectiveness and does not require additional electronics to produce the command signal.

In order to address all the aforementioned design requirements, including response time and latency, the vibration motors ERM 308-102 and 304-111, Precision Microdrives

TABLE I

TECHNICAL CARACTERISTICS OF ERM MOTORS 308-102 AND 304-111 (PRECISION MICRODRIVES LTD.)

| | 304-111 | 308-102 |
|---|---|---|
| VIBRATION FREQUENCY [Hz] | 125±200 | 180±260 |
| VIBRATION AMPLITUDE [m/s$^2$] | 0.55±0.95 | 1.2±3.6 |
| LAG TIME [ms] | 16 | 9 |
| RISE TIME TO 50% [ms] | 28 | 21 |
| OVERALL DIMENSION [mm] | 15.7×4.50×4.25 | 18.3×8.0×6.0 |

Ltd., have been selected. Their technical characteristics are reported in Tab. I.

The two vibration motors have been positioned in the hollow hemisphere of the end-effector of the Novint Falcon. A small amount of material has been removed and hot melt adhesive has been used to block them (as shown in Fig. 2).

It is shown in the literature [18], [19] than an effective distance for discriminating vibrotactile stimuli on a spherical handle is around 25 mm. This is named Just Noticeable Difference (JND). The Novint Falcon end-effector structure does not allow to place the actuators at a distance greater than the aforementioned JND without further changes; hence, it is not possible to discriminate between the vibrating stimuli produced by the two motors. Nevertheless, since the two motors work at a different range of amplitude, the range of vibrating patterns is highly widened.

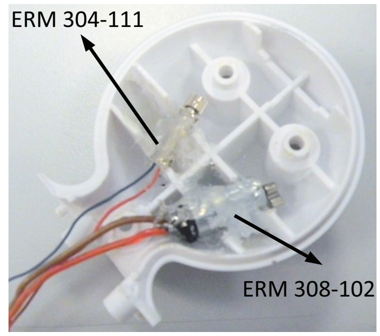


Fig. 2. Hollow hemisphere of the end-effector with two ERM motors housed in.

## III. EXPERIMENTAL SETUP AND VALIDATION

In the experimental validation of the vibrotactile feedback module, the Novint Falcon is used to control the movement of an object in a virtual scene (Fig. 3). Apart from scaling and indexing, the end-effector position in the Novint Falcon workspace corresponds to the position of a red sphere in the scene.

The experimental validation is aimed at assessing the efficacy of a vibrotactile feedback with respect to other feedback modalities. In particular, the following four conditions were tested: 1) absence of feedback (No FB), 2) vibrotactile feedback (VT FB), 3) visual feedback (VS FB) and 4) combined vibrotactile and visual feedback (VT+VS FB).

### A. Setup

The experimental setup for the validation of the developed module is shown in Fig. 3, while the functional scheme is outlined in Fig. 4. The Novint Falcon has been controlled from a Linux terminal, through the API (Application Programming Interface) named *libnifalcon library*. The graphical interface has been developed with LabVIEW control ActiveX 3D Graph under Windows OS (i.e. Windows Terminal in Fig. 4).

The communication between the Linux and Windows Terminals has been established through the UDP communication protocol. It allows sending the end-effector position from the Novint Falcon to the graphical interface, with a scaling factor of 50. The position of the Novint Falcon end effector is mapped in the virtual scene through the red sphere.

The four experimental conditions are implemented as follows. When the sphere is on the desired path (i.e. the middle of the white band in Fig. 3), no feedback is produced.

The visual feedback consists of a bar whose width and color intensity increase gradually when the sphere approaches the path boundaries, as shown in Fig. 3.

Vibrotactile feedback is activated by the deviation of the sphere from the desired path. The deviation magnitude from the desired path determines the activation level of the vibrotactile feedback (through a variation of motors voltage). Deviations in the north and south directions cause the activation of motor 304-111; on the other hand, deviations in the east and west directions cause the activation of motor 308-

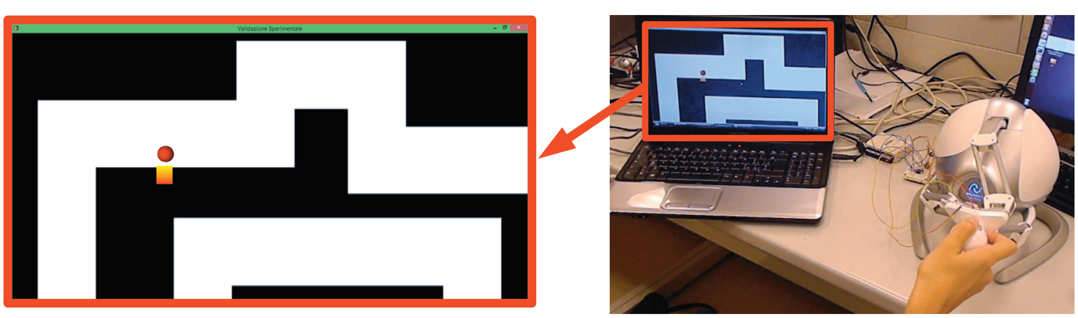

Fig. 3. The virtual scene and the experimental setup.

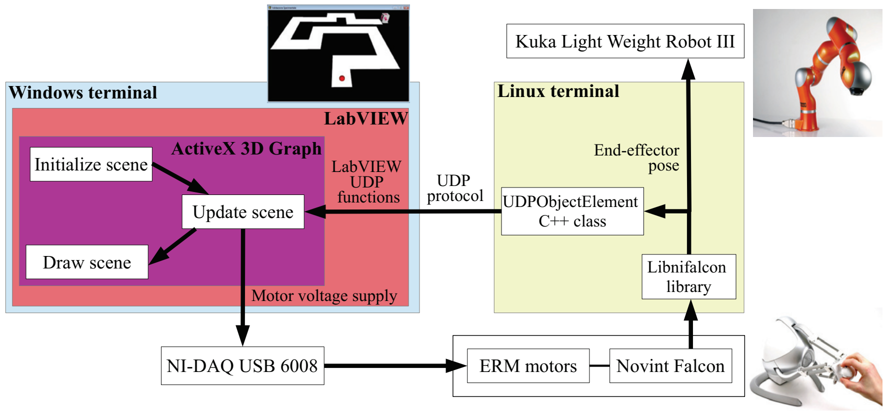


Fig. 4. Block diagram of the setup for the validation of the vibrotactile feedback module.

102. The command voltage is inversely proportional to the distance from path boundaries. It is provided to the motors via LabVIEW through the analog outputs of NI-DAQ board USB 6008. Power amplifiers in buffer configuration have been used in the supply circuitry to raise the power of the output channels (from 25mW up to 600 mW).

## B. Experimental protocol

Twelve participants (8 males and 4 females, aged 23±2 years) participated in this study. The participants sat on a chair in front of the haptic manipulator Novint Falcon and a monitor showing the virtual scene.

Subjects were asked to control the movement of the sphere by handling the Novint Falcon end-effector. They were required to maintain the sphere as much as possible in the middle of the path; the trial terminated when the sphere went beyond the border of the path. To measure subject performance, time taken to perform each task and the coordinates of the sphere in the *xy* plane during the trial were recorded. Fig. 5 shows in red the desired path and in blue the path executed by a couple of subjects. The area between the desired path and the actual path described by the sphere was calculated for each trial.

They held the Novint Falcon end-effector with their dominant hand in the way they felt more comfortable (Fig. 3). The experiment was performed under the aforementioned four conditions: 1) No FB, 2) VT FB, 3) VS FB and 4) VT+VS FB.

The subjects tested each condition for four trials (for a total of 16 trials per subject). The order of the four set of trials was randomized. Before starting the experiment each subject had 30 seconds to become familiar with the Novint Falcon.

## C. Results

Each subject was required to complete a questionnaire at the end of the trial about their preferred feedback modality. The results of the questionnaires showed that the subjects preferences were for the VT FB (45% of preferences), followed by VT+VS FB (40% of preferences). The 10% of

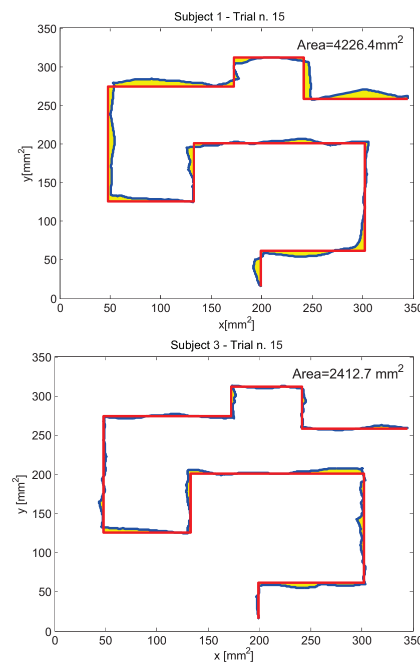


Fig. 5. Plots of the desired path (red) and the actual path (blue) described by two representative subjects during one trial assisted by vibrotactile feedback.

volunteers did not find useful any kind of feedback, while the remaining 5% had no preferences (Fig. 6).

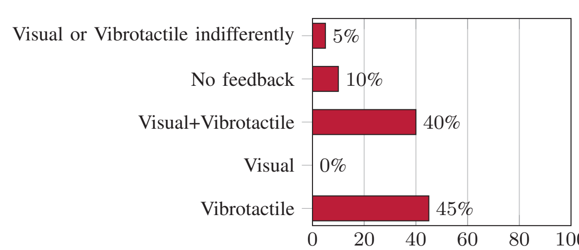


Fig. 6. Subjects evaluations expressed at the end of the trial.

For a more objective comparative analysis of the four feedback conditions, two quantitative indicators were used to measure the performance of the subjects: trial duration and the area between the desired path and the actual path described by the sphere.

For each subject and each condition (VT FB, VS FB, VT+VS FB, No FB), mean value and standard deviation of the two parameters were calculated over the four trials. Results are reported in Tab. II.

A statistical analysis based on Friedman non-parametric tests with Wilcoxon post-hoc test and Bonferroni correction was carried out to compare subjects' performance in the four aforementioned conditions (Tab. III).

As concerns the area index, Friedman test shows a statistically significant difference between mean rank in different levels ($\chi^2(3) = 9.300$, p=0.026). Despite the benefit perceived by the 40% of the subjects, the difference between VT+VS FB and No FB trials is not significant (Z=-1.726, p=0.071). As regards VT FB trials, the performance measured through the area parameter is significantly better than the overall performance registered in No FB trials (Z=-2.746, p=0.006).

Friedman test for the duration index also presents a statistically significant difference between mean rank in different levels ($\chi^2(3) = 12.900$, p=0.005). The post-hoc test (Wilcoxon signed-rank test) points out that the difference is statistically significant only between VS FB and No FB trials (Z=-3.059, p=0.002). By contrast, no significant difference exists between No FB and VT FB trials (Z=-1-560, p=0.117).

Finally, Fig. 7 shows the trend of trial duration over the four consecutive trials with the same feedback modality. It can be observed that No FB trials have nearly the same duration (mean values 55÷60 s). A notable improvement is obtained in the case of VT FB: trial duration moves from the value of 72.1±3.1 s to the value of 55.7±1.6 s lower than the case of No FB) thus showing an interesting learning trend. Furthermore the histogram shows that the use of VS FB is less intuitive than VT FB.

## IV. CONCLUSIONS

In this paper a low-cost vibrotactile feedback module has been developed and embedded in the end-effector of the master interface of a tele-operated robotic system. It consists of two ERM motors integrated in the spherical end-effector of the Novint Falcon haptic interface. Amplitude and frequency of the vibrating stimulus have been modulated through voltage commands. The vibrotactile module has been conceived as a tool for sensory substitution/augmentation of the kinesthetic feedback for the surgeon, to correctly guide the surgical instrument towards a target or prevent collisions and dangerous situations. Furthermore, it can be used in surgical simulators to train unskilled surgeons.

A virtual scene has been developed and experimental trials on 12 subjects in four different conditions (no feedback, VT FB, VS FB, VT+VS FB) have been carried out. Experimental results have demonstrated the advantages of using a vibrotactile feedback with respect to the other feedback modalities. Vibrotactile feedback allows improving the accuracy of task with a notable learning rate. In addition, it resulted to be the feedback modality preferred by the users.

This study is focused on the validation of the master side of a teleoperated surgical system in a virtual environment. Future efforts will be addressed to the application of the developed module to surgery, by using the Novint Falcon with the embedded vibrotactile feedback to command a laparoscopic tool connected to the Kuka LWR III, and the evaluation of the vibrotactile feedback when compared with other feedback modalities. Finally, the validation of the vibrotactile module with expert surgeons is envisaged, in order to characterize the effects of the tactile guidance in real operating conditions.

TABLE II
RESULTS OF THE EXPERIMENTAL TRIALS.

| | **Area** [$mm^2$] | **Time [s]** |
|---|---|---|
| VT+VS FB | 3253.1±918.0 | 65.1±19.3 |
| VT FB | 3140.7±772.5 | 59.9±16.9 |
| VS FB | 3275.4±852.8 | 67.1±26.7 |
| No FB | 3854.6±974.4 | 55.6±23.9 |

TABLE III
STATISTICAL ANALYSIS OF EXPERIMENTAL RESULTS.

| | **Friedman test** | | **Wilcoxon test** | | |
|---|---|---|---|---|---|
| | $\chi^2(3)$ | p-value | | Z | p-value |
| *Area* | 9.300 | 0.026 | VT+VS FB/VT FB | -0.628 | 0.530 |
| | | | VT+VS FB/VS FB | -0.078 | 0.937 |
| | | | VT FB/VS FB | -0.863 | 0.388 |
| | | | VT FB/No FB | -2.746* | 0.006 |
| | | | VS FB/No FB | -1.726 | 0.084 |
| | | | VT+VS FB/No FB | -1.804 | 0.071 |
| *Time* | 12.900 | 0.005 | VT+VS FB/VT FB | -1.883 | 0.060 |
| | | | VT+VS FB/VS FB | -0.314 | 0.754 |
| | | | VT FB/VS FB | -1.569 | 0.117 |
| | | | VT FB/No FB | -1.569 | 0.117 |
| | | | VS FB/No FB | -3.059* | 0.002 |
| | | | VT+VS FB/No FB | -2.510 | 0.012 |

Bonferroni correction sets the significance cut-off of Wilcoxon test at 0.0083. Only Z-values marked with * are statistically significant.

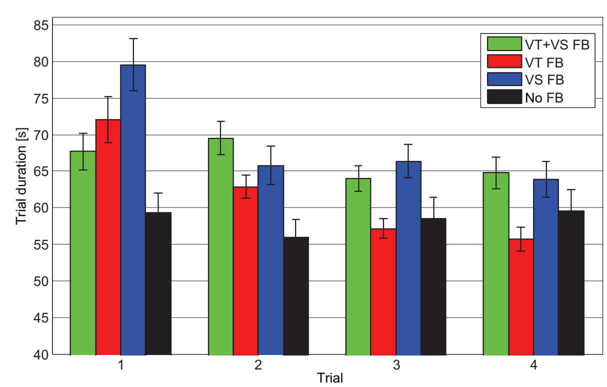


Fig. 7. Time index along trials for different types of feedback.

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