Evaluation of Force Feedback for Palpation and Application of Active Constraints on a Teleoperated System

Chapter · September 2019

DOI: 10.1007/978-3-030-31635-8_194

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Abstract. A desktop haptic device is used to teleoperate an industrial redundant and compliant robotic arm with a surgical instrument mounted on its end-effector. The master and slave devices are coupled in a bilateral position-position architecture. Force feedback is provided by the master haptic device to the user, from the position of the slave's wrist. A surgical task (palpation) that involves force feedback is presented and tested in a user study with surgeons and non-medical participants. Results show that users easily discern between three different materials during palpation given minimal familiarisation time. Active constraint enforcement is also integrated with the system as a sensitive area around the palpation samples which the slave instrument is prohibited to enter.

Keywords: Force feedback · Teleoperation · Medical robotics · Palpation · Active constraints

1 Introduction

Minimally Invasive Surgery (MIS) has become an established alternative to the conventional open approaches in a significant number of surgical fields and teleoperated surgical systems have been increasingly used in MIS procedures over the past decade providing 3D vision and better ergonomics for the surgeon. However, further developments are needed to create more sensitive robotic systems with new teleoperation interfaces to restore the dexterity and haptic feeling of open surgery, thus improving their efficacy and expanding their applicability to more complex surgical procedures. Teleoperated systems with force feedback have been used in various robotic applications over the years. However, current commercially available systems for MIS robots do not include significant haptic feedback to the operator, mainly because of the associated stability issues [1]. A significant amount of effort has been put into this research area by the scientific community. Some works look to improve the currently used RA-MIS systems like the DaVinci Surgical System by adding force feedback [2]. There is always a trade-off between transparency and stability of a teleoperated system with force feedback [3] and there are stability issues when non negligible time delays are introduced [4]. Other works investigate the combination of visual, tactile and force feedback towards the improvement of telepresence [5,6] showing that depending on the task, multi-modal feedback can improve the accuracy of perception of the remote environment.

One of the main tasks that require force feedback in remote medical examinations or MIS procedures is tissue palpation [7,8]. Our study uses a lightweight haptic device as a master and a redundant industrial compliant robotic arm with a daVinci instrument as a slave in a bilateral teleoperation architecture to evaluate the force feedback during a palpation task and test a safety feature in the form of active constraints enforcement using the methodology proposed in [9].

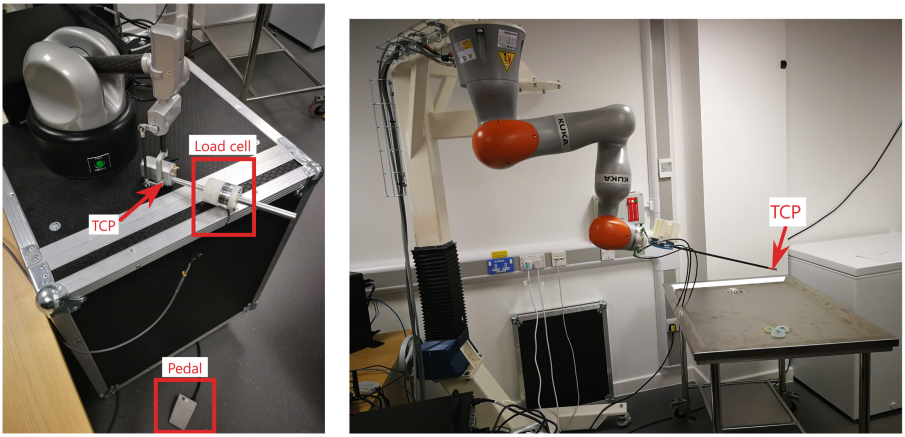
Section 2 provides the description of the teleoperated system setup; experimental results on the palpation of three different sample materials are given in Sect. 3 and a user study evaluating this surgical task is provided in Sect. 4; Sect. 5 gives preliminary results on the enforcement of active constraints around the area of palpation; the conclusion and future work are presented in Sect. 6.

2 System Description

The system is comprised of kinematically dissimilar master and slave robotic manipulators. The master arm is the Haption Virtuose 6D Desktop, shown in Fig. 1a, which is a haptic device that provides 6 degrees-of-freedom (DOF) of force feedback with continuous force of 3 N and continuous torque of 0.2 Nm. A load cell (6 DOF force/torque sensor) is mounted on the Haption end-effector to measure the force that the user applies on the master and a pedal is used as a clutch during teleoperation. The slave arm is the KUKA LBR iiwa, a serial link manipulator with 7 DOF and a payload of 14 kg. The slave arm is mounted upside down on a gantry and a daVinci Endowrist instrument with monopolar curved scissors is attached to the KUKA flange, Fig. 1b. The instrument is not actuated in this work but its wrist (the point just before the jaws) is used as the tool centre point (TCP) of the slave arm.

Bilateral Teleoperation with Force Feedback

A position-position control architecture is utilised to provide force feedback where both robots are controlled to track each other's TCP [10]; the wrist of the haptic device controls the wrist of the instrument, meaning that the force feedback is provided from the position of the instrument's wrist to the TCP of the master. The coupling gains between the two robots can be interpreted as a spring and damper between their end-effectors. Since the two robots are substantially different in terms of size and dynamics, the master-slave forces are



(a) Master haptic device: Haption Virtuose 6D Desktop with a load cell attachment and a pedal clutch.

(b) Slave manipulator: KUKA LBR iiwa mounted on a gantry with a daVinci tool attached on the flange.

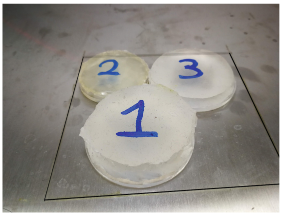
Fig. 1. Master-slave teleoperation system

scaled by a factor of 0.4 and their velocities are scaled by 1.5. This means that the movement of the slave is larger than the movement of the master and the force felt at the master is smaller than the force measured at the slave. By construction, this architecture provides to the user the external environment forces as well as the slave's controller forces which include forces associated with the spring-damper and slave inertia.

The teleoperation control loop is implemented on a machine with a real time kernel patch for Linux at a 2 ms rate. Experimental results show that any time delays introduced by the communication network between the controller and the robots do not exceed a control loop of 2.7 ms.

3 Palpation of Soft Tissue-Like Materials

First, a palpation task was considered, where the TCP of the slave was controlled to press gently and repeatedly the surface of tissue-like materials. Three samples from bolus material [11] were placed inside an area of 10.5 × 10.5 cm, as shown in Fig. 2a, and on a horizontal table within the workspace of the slave arm. The bolus material is made of a synthetic gel with specific gravity close to that of water (1.02), approximating tissue equivalence very well [11]. The properties of the samples are given in the table of Fig. 2b. Sample #2 is the softest material of the three while samples #1 and #3 are made of a stiffer material. However, because of the difference in their thickness, sample #1 feels softer than #3 during palpation.



(a) Bolus materials with properties shown in Table 2b.

Material	**Thickness**	**Young's Modulus**
#1	10 *mm*	184709 *Pa*
#2	5 *mm*	103539 *Pa*
#3	5 *mm*	171404 *Pa*

(b) Properties of the materials used in the palpation task.

Fig. 2. Materials used for palpation task

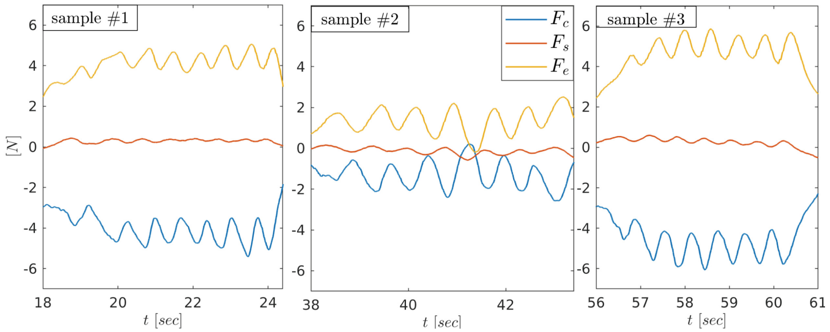
Figure 3 presents the experimental results of the task, when palpating consecutively the three samples. Figure 3a shows the z-axis components of the force as measured by the load cell at the master side (F_s), the control input to the slave (F_c) and the external environment force as estimated by the joint torque sensors of the slave (F_e). It is clear that the external forces are exerted in the opposite direction to that of the control forces of the slave, as was expected. Moreover, the force being felt at the master is much smaller since a factor of 0.4 was applied, amplifying the forces at the slave. It is also easy to see that the forces are proportional to the stiffness of the samples, as shown by their Young's modulus; the softest sample (#2) produces the smallest forces, etc. In order to better highlight this, the magnitude of each force was calculated from the recorded generalised vector as shown in Fig. 3b and the mean values for each sample are given in Table 1. Figure 3c shows the z-axis component of the position error between the master and the slave where it is clear that larger forces correspond to larger position errors and to stiffer materials. The mean value of this error is also included in Table 1.

Table 1. Mean values for each sample

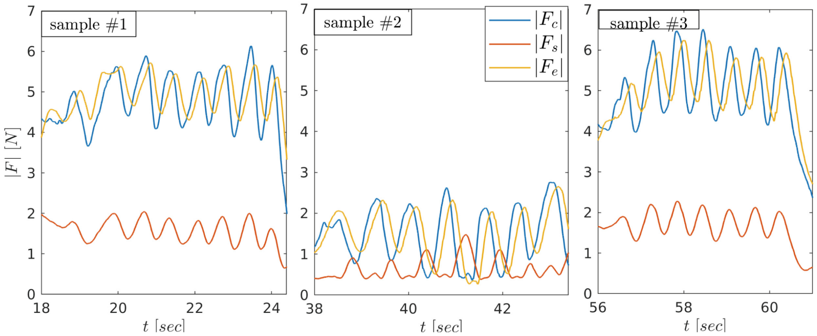
	Sample #1	**Sample #2**	**Sample #3**
$\lvert F_c \rvert$ $[N]$	4.74	1.49	4.88
$\lvert F_e \rvert$ $[N]$	4.9	1.5	4.99
$\lvert F_s \rvert$ $[N]$	1.56	0.64	1.65
$\lvert e_z \rvert$ $[m]$	0.013	0.004	0.015

4 Evaluation of the Usability and Force Feedback Perception of the Teleoperated System

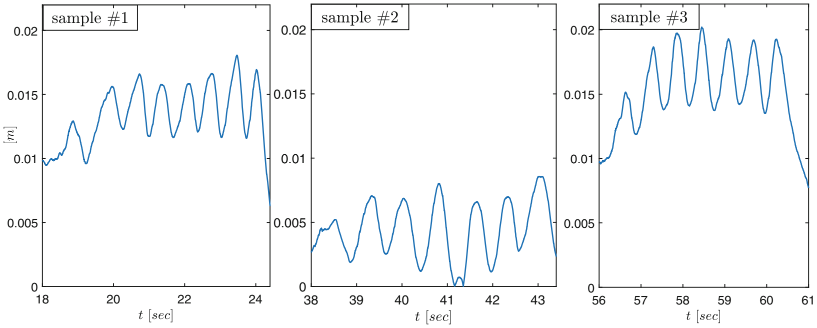
A user study regarding the palpation experiment was conducted in order to evaluate the perception of the provided force feedback as well as the ease of



(a) Applied and measured forces on the z axis. F_s is the force as measured by the load cell at the master side, F_c is the control input to the slave and F_e is the external environment force



(b) Forces magnitude

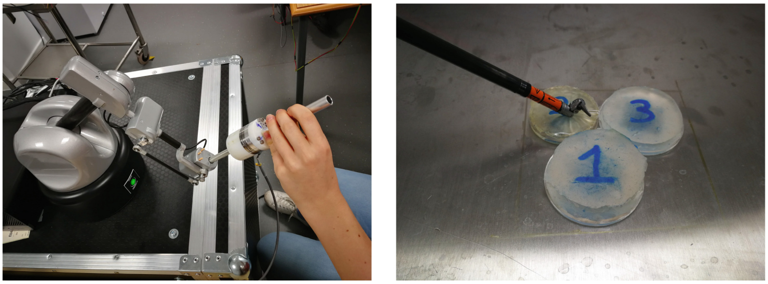


(c) Position error between master and slave on the z axis

Fig. 3. Experimental results while palpating consecutively the three samples.

use of the system. Eleven subjects were asked to perform the palpation task. Two of the users were surgeons with more than 10 years of experience in using the DaVinci surgical system, one of the users had previous experience with the developed system and most users had little to no experience with haptic feedback in virtual or teleoperated environments.

Each subject was asked to palpate all three samples one time for as long as they felt necessary to appraise the softness of each sample. Then, they were asked to repeat the procedure two more times. The choice of the palpation technique was left to the discretion of the subject. The most common technique involved pressing the wrist of the tool on the samples repeatedly while there were a few subjects who dragged the wrist of the tool across the surface of the samples (Fig. 4). All subjects were positioned at a ∼1 m distance from the operating table and had direct visual contact with the samples (i.e. not through glasses or a camera). All subjects were given approximately 2 min to familiarise themselves with the operation of the teleoperated system prior to the palpation task.



(a) User operating the master device for a palpation task.

(b) Slave in contact with soft material.

Fig. 4. User palpating sample #2

After the completion of the task, all subjects were asked to rate the softness of each sample, whether their perception changed after the first trial and the level of confidence in their final perception. They were also asked to rate the ease of use of the teleoperated system and if the provided force feedback felt sufficient.

Perception of Environmental Stiffness

Results showed that 54% of the subjects accurately perceived the order of softness of all three samples. 72% of the subjects accurately appraised sample #2 as the softest but 25% of them had difficulty discerning the difference between samples #1 and #3 due to their similar properties. Moreover, 27% of the subjects rated sample #2 as the hardest. This is because that particular sample is very soft and thin, and when applying a large force on its surface, the TCP can easily reach the bottom of the sample resulting in the user perceiving the stiffness of the table underneath instead. Only 18% of the subjects didn't feel they could easily perceive differences between the samples and were among the group that rated sample #2 as the hardest. The data collected during the trials showed that in these cases, the subjects were applying much higher forces on the samples overall, e.g. a mean value of $F_c = 9N$ and $F_s = 3N$ for the stiffest material while $F_c = 5N$ and $F_s = 2.1N$ for the softest respectively. Further discussions with the subjects after the completion of the task revealed that these cases were caused by different expectations of how a teleoperated system works.

45% of the subjects felt confident in their final perception and 80% of them were indeed accurate. 33% of the subjects that didn't feel confident were however accurate in their perception.

Ease of Use

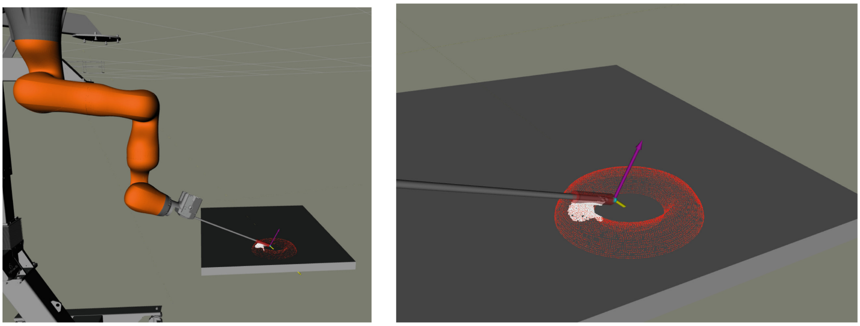
The subjects were asked to rate the ease of use of the system on a scale of 1 to 10. 72% of them rated it as more than 6 and 38% of them as more than 8. 27% of the subjects rated the system as less than 4. This was mainly because of the point of view of the user with respect to the area of operation, an issue that can be addressed by using a camera to provide a better viewpoint. Moreover, only 9% of the subjects suggested that the force feedback could be stronger while the rest were satisfied with the feeling of the force provided by the master.

5 Preliminary Application of Active Constraints Enforcement

In the previous sections, the slave manipulator had unconstrained access to the samples as they could be approached from any direction above the operating table. However, in RA-MIS procedures, this is not always the case. A core issue is to ensure the safety of the patient by minimizing the risk of unintentional tissue damage. This objective can be fulfilled by determining the forbidden areas of operation in the tissue and by constraining the instrument path within the acceptable regions. A methodology applied to this end is the implementation of active constraints.

Consequently, a virtual wall is created around the samples and active constraints are enforced to produce repulsive forces on the slave when it approaches the wall. The wall emulates a sensitive area that a surgeon using this system would not be allowed to enter for safety reasons. The repulsive forces due to the active constraints are calculated using the methodology proposed in [9]. The virtual wall is introduced as a point cloud of a torus with inner diameter 10.5 cm, outer diameter 24 cm and height 10 cm. The centre of the torus is located on the surface of the operating table meaning that its height above the samples is 5 cm.

Figure 6 shows the real world scene where the TCP of the slave is approaching the samples on the table while contacting the virtual restricted area as seen in



(a) Virtual representation of the configuration of slave while in contact with active constraints.

(b) Focus on the area of the active constraints.

Fig. 5. Representation of the slave manipulator in a virtual environment while in contact with the active constraints.

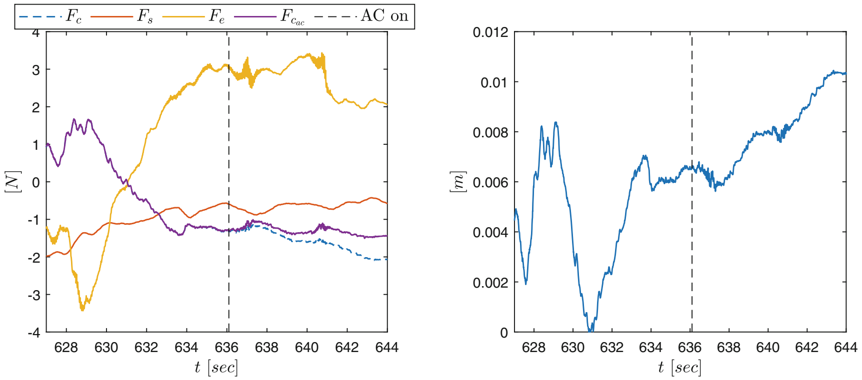
(a) Actual configuration of slave while in contact with active constraints.

(b) Focus on the area of the active constraints.

Fig. 6. Actual slave manipulator in contact with the active constraints.

Fig. 5b. Figure 5 shows the representation of the slave manipulator in the virtual environment RViz at the same instance where a portion of the tool shaft has approached the virtual wall and repulsive forces are generated. The white area consists of the virtual wall points that are activated due to the proximity of the tool shaft and are generating repulsive forces using the methodology proposed in [9]. These repulsive forces are represented by the purple arrow in the virtual environment and are added to the control input F_c of the teleoperation.

Figure 7a depicts the z-axis components, for simplicity reasons, of the system's forces, i.e. the force as measured by the load cell at the master side (F_s), the external environment force as estimated by the joint torque sensors of the slave (F_e) and the control input to the slave with ($F_{c_{ac}}$) and without the repulsive forces (F_c). The active constraints are enforced at the time instant $t = 636\,\mathrm{s}$ (dashed line in Fig. 7). Figure 7b shows the respective position error between the master and the slave. It is clear that at the same time instant, the position error increases, thus, based also on the results of the previous section, the force fed back to the user is larger once active constraints are activated.



(a) Applied and measured forces on the z axis. The dashed line indicates the time instant when the slave contacts the active constraints area.

(b) Position error between master and slave on the z axis.

Fig. 7. Active constraints enforcement results.

It is important to note that the processing related to the calculation of the repulsive forces increases the time delay of the control loop to an average rate of 6 ms. Preliminary testing showed that this delay as well as the use of a long tool on the slave manipulator narrow the stability limits of the system. In order to achieve stability, the magnitude of the force feedback was reduced. This can be displayed by the smaller magnitude of the control input force F_c with respect to the magnitude of the external force F_e in Fig. 7a compared to the same forces during the palpation experiment (Fig. 3a). Consequently, further investigation is required towards an improved experience of the active constraints.

6 Conclusion

A teleoperated system comprised of a desktop haptic device and an industrial redundant and compliant robotic arm with a surgical tool mounted on its end-effector is used in a user study for a palpation task. Results show 72% success in discerning the difference between different materials when the applied force allows for palpation on the surface of the samples. Active constraints enforcement was also applied on the system to emulate a sensitive no-go area around the palpation samples providing repulsive force feedback when in proximity. Future work will include obtaining user feedback on the active constraints enforcement, evaluation of the system when teleoperating through a trocar and investigation of stability issues related to communication and processing delays.

Acknowledgements. This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 732515.

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