TRENDS IN SURGICAL ROBOTICS

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Abstract. Surgical Robotics today is essentially about two families of devices, namely telemanipulators and simulators for mini-invasive (endoscopic) procedures. In both cases, the user–interface, *i.e.* the "joystick" to be manipulated by the surgeon is one of the key elements. Today's commercial telemanipulators still rely almost exclusively on visual feedback only. Some surgery training simulators already have haptic (or force–) feedback. It is only a question of time until most surgical robots will have haptic feedback. In this contribution, we describe trends of surgical robotics with special emphasis on the possibilities and the significance of haptic man-machine interface. Potential synergies with cognitive neuroscience are highlighted.

Key words: force feedback, haptics, telemanipulator, mini-invasive surgery, embodiment.

1. INTRODUCTION

Surgical instrumentation and surgical techniques as a whole are in the midst of a rapid and profound evolution which started already three or four decades ago with the introduction endoscopic technologies. This development has first led to Mini-Invasive surgery (MIS), sometimes called "keyhole surgery". This technique is now widely accepted in laparoscopic surgery and in most other domains as well. The next logical step has been the introduction of electromechanical telemanipulators. The best known of the commercially available systems (since now more than ten years) is the DaVinci™ Robot by Intuitive Surgical (Fig. 1), but several new systems by other makers are just about to be commercialized. Such telemanipulators are called "Surgical Robots" although they lack the main characteristic of what is typically called a "Robot", namely the autonomy (the execution of programmed or event guided motion sequences).

In spite of this key distinction to *e.g.* industrial or service robotics, everyone agrees to call surgical telemanipulators "robots", so we will not make an exception. As this contribution is entitled "Trends in Surgical Robotics", we might as well add the conviction of the authors that surgical robotics will eventually, step by step, evolve in the direction of "true" robotics by including semi-automated and later

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automated motion sequences, *i.e.* for sub-tasks such as suturing. But this will be for the more distant future. The immediate trend of robotics will include, among other, rather obvious, improvements, haptic (*i.e.* force–) feedback. That is to say that the user interface will provide at the "master" console the sensation of touching the tissue operated on by the "slave" manipulator. In the following sections, we will focus on some aspects, possibilities and implications of the introduction of haptic consoles in surgery robotics (Fig. 1).

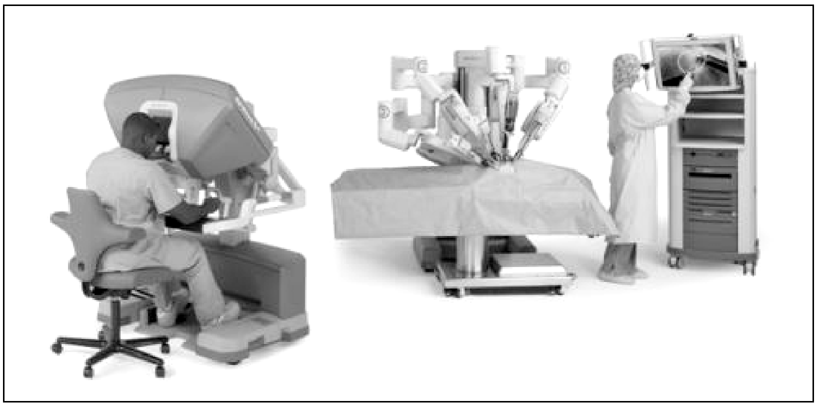

Fig. 1 – DaVinci surgical robot from Intuitive Surgical.

2. HAPTIC INTERFACE FOR TELEMANIPULATORS

There are many very different ways to design the kinematics of the handles of a master console for a telemanipulator. The number of degrees of freedom usually exceeds 14, the minimal number for two grippers or tweezers: They are the 6 positions and orientations for each "hand" plus the opening/closing of the gripper. It is obvious that such a number of degrees of freedom can only be operated efficiently if the manipulation is very intuitive. The console without force feedback of the DaVinci robot provides indeed a very intuitive manipulation, which is one of the reasons for its popularity among many surgeons and for its commercial success.

The kinematics of an intuitive handle will therefore more likely not be a joystick, but rather a kind of gripper with opening and closing motion and with the six main degrees of freedom of rigid body motion for positioning the gripper.

The essential requirements of a haptic tele-manipulator can be summed up in the requirement of a maximal Z-width.

Z-width, refers to the space between minimal and maximal impedance curves as function of frequency. Ideally, these impedances should be zero when the telemanipulator operates in free space, without contact, and infinite, when the slave hand touches a rigid wall. In reality, such ideal impedances cannot be rendered at the handle. Modelling of an ideal impact would result in instability. However through appropriate control strategies, introduced by Colgate and Brown in 1994 [7], and presented recently by Metzger, Lambercy and Gassert [8]. This last paper also describes in detail the crucial points for such requirements, namely the sophisticated velocity estimation which needs to be adapted on-line to a given impedance requirement. This defines the maximum impedance which can be rendered in a stable way by a force-feedback system.

The second important limit of a force feedback system is known as transparency. It concerns the lower limit of the z-width. It essentially means that inertias and friction losses of the telemanipulator, both on the master side as on the slave side, should not be felt. The handle will therefore aim for a low inertia design. Friction losses and on the slave side, if detectable by force sensing, can in principle be compensated by the controller. The same is true for inertias, here a dynamic model of the system along with the knowledge of the position, can allow compensation even without force sensing.

Inertia on the master side however can only be compensated if actuators are provided. This is not the case for most master consoles, where only position is measured. For high-end interfaces however, actuators will be use. In this case, the telemanipulator cannot only compensate inertias and frictions, but it can, at least in principle, also render forces at the slave side. As an actuator (usually an electric motor) is of non-neglectable mass, a parallel kinematic structure may be of advantage. In this way, the actuators can be on a fixed basis and do not need to be moved. The handle itself can have very low inertia and the (fixed) actuators can nevertheless exert strong forces.

Two examples based on this principle are the Novint Falcon and the interface (Fig. 2) handles of Force Dimension (a start-up company from our Lab LSRO).

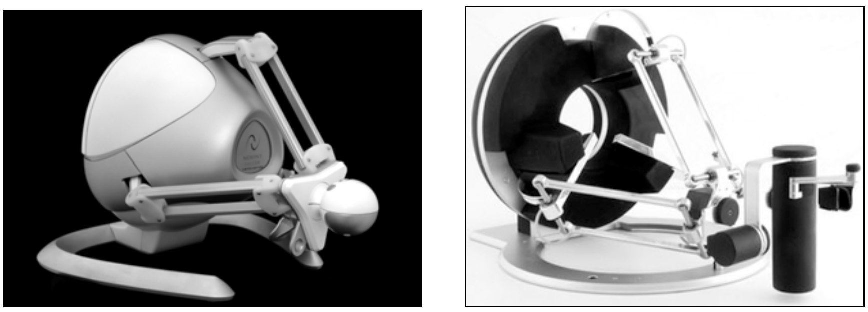

Fig. 2 – The Novint Falcon and the Force Dimension OMEGA 7, two haptic handles based on the parallel kinematic structure of the Delta Robot. While the Novint Falcon, with 3 degrees of freedom, is a game device, the Force Dimension OMEGA 7, with 7 degrees of freedom, has been developed specifically for surgery robotics.

Comparison criteria for force feedback device have been introduced by many authors. An important early contribution in this area was by Hanaford *et al.* [13], where a peg-in-hole test is used to assess performance of a 6-DOF manipulator. An optimized handle should respect the ergonomic range of motion of the human hand, considering the long (several hours) duration of surgical interventions. For safety, it should stop when the hand lets go the interface handle. Rotational force feedback is less essential than positional one. Therefore, on the delta-robot base of the Force Dimension device with the 3 DoFs *x, y* and *z*, a light-weight serial handle with only brakes in place of torque actuators could be used. Such a device was designed and realized by one of the authors (Laura Santos-Carreras), [6] and Fig. 3.

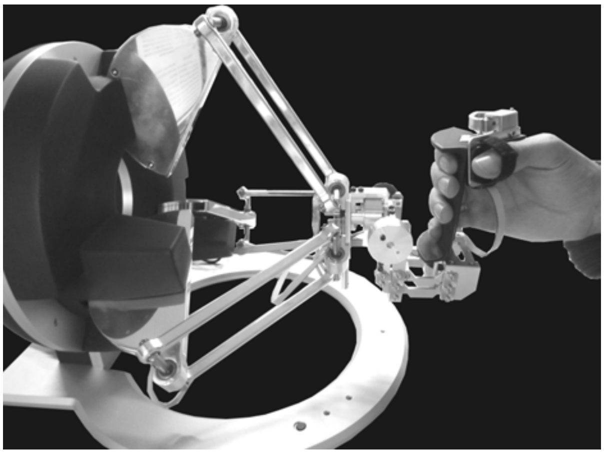

Fig. 3 – Haptic handle with pneumatic torque brakes, ergonomic motion range & contact detector.

The essential component necessary for a haptic handle, *i.e.* a handle rendering the sense of touch from the operation scene to the hand of the operator, is a force sensor at the manipulator (the slave side). In case of surgery, this force sensor will need to be integrated into a miniaturized manipulator and will have to be sterilizable or disposable. These non-trivial technological problems might be the major reason why there are not yet many haptic consoles available for surgery robotics.

3. MULTIMODAL HAPTIC CONSOLE

Up to now, we have used “haptic console” and “force feedback” as equivalent terms. Actually, force feedback is only one component of haptic feedback. There are many more dimensions (or modes) of haptic rendering. Besides force, these include essentially texture, temperature and sensations such as palpation. A combination of these, *e.g.* the loosely defined "texture" and temperature, might convey the sensation of touching a wet object. "Palpation" somehow is felt as a motion or a local change of stiffness. Together with temperature, this will convey to the surgeon the sensation of touching a nerve. We aim therefore to give the surgeon the sensation of truly touching living organic tissue.

There are surprisingly few publications on multimodal haptics and modalities such as temperature have rarely been investigated. An early example of temperature feedback is [9], 1997. A few recent papers start to investigate multimodal haptics, *e.g.* [10] and [11].

With his hands, in conventional open surgery, the surgeon could obtain a great wealth of information on the tissue manipulated by his fingers. If we succeed in restoring just a small subset of those sensations in a multimodal haptic console, the surgeon will more easily forget about the complex inner working of the telemanipulator. Ideally, he should be led into feeling as if he would be operating with his own hands. Actually cognitive neurosurgery teaches us that the sensori-motor system greatly supports such an illusion: A tool is "embodied", *i.e.* a well mastered instrument, even when complex, is efficiently modeled in the brain and feels as if it becomes part of the body. This topic will be addressed in the next section. Previous work (*e.g.* [12]) has shown how to measure tactile stimuli, but they were presented optically and not through touch at the master console.

Here we just would like to close the discussion of multimodal haptics by mentioning a project of a multimodal haptic interface combining temperature, palpation and force feedback in a single surgical master device. Temperature and palpation. We have tried each modality alone (palpation, as shown in Fig. 4, and temperature) [1, 2] and we plan to combine them in our next prototype.

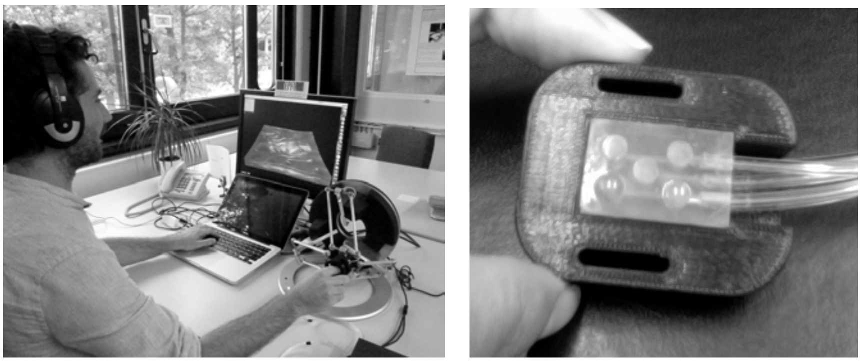

Fig. 4 – Palpation Feedback realized with five small balloons in an epoxy matrix actuated by compressed air. This device was mounted on an the OMEGA handle and used for finding a hidden artery in the piece of Virtual Reality (VR) soft tissue represented on the computer screen.

4. HAPTIC HANDLES, VR AND COGNITIVE NEUROSCIENCE

As we have just seen in the palpation example above, it is straightforward to replace the slave-side of a teleoperator by Virtual Reality (VR). This allows great freedom in designing preliminary experiments on handle design, ergonomics and efficiency, before developing the "hard" part of the telemanipulator, the miniaturized and instrumented slave manipulator. This possibility of quickly running complex experiments in telemanipulator operation is especially interesting for assesement of the tool "embodiment" described above. Efficient tool embodiment, *i.e.* adaption by the sensori-motor system of the surgery tool as part of the body, is essential for optimal performance of the surgeon, just as a master musician has "embodied" his instrument.

It turns out that the combination Haptic-Handle – VR represents a novel and very promising track for exploration of embodiment. Classical neurological experiments in this domain, such as the cross-modal congruency effect and other related topics can be realized in a very efficient manner. In [3] we present experimental results acquired with the MIMICS interface, developed by Dr. Marc Vollenweider, an LSRO PhD. The MIMICS haptic interface is now commercially available as training tool for the Da Vinci robot. It consists of a frame with two tweezer-like handles mounted on incremental rotational sensors and fixed each by four cables in tetrahedrical arrangement. The cables are actuated by fixed motors in the basis. A head-mounted display provides 3-D vision of the scene to be manipulated. In our experiments, this scene consists of simple tasks to be accomplished in a VR setting. In the experiments described in [3], the effect of cross-modal congruency on embodiment was tested (Fig. 5).

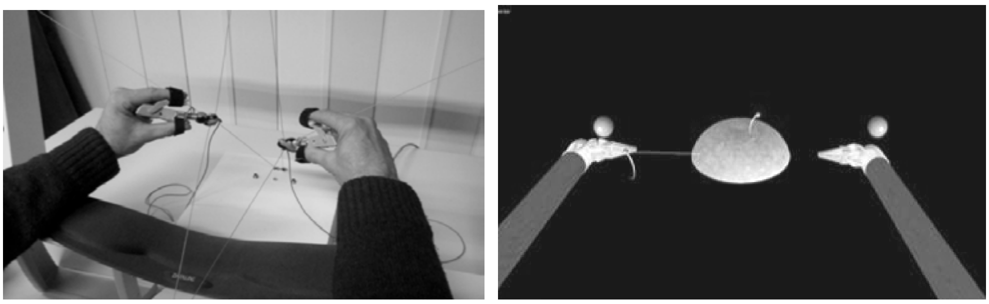

Fig. 5 – Testing cross-modal congruency with a master console operating in VR. The congruency of optical and tactile stimuli could be turned "on" (congruent stimuli) or "off" (contradiction between haptics and vision). The effect on embodiment was then assessed. See details in [3].

5. SURGERY SIMULATORS

With the VR replacing the real operating theater, we have moved from a fully operational surgical telemanipulator to a training simulator. Indeed, the VR may represent a generic patient's organs for all kinds of training or, in the near future, the anatomy of the actual patient for pre-op planning. Indeed, at the present time, the training demand is even greater for non-robotic mini-invasive surgery (MIS) than for the still relatively new (and expensive) robotic surgery.

Haptic interfaces are a key component of MIS training simulators. Several such simulators have been developed at LSRO or its start-up company xitact (now merged with Mentice, Sweden), or have been licensed to other producers (Virtamed, Zürich, Surgical Science, Sweden). These training devices include, in chronological order, simulators for laparoscopic surgery (Fig. 6 [4]), hysteroscopy (Fig. 7 [5]), radiology (xitact), colonoscopy.

Fig. 6 – Simulator for laparoscopic surgery with force feedback (xitact SA, Morges).

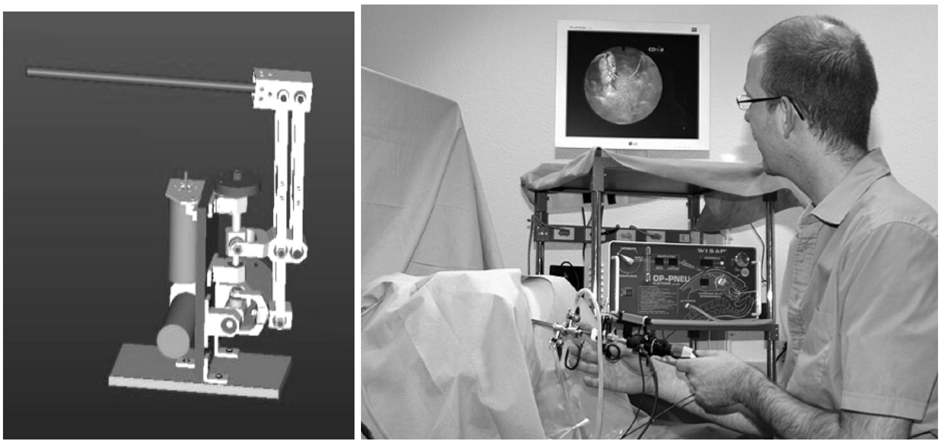

Fig. 7 – Simulator for hysteroscopy (Virtamed SA, Zürich).

6. CONCLUSIONS

Haptic human-robot interface are particularly important for improving robotic surgery telemanipulators. They may contribute to give a very realistic “feel” to the surgeon, although he is operating through a telemanipulator. Such multimodal interfaces will include force-feedback, palpation and temperature. They can be used not only for robotic surgery, but also, when combined to a virtual reality operating scene, for surgery simulators. In this VR setting, they are also most interesting as a tool for research in cognitive neuroscience. By studying the mechanisms of embodiment, it will become possible to develop more performing man-machine interfaces, especially for remote handling tasks such as robotic surgery. For all these reasons, it is believed that haptic interfaces will be one of the main directions of development in the near future trends in surgery robotics.

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