COMPARATIVE OF HAPTIC INTERFACES FOR ROBOT-ASSISTED SURGERY

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Abstract: This paper presents a comparative of different non-specific haptic interfaces that could be used for robot-assisted surgery. The purpose of this analysis is to determine which master interface has the best performance for a specific task in which the master-slave scale factor is less than one. Three haptic interfaces have been considered: two commercial masters, one with serial configuration, the PHANToM 1.5 prototype master, and one with spherical setup, the Microsoft Force Feedback 2 Sidewinder; and other one non commercial with a parallel architecture designed in our laboratory, the Magister-P. Two experiments performed to measure the fidelity of the haptic interfaces have been described and the results obtained have been discussed on this paper.

1 INTRODUCTION

Robot-assisted surgery has became a new research focus of the robotics community during the last years. The followed objective is to develop “a partnership between man (the surgeon) and machine (the robot) that seeks to exploit the capabilities of both to do a task better than either can do alone” (Taylor et al., 1991). Telesurgery and surgical simulators belong to this new robotics area. Telesurgery allows surgeons to perform remote surgical operations using robots and haptic interfaces. On the other hand, surgical simulators are based in virtual environments where the surgeon uses a haptic interface to control the medical robot. These virtual environments incorporate accurate and reliable mathematical models of the human body part that is going to be operated and of the rigid bodies of the medical apparatus involved. Surgical simulators can be applied to surgical training (Kühnapfel et al., 2000), avoiding the use of other expensive learning techniques as experiments with cadavers, and to biomedical research. In addition, these surgical simulators become an indispensable tool in telesurgery, since any action performed by the surgeon over the patient can be verified in the simulator before it would be executed by the remote robot.

Nowadays, a great research effort is being made on the robot assisted surgery, and several universities and enterprisers have presented their developments with applications on orthopedic, microsurgery, laparoscopy,...(Cleary and Nguyen, 2001). Nevertheless, as it is suggested on (Taylor and Stoianovici, 2003), it is necessary to made significant advances on several aspects, like the interface technology, where better surgeon-machine interfaces are needed. The work presented here is focused on this aspect, and it presents some discussion of a comparative analysis of different general purpose haptic interfaces that would be able to be used as robot-assisted surgery input devices. Although near almost the actual developments use particular devices designed for an specific task, as for example the Laparoscopic Engine of Immersion for endoscopic surgical systems, our interest is made such tasks with general purpose haptic interfaces, so we can take benefit of the different kinematic structures of master and slave to improve the ergonomics and/or the manipulability of the surgical tools. Two of the used interfaces are commercially available, while the third one has been designed in our laboratory.

To our knowledge, there are not many research works in the literature that analyzes which haptic interface achieves a better behavior in determined surgical interventions. Some work has been done trying to obtain general indexes that help us to classify the performance of haptic devices (Moreyra and Hannaford, 1998),(Hayward and Astley, 1996). The purpose of the current analysis is to discuss the desirable characteristics of a haptic interface to be used for robot-

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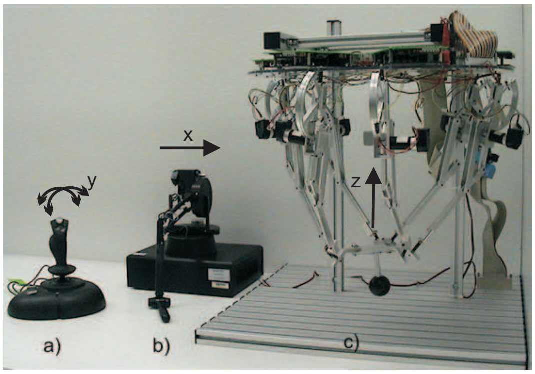

Figure 1: Masters considered in the analysis: Microsoft Force Feedback (right), Phantom (center), and Magister-P (left).

assisted surgery.

The paper is organized as follows. Section 2 describes the three haptic interfaces that have been used in the comparative analysis, explaining its characteristics. The experiments performed and the results obtained are showed in section 3. Finally the main conclusions of the paper are summarized in section 4.

2 MASTER INTERFACES FOR ROBOT-ASSISTED SURGERY

In this section, the three haptic interfaces used on this work are presented. All the experiments are limited to a 1 DOF of the interfaces, trying to mimic the force sensed on the movement along the axis of a typical endoscopic device. We assume that a minimally invasive surgery (MIS) is simulated. In MIS the operation is performed with instruments and viewing equipment inserted in the human body through small incisions (typically less than 10mm in diameter). The main advantage of this technique is the limited trauma to healthy tissue, reducing the post-operative hospital stay of the patient (Ortmaier, 2002). However this technique has a difficult learning process since the surgeon must learn to navigate using visual information provided by cameras with non orthogonal optical to the scene observed.

The three master used are the low-price spherical Microsoft Force Feedback (MMF- fig. 1 - a)), the well known 6 d.o.f. serial arm Phantom master 1.5 Prototype (fig. 1 - b)), and a parallel configuration device, the Magister-P (fig. 1 - c)). The spherical and the serial master are commercially available, while the parallel master has been designed in our laboratory (Sabater et al., 2004). All devices incorporate force feedback. Force feedback improves the task performance in spite of the necessity of having a measure of the force/torque sensor in the robot that executes the operation. Without force feedback, the forces that the surgeon feels only depends on the master characteristics, independently of the remote environment situation. This way, e.g., the surgeon can not determine the quantity of forces to exert in a suture operation if only exists visual feedback.

On many of the recent developed systems, the force reflection is neglected. This could be accepted by the moment that, in a real classic MIS technique, the real forces sensed by the surgeon are minimal. Nevertheless, if our future goal is not to copy the classical MIS techniques, but to give the surgeon new tools that allow him to increment the useful information that way the surgical procedures can be improved, it is necessary to have an accurate force reflection system.

About the number of DOF, the Phantom and Magister-P masters have 6 DOF, while the Microsoft Force Feedback master has only 3 DOF (spherical motion with 2DOF force feedback). Therefore any device have the same number of DOF that the laparoscopic instrument (4 DOF). Next, how these masters can be used in an endoscopic operation is explained:

Microsoft Force Feedback Master. This device has only 3 DOF to control the 4 DOF of the laparoscopic slave, so the use of additional master buttons is necessary. The ascend and descend motion of the tool can be achieved with the motion of the joystick Y axis (fig. 1-a)). In this way, the force feedback is possible when the tool interacts with the deformable object. The Z-axis rotation movement can be achieved with the Z-axis joystick rotation movement, and the XY rotation movement of the tool around the fulcrum point can be achieved with the movement XY of the joystick at same time a button is pressed.

Phantom Master. At this device it is necessary to constraint (or neglect) 2 DOF in order to control the 4 DOF of the surgical tool. The ascend and descend motion of the tool can be linked with the Z movement of the Phantom final effector. The Z-axis movement can be achieved with the Z-rotation of the Phantom, and the fulcrum XY rotation can be represented by the XY translation movement of the device. That way 2 rotation DOF of the effector of the Phantom are neglected.

Magister-P Master. The ascend and descend motion of the tool corresponds to the Z movement of the lower platform (fig. 1-c)). The 3 orientation DOFs of the surgical tool are given by the orientation of the lower platform. The X and Y position of the final effector are neglected, and are only used to increase the ergonomic feeling of the surgeon.

The most important features of the devices that are related with the task they are going to be used are summarized on table 1.

Table 1: Main features of used devices

	MFF	Phantom	Magister
DOF	3	6	6
Configuration	Spherical	Serial	Parallel
Prog. Interface	DirectX	Ghost	C-interface
Range Forces	0-4 N	0-8.5 N	0.3-90 N
Bandwidth	$\approx$ low	1000Hz	320 Hz
Linearity at low range	no linear	almost linear	no linear

The three master devices have enough bandwidth for the designed experiments. Nevertheless, for a high fidelity haptic rendering, devices must have at least 300 Hz or higher, so the MFF is not an appropriate device. Besides, the DirectX library does not permit to modify the frequency of the haptic loop. All the same, the designed experiments try to measure the performance of the kinesthetic rendering (at frequencies lower than 0.5 Hz) in a low velocity task, as a surgical operation, so the three devices are valid ones from the point of view of bandwidth. Mechanically speaking, the Magister-P has some fabrication errors that make that we need to overcome a friction threshold to render forces.

3 EXPERIMENTAL RESULTS

At this section the setup of the comparative experiments is explained. The results are plotted and some comments for their use as master devices in an endoscopic robotic surgery are made.

Two psychophysical kind of experiments have been performed over a group of users with previous experience with the three master devices. Users have made each experiment twice, with at least one day between them. A total of 10 users (6 male and 4 female) have done a number of 40 experiments. The goal of the first group of experiments is to get data of the force/torque interaction of the surgeon with the master device, measuring the minimum force sensed, what is related with the capability of detecting little deformations on a deformable tissue. Similarly, the second group of experiments tries to determine the minimum difference on the increment of force/torque that can be sensed, what is related with the ability of distinguish between similar tissues.

Forces and torques are needed to be introduced to the devices to make the experiments. In the Phantom case, the Ghost library allows directly to program them in cartesian space. In the Magister-P case, our own library takes care of the calibration test to allow a direct input of forces/torques in cartesian space. Nevertheless, in the MFF case, the DirectX library does not allow to introduce force/torque values on cartesian or joint spaces. Instead of that, the own library units are used. That way, a previous experiment of dynamometry-calibration to find the relation of these units with the force values must to be done. Next, each one of the experiments is detailed and the results are plotted.

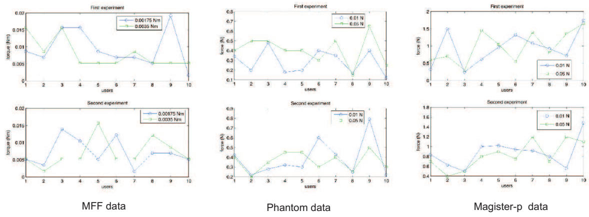

Figure 2: Experiment 1 results

3.1 Minimum sensed force value

On this experiment, starting with a null value of the displayed force/torque, the value is being increased each 2 seconds a determined value F_{inc}/τ_{inc} until the users is being able to sense the force, recording the value of this force. The process has been made with two different increment values for each master. Figure 2 shows the results of the minimum force experiment. Some remarkable aspects are:

- The first time the experiment is done (upper part of figure 2), the operators use to detect the force earlier when the increment is the higher one. Besides, there are significant differences when the increment is one or another.
- The second time the experiment is done (down part of figure 2), the difference between the two increments is reduced, and the torque is detected earlier in general.
- In the Magister-P experiments, the minimum value is above 0.4 N, due to the friction threshold that this device has.

3.2 Minimum increment of force perceived by the user

The goal of this experiment is to get the minimum difference between consecutive forces that a user can feel. This experiment tries to evaluate the ability of the devices to display the changes on the stiffness of the tissues.

To make this experiment, an initial force/torque nominal value (F_{nom}/τ_{nom}) has been chosen for each

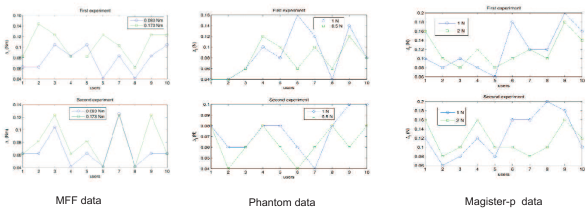

Figure 3: Experiment 2 results

master. This value is kept constant during a period of time (at least one second) and next the force/torque increment (F_{inc0}/τ_{inc0}) is added to this value and rendered. If the operator feels the increment, the value of the increment is reduced a certain quantity (F_{red}/τ_{red}), and the experiment in repeated with the new values. This process is repeated while the operator feels the increment. The last value of increment is noted as a result. Figure 3 plots the results obtained on the two experiments made with the different masters. The average data are:

- In general, users detect a lower torque increment (Δ_τ) when the nominal initial value is the lowest.
- On the second experiment, the values are lower than in the first one.

3.3 Comparative aspects

Some conclusions can be obtained from the previous experiments:

- In the fist experiment, in all the devices, when the increment of forces is small enough, and working in low frequencies, some users get used to this increment, and they do not detect the force until its value is significantly higher than when the increment is given in bigger steps. This is because the human sensors that work at low frequencies are fast adaption sensors, and they get used to the new value of the force.
- The mechanical configuration of the devices plays an important role in the ability of the users to feel forces. The workspace is also a key parameter. The ability of translation in the Phantom and in the Magister-P provokes that the user can move his hand, hiding some forces, and so that force values are smaller on the spherical configuration.
- In all the cases, on the second turn of the experiments, values are smaller, due to the experience acquired by users on the first turn.

4 CONCLUSION

A comparative analysis of general purpose haptic devices in a robotic assisted surgery environment has been made. The studied devices are not task-specific devices, and they can be used on other teleoperation tasks.

All the master devices have the capacity of rendering forces to the operator. Using this feature, the comparative is focused on this rendering ability, and it tries to determine the minimum change in the stiffness of a tissue that could be perceived by the operator-surgeon. For that, the experiments have been limited to the input of a determined force/torque on an axis for each device.

Future work must include the rendering of forces on arbitrary directions, considering the isotropy of each device. Besides, the workspace and the ergonomics of each device are also parameters that must be included on a deeper study.

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