EXPERIMENTAL VALIDATION OF AN INNOVATIVE HAPTIC SYSTEM FOR SURGICAL ROBOTICS

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ABSTRACT. In this paper a novel system design for haptic master-slave control of surgical robots is presented. The design is based on both force-reflecting and DRC control schemes. Experimental results are included to show the capabilities of the proposed solution, using the DAANS master-slave robotic system for Minimally Invasive Radio-Surgery. A wide range of operative conditions are analyzed experimentally. The controller is aimed at safety, since the controller inhibites the motion of the slave device without the operator's grasp. Therefore unwanted slave motion are avoided, even when it is subject to environmental force.

1 INTRODUCTION

In the last decade, there has been a growing awareness, within the medical community, of the benefits offered by using robots in various surgical tasks. In particular, Minimally Invasive Surgery (MIS) is a cost-effective alternative to open surgery. Basically, the same operations are performed using instruments designed to enter the body cavity through several tiny incisions, rather than a single large one. By eliminating large incisions, trauma to the body, post-operative pain, and the length of hospital stay are significantly reduced. However, new problems connected to the use of robots in surgery have arisen, since there is no direct contact with the patient. For this reason, it is necessary to develop suitable devices to provide surgeons with the perception of directly operating on the patient. Such a result can be achieved by using force feedback systems, in which the force applied to patient's tissue is fed back to a robotic device (haptic master) directly operated by the surgeon.

Medical robotics has found fruitful ground especially in neurosurgical applications, owing to the accuracy required by the high functional density of the central nervous system [1]. In past decades, several different robotic neurosurgical devices have been created. A comprehensive survey can be found in [2].

We have developed a master-slave haptic system for neurosurgery which falls into the second area. The surgical robotic system is based on a modified Neuromate robot in such a way that it can easily and accurately move a miniaturized *x*-ray source. Even if the system would be able to perform fully automated procedures, the surgeon controls every single motion of the robot in a master-slave, tele-operated manner, with force-feedback from the surgical tool. The master-slave solution permits highly safe conditions during treatment and it is the only control scheme accepted by the Ethic Committees of the hospitals where the robotic system is under test.

This papers introduces a new force-reflecting controlled for master-slave haptic systems. The main feature of the controller is the ability to faithfully reproducing on the master side of the force measured by the slave system, allowing at the same time to precisely control the position of the slave device. This kind of controller merges the structures of Force-Reflecting controller and DRC scheme, which are briefly recalled in Section 2 and 3. In comparison with these two controllers, the proposed system does not produce any unwanted motion of the master device in the presence of a force measured by the slave device when the master device is not operated (i.e. when the surgeon does not grasp the master knob). This feature increases by a notable extent the safety of the closed-loop control system. The results of extensive experimental tests are provided in Section 5, where the behavior of the novel control system is tested in several different operative situations. In particular, master only, master-slave operation with virtual environment, master slave with real environment are investigated carefully and experimental results are analyzed. All the results have been obtained using the DAANS master-slave robot [5], but the field of possible application of the proposed system is much wider, since it can be easily applied to most master-slave robotic devices.

2 THE ROBOTIZED RADIOLOGICAL TREATMENT

The PRS (Photon Radiosurgery System by Carl Zeiss®) is a miniaturized radio-surgical device for Interstitial Radiation (IR) with radioisotopes [3, 4].The device emits low energy *x*-rays from the tip of a cylindrical probe. From the point of view of radiology, the IR with PRS aims at delivering a necrotizing dose of radiation in the tumor volume, thus minimizing the dose in the surrounding tissue. The use of PRS in neurosurgery provides considerable advantages over traditional techniques [3, 4]. Specifically, compared with conventional radio-surgery, IR with PRS provides dosimetric advantages, since adjustable dose rates and steep dose gradients can be obtained by adapting the electron acceleration potential.

The use of robotic systems to position, orientate and guide the PRS and other surgical tools into the brain can obviously guarantee a much higher level of accuracy than classical stereotactic head-frame based techniques. Undoubtedly, precision, accuracy, repeatability and force control are all critical features in surgical procedures, and in particular in PRS IR, not only because erratic motion can be very traumatizing, but also because any deflection of the PRS probe has to be avoided in order to prevent the dissipation of the beam energy and, consequently, a drop in the therapy's beneficial effects. Probe deflections are chiefly caused when the probe makes contact with the skull of the patient. The above considerations provide evidence that the robotic systems that are suitable for neurosurgical interventions by PRS, besides being very accurate, must allow real-time measurement of the contact force between the surgical tool and the tissue touched. The contact force has then to be fed back to the surgeon through the interface used to guide the tool's insertion.

This is the robotic configuration adopted in the robotic system for neurosurgery (named DAANS) developed by our Research Group [5]. This system includes a haptic master module (Figure 1), operated by the surgeon and a slave module (Figure 1), able to move the PRS along a linear trajectory which can be controlled by rotating the knob of the master device.

During a typical procedure, a commercial 5-axes robot (NeuroMate by Renishaw, UK) is used to bring the slave module (DAANS) close to the insertion point and give the correct orientation to the surgical tool. Following this, the Neuromate's task is over and the insertion of the tool into the brain is entirely executed by the slave module. This procedure allows the motion of the robotic system as a whole to be decoupled into the Neuromate "gross" motion and the slave "fine" motion, and enhances the system's safety and performance. The high precision ensured

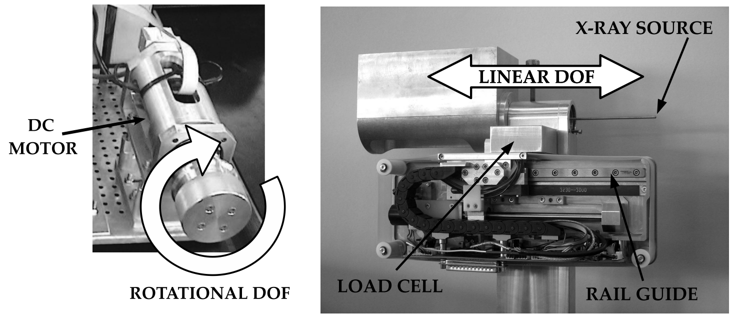

FIGURE 1: DAANS - Master haptic knob (left), Slave system (right)

by DAANS in the positioning of the tool improves the outcome of stereotactic neurosurgical procedures. As mentioned above, DAANS has been designed to perform interventions in teleoperation mode. The surgeon moves the master handle determining the longitudinal position of the PRS, and perceives a force feedback proportional to the contact force between the PRS and the brain. As a result, the surgeon is given the sensation of directly operating on the patient.

A load cell is integrated on the support holding the PRS (Figure 1), which allows the measurements of the contact force between the surgical tools and brain tissue. This signal is read by the controller in order to provide the surgical task performed by the surgeon with a realistic feeling. A linear encoder measures the position of the PRS. The master unit is the device on which the surgeon operates. It is made up of a haptic knob. The knob is a 50mm cylinder connected to a torque-controlled DC motor. The knob angular displacement is measured by an incremental encoder mounted on the motor shaft. A NI cRIO-9014 embedded system is used as the controller for the whole system. By operating the master handle, the surgeon moves the tool actuator and feels the interaction force between the surgical instruments and the cerebral tissue. Therefore, the control system has to manage the signals passing from the environment to the surgeon and vice versa. Clearly, meeting all the control requirements defined above makes the design and tuning of the control a very challenging task: it has to both assure robust and stable position control for the slave, as well as force control for the master. The control scheme here proposed draws inspiration from the classical Force Reflection architecture and the Delayed Reference Control scheme introduced in the next sections.

2.1 CLASSICAL BILATERAL FORCE REFLECTING CONTROLLER

Sense of touch and force feedback are important features that have to be created in order to develop an effective haptic interface and improve the performance of medical procedures or clinical skills [6, 7]. In master-slave teleoperation using a force-reflecting human-machine interface (HMI), two basic control architectures are proposed in literature: position-position and position-force [8, 9, 10] schemes. In the first case, the slave-environment interaction forces are reflected to the user's hand merely by minimizing the difference between master and slave positions. Slave-environment or hand-master contact forces are not measured. On the other hand, the position-force architecture establishes a bilateral controller by exploiting the measurements

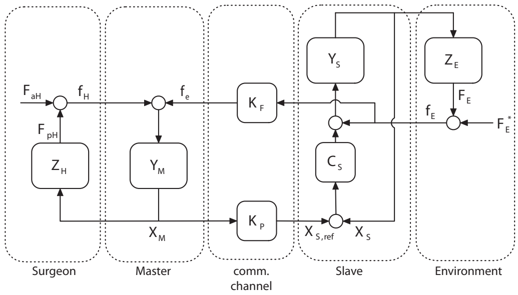

FIGURE 2: Direct Force Reflection (DFR) control scheme

of master-side and/or slave-side force sensors. Compared to the position-position method, the fidelity and reliability of haptic teleoperation is enhanced. The most common implementation of position-force scheme is the Direct Force Reflection (DFR) architecture. This method features a force sensor to measure the interactions between the slave and the environment. The measured signal, suitably scaled, is then transmitted to the master to close a force loop (e.g. [11]).On the other hand, the slave is controlled to follow the position of the master. In such a controller, while the perception of free motion is still less than ideal (the user feels the small inertia of the master when the slave is not in contact), perfect force tracking is attained. In Figure 2 the DFR controller is depicted. The human effect is modeled by the Z_H impedance block, Z_E represents the impedance of the environment and Y_M and Y_S are the admittance of the master and slave interfaces. The controller of the slave is represented by the C_s block.

When the surgeon grasps the haptic handle, his/her impedance closes the force-position loop. This kind of controller allows for an accurate reproduction of force sensation, but its main drawback is that when the operator releases the grasp on the master device, unwanted feedback forces are produced on the master side. This feature can lead to poor performance and represents a source of instability (Figure 2).

For this reason a new control scheme, able to provide a good haptic sensation and a high safety degree, has to be designed.

3 DELAYED REFERENCE CONTROL

The Delayed Reference Control (DRC) [12, 13]is a non time-based controller usually adopted in trajectory following and path control problems. In a traditional control system (time-based controller), the reference signal is time-dependent. In the DRC structure, on the other hand, the reference trajectory depends on the state of the plant, instead of the current time. The status of the plant together with the external conditions set the value of a suitable parameter of the controller that plays the role of a pure time delay for the reference signal. In this way, the reference input can be considered as a sensitive parameter and not only as a function of time; this parameter is directly affected by the sensor measurements and the state of the plant. The structure of the DRC scheme differs from that of traditional controllers, as it is shown in Figure 3. The DRC scheme can be seen as a position controller where the reference x_R is generated by a suitable planner that changes on-line its action. The inputs of the planner are the time t and the plant status z

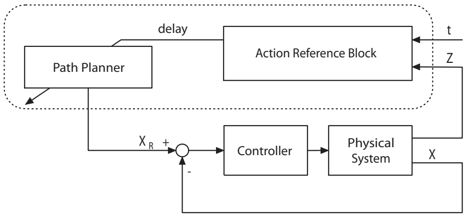

FIGURE 3: Scheme of a DRC controller

respectively. Further details on the DRC control can be found in [13].

4 A NEW FORCE-REFLECTING CONTROL

The new control structure can be thought as a Force-Reflecting position-based control scheme for the master device. The reference force that has to be applied to the master is generated through a virtual wall whose stiffness and position change continuously. The position of the wall follows the reference signal generated by a DRC controller, so that the resulting force on the master matches the value of the interaction force between the end effector of the slave system and the environment.

This control system avoids all the problems that can occur when the haptic system is active and the surgeon releases the handle of the master. Moreover, it can maintain satisfactory haptic capabilities. In order to explain this control scheme and its properties, suitable models of the physical system and the human operator have to be defined.

The master device is an extremely simple haptic knob. It comprises an electric motor, a knob and a position transducer. Therefore, its dynamics can be modeled by the equivalent inertia J_M and mechanical damping b_M, as shown in Figure 4. In this work the effects of the operator's hand have been approximated by a simple spring-damper coupling, by using the results and the model proposed in [15, 16]. This model allows to ignore the dynamics of the operator's hand and focus the attention on the grasping forces. Therefore, the mechanical impedance of the operator's hand can be modeled trough the spring stiffness k_H and the viscous coefficient b_H.

The positions of the master and the hand are x_M and x_H, respectively. As it is shown in Figure 4, X_H can be thought as the input to the system: any change in its value generates a suitable force on the master, through the spring-damper coupling.

The new controller merges the classical structure of a Force-Reflecting controller (the interaction forces between the slave and the environment are measured and then fed back to the master) and the DRC scheme, which uses the sampled forces f_e and f_a as sensitive parameters for the *active reference block* (Figure 4).

By referring at the Figure 4, the new control scheme can be explained easily. When the operator handles the knob, any change in the hand position, x_H, causes the force f_H on the knob, through the spring-damper coupling. The effects of this force can be modeled as a disturbance for the position control loop of the master. Therefore, the position controller acts to reduce this disturbance, by producing a suitable force f_a. The "DRC" element generates the actual reference $x_{M,ref}$. It receives as inputs the desired force f_e (related to the measured interaction force between the slave and the environment) and the torque command, f_a. This signal creates

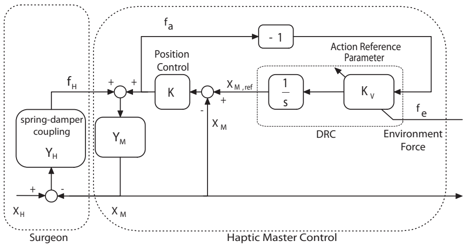

FIGURE 4: Scheme of the new force-reflecting controller

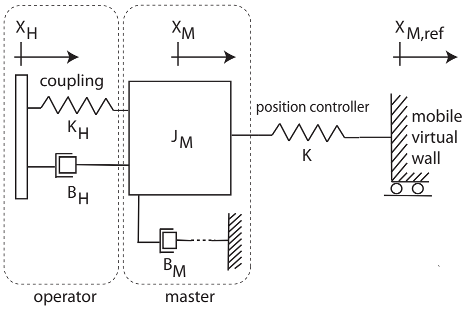

FIGURE 5: Simplified mechanical model of the overall system

the velocity reference for the master, once it has been amplified by a suitable gain k_V. Eventually, an integrator transforms the resulting signal to the reference position, $x_{M,ref}$.

In particular, k_V depends on the value of f_e. As such, this gain changes as the interaction force between the slave and the environment. The effect of this controller can be understood also by looking at the simplified mechanical model of the closed-loop depicted in Figure 5.

The reference $x_{M,ref}$ is the position of a virtual wall. This wall is connected to the master through the position control block (usually a simple PID). In our system, this controller is a modifiable proportional gain k. As such, it has been modeled as a spring. If we are able to modify the position of the wall quite quickly, the desired resistive force to any operator's movement can be created. In other words, the force that the operator must apply to move the master from its current position depends both on the position of the virtual wall, $x_{M,ref}$, and the stiffness of the spring, k. The force felt by the operator on his hand changes according to the position of the virtual wall and the value of the proportional gain k.

Accordingly, in the absence of the grasp or when the operator action is missing, the controller stays in its steady state, because the input command is null and the position error $x_H - x_M$ and the f_H signals fall down to zero. Therefore, if f_H has been zeroed, the system quickly reaches the target condition ($x_{M,ref} - x_M = 0$), through a suitable tuning of K. In such a situation, the signal f_a quickly falls toward zero and any further variation of f_e has no effect on $x_{M,ref}$ which, in turn, stays in its steady state. Consequently, any accident or unwanted force signal measured on the slave when the surgeon is not grasping the master knob does not generate any motion. Therefore the control system is enabled only by a surgeon's command. A possible drawback that affects this kind of controller is that in this manner the operator can feel the force on the slave only when he/she tries to change the slave position. However, the safety condition has been greatly improved.

4.1 SYNTHESIS OF THE SYSTEM EQUATIONS

The new controller makes the behavior of the overall system depend on two parameters only: K and K_V. In this section, the main transfer functions of the system will be evaluated.

Let the operator's position, x_H, be the input and the master position, x_M, the output. Therefore, the transfer function between the displacements of the operator and the master, $G_p(s)$, can be obtained as:

$$G_p(s) = \frac{x_M(s)}{x_H(s)} = \frac{b_{1,2}s^2 + b_{1,1}s + b_{1,0}}{a_{1,3}s^3 + a_{1,2}s^2 + a_{1,1}s + a_{1,0}} \tag{1}$$

where:

$$\begin{aligned} b_{1,2} &= b_H \\ b_{1,1} &= b_H k k_V + k_H \\ b_{1,0} &= k k_V k_H \\ a_{1,3} &= J_M \\ a_{1,2} &= b_M + b_H + J_M k k_V \\ a_{1,1} &= k + a_M k k_V + k_H + k k_V b_H \\ a_{1,0} &= k k_V k_H \end{aligned} \tag{2}$$

The force felt by the operator depends on the master displacements through the spring-damper coupling. Consequently, it is useful to evaluate how a position displacement $\dot{x}_H$ affects the behavior of the force signal f_H:

$$G_f(s) = \frac{f_H(s)}{\dot{x}_H(s)} = \frac{b_{2,3}s^3 + b_{2,2}s^2 + b_{2,1}s + b_{2,0}}{a_{1,3}s^3 + a_{1,2}s^2 + a_{1,1}s + a_{1,0}} \tag{3}$$

where:

$$\begin{aligned} b_{2,3} &= b_H J_M \\ b_{2,2} &= b_H b_M + J_M k_H + b_H J_M k k_V \\ b_{2,1} &= b_M k_H + b_H b_M k k_V + J_M k k_V k_H + h_H k \\ b_{2,0} &= k k_H + b_M k k_H k_V \end{aligned} \tag{4}$$

The operator handles the master device by turning its knob. Owing to the kinematic structure of the human wrist (i.e. limited range of the wrist torsion), this action can be thought as taken between two rest conditions: (1) the knob is grasped at the beginning of the movement and then (2) released at the end of the wrist torsion. Therefore, the curve that represents this movement over the time can be approximated by a straight line with a suitable slope. As such, in order to analyze the behavior of f_H, it is convenient to approximate the input command x_H with a linear ramp or its velocity $\dot{x}_H$ with a step. The Final Value Theorem states that, with such an input, the steady state force f_H is:

$$f_H(t \to \infty) = A(b_M + \frac{1}{k_V}) \tag{5}$$

where A is the velocity step amplitude. Consequently, after the transient condition, only k_V affects the performance of the system, because both the gain of the velocity input (A) and the damping b_M can be considered constant. Moreover, being b_M generally in the order of 10^{-3} Nms/rad, its contribution is not negligible only in case of very low forces, hence when the human perception does not allow to distinguish small differences.

4.2 TUNING OF THE SYSTEM GAINS

The accuracy of the kinestetic sensation is directly related to the readiness of the system to an input command.Starting from the mechanical model and neglecting in a first approximation the damping terms, that can be reasonably assumed much smaller than the others, the force equation is:

$$f_H(t) = J_M \ddot{x}_M(t) + k(x_{M,ref}(t) - x_M(t)) \tag{6}$$

In Eq. 6 the first term $J_M \ddot{x}_M(t)$ can be reasonably neglected because, in general, the inertia J_M is designed to be small (e.g. in the order 10^{-5} kgm^2) and the acceleration signal $\ddot{x}_M(t)$ is very low since the position signal can be assimilated to a linear ramp. By considering that:

$$x_{M,ref}(t) = -\int k_V f_a(t)dt \tag{7}$$

and studying the loop that generates $x_{M,ref}$ (see Figure 4), the simplified relation between the haptic force f_H and the position x_M can be computed as:

$$f_H(s) = -f_a(s) = \frac{ks}{s + kk_V} x_M \tag{8}$$

The time response when a velocity step is applied as input, is:

$$f_H(t) = \frac{A}{k_V}(1 - e^{\frac{t}{T_i}}) \quad with \quad T_i = \frac{1}{kk_V} \tag{9}$$

The readiness of the system depends upon the time constant T_i: the smaller T_i, the more ready the system. Remembering that the haptic force feedback is inversely proportional to the k_V parameter (Eq. 5), the tuning of the overall system must consider this constraint. The idea is to set the time constant in order to maintain the same readiness in all the working conditions. Consequently, the goal is to change k according to the variation of the external force signal in order to maintain T_i constant.

Now, considering that the human perception is upper bounded at $30 - 50$ Hz [17, 18], the bandwidth of the system has been suitably chosen as 100 Hz. With this choice the time constant T_i results be equal to 0.01 s and the ratio between k and k_V becomes $k = \frac{100}{k_V}$. In order to obtain a good haptic sensation it is necessary to scale the force signal measured on the slave to realize a suitable ratio from the real force and the applied resistance to movement at the master side.

The velocity reference for the master $\dot{x}_{M,ref}$ (Figure 4), is given by the product between f_a and k_V. k_V is directly related to the interaction force between the slave and the environment. According to Eq. 5, to have a suitable force sensation, k_V has to be inversely proportional to the velocity signal. Due to this relation, the *action reference parameter* of the system depends on the time (through the velocity term) and on the external condition variations (through the f_e signal).

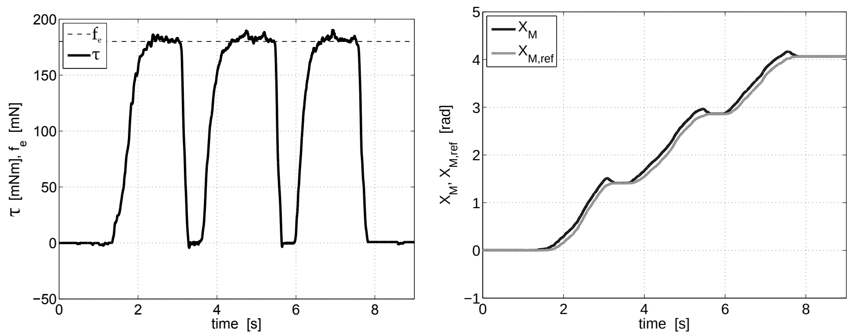

FIGURE 6: Experimental test with constant f_e

5 EXPERIMENTAL TESTS AND RESULTS

In order to test the capabilities of the new controller some experimental tests have been carried out. The experimental setup consists of the DAANS master-slave haptic system, controlled by a NI-9014 cRIO. All the software running on the cRIO is implemented using LabVIEW 2009.

5.1 EXPERIMENTAL EVALUATION OF THE CONTROLLER PERFORMANCE

In this section the results of several experimental tests conducted on the DAANS master-slave system are reported. The tests are aimed at showing the correct and accurate behavior of the controller in different operative conditions.

The first experimental test presented here involves only the master element of the robotic system. In this case, the target is to produce a constant torque on the master knob when it is rotated in clockwise direction. In order to prove the readiness and the accuracy of the system, the external force f_e is set to a constant value and the torque fed back to the operator τ is evaluated when the operator acts on the haptic knob. In this test, the time constant is set as $T_i = 0.02$ s and the control loop runs with at 1 kHz refresh frequency, i.e $T = 1$ ms. Clearly, in order to use the force f_a as a reference for the torque τ, a scaling factor must be used. In this case the scaling factor is unitary, but its value can be tuned to reproduce a suitable range of haptic forces. In Figure 6 the measured signals are reported. x_M represents the angular position of the master knob. The value of τ (i.e. the feed-back torque) responds in a fast manner to a step variation of the input. It can be noticed how the haptic force τ falls rapidly to zero when the knob is not moved. In the same figure it can be clearly noticed how the position $x_{M,ref}$ "follows" the master position x_M, and how the difference between the two signals falls to zero when the knob is not operated. The reference torque is set to $f_e = 180$ mNm.

In Figure 7 the experimental results of an interaction between the haptic knob and a virtual elastic wall are presented. This test is provided in order to show that the proposed controller can give an accurate force feedback perception also if the reference force signal f_e is continuously changing. Moreover, this test can faithfully simulate the interaction between the slave end effector and an elastic object. In this case, the force reference signal f_e is directly proportional to the

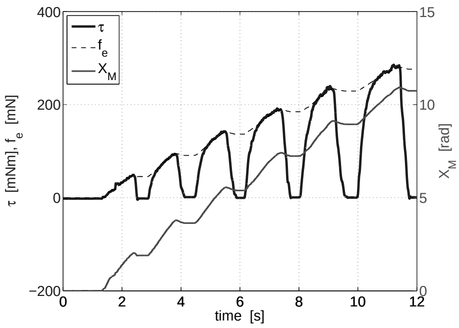

FIGURE 7: Experimental test with virtual elastic wall

master knob position x_M. As it is visible in Figure 7, the haptic force τ reaches the value of f_e rapidly when the knob is rotated. After each movement of the knob, the operator released the handle of the master. It is clear from Figure 7 that no torque is produced by the master actuator when the knob is not operated and that the stability of the closed-loop system is preserved in such a situation, even if the external reference force f_e is nonzero.

The third experimental test involves the haptic knob and the DAANS system in master-slave operation. The external interaction force between the end-effector of the slave and the environment is measured through the load cell. When there is no command or the slave end-effector is not touching anything, no force is fed back on the operator's hand as the f_a signal is null. When the surgeon is not acting on the knob, the force signal quickly falls down to zero. This demonstrates again that the controller is active only in presence of the human's command. When the value of x_M decreases, the force fed back to the operator is null, due to the implemented control that sets the forces to zero according to the direction of motion. By looking at the force signal f_e that comes from the slave, it can be seen how, besides a small coupling effect between the load cell and the position signal that can be considered as a disturbance, the two force signals have similar characteristics demonstrating the effectiveness of the controller in rendering the feedback sensation.

Again, the feedback torque τ can track the force measured by the load cell (through a scaling factor equal to 10) with high accuracy and with a fast rising time. The response of the system is very similar to the one revealed in the previous test case, meaning that the control system is not affected by the noise which affects the force measure f_e.

6 CONCLUSIONS

In this paper a new control system for haptic master-slave operation has been presented. The novel solution allows to operate a remote device and to feel the interaction force between the slave system and the environment. The design of the new control system is aimed at safety, since it inhibites the movement of the master device when the operator leaves the grasp on it. The Real-TIme control prototype has been developed using FPGA technology and the DAANS robotic system for neurosurgery. Extensive tests are reported here to show the accuracy in providing the

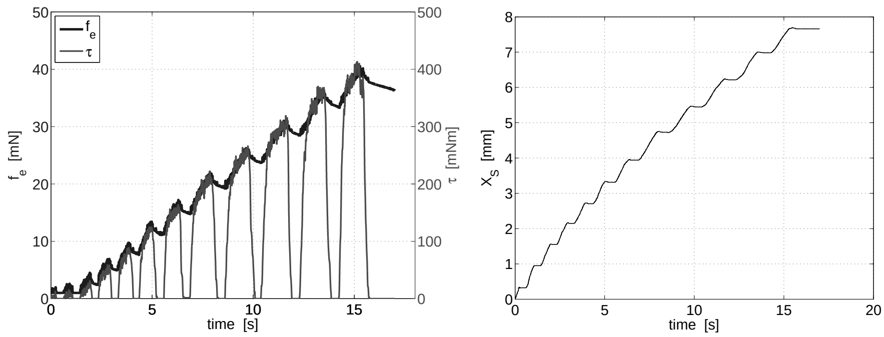

FIGURE 8: Experimental test in master-slave operation: interaction with an elastic wall. Comparison of measured external force f_e and feedback torque τ

user with correct feedback sensation.

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