A Delayed Force Reflecting Haptic Controller for Master-Slave Neurosurgical Robots

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Abstract

This paper presents a new force-reflecting control system for master-slave haptic devices. This controller has been implemented and tested on the robotic systems for minimally invasive neurosurgery developed by our Research Group. Robot-assisted surgery is a very valuable treatment, since it allows to benefit of the high precision, accuracy and repeatability of robotic devices. The proposed controller is meant to be used for master-slave haptic robotic surgery, but it can be used for any device that provides haptic feedback. The new controller merges the paradigms of Force Reflection (FR) control and Delayed Reference Control (DRC). Unlike FR control, the proposed solution enhances the safety since it does not allow an unwanted motion of the slave device once the operator releases the haptic controller. Experimental tests are provided to show the capabilities and the performance of the controller. Closed-loop stability is investigated both theoretically and experimentally. The analytic results on stability impose a limit on the ratio between the measured contact force and the sampling frequency of the closed-loop controller.

Keywords: haptics; force reflection; Minimally Invasive Surgery; surgeon training

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. Therefore, the interaction between robotic systems and surgeons is causing a new worldwide interest in the fields of medicine and robotics. At present, this co-operation between engineers and physicians leads to considerable innovations. Surgeons can make use of new capabilities to perform less invasive and more accurate interventions. 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. Both arthroscopic [1] and laparoscopic [2] devices can be used in this kind of procedures, as well as interventional radiology [3]. 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 between the surgeon and 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 (through the slave device) is fed back to a robotic device (haptic master) directly operated by the surgeon.

Medical robotics has found fruitful ground especially in neurosurgical applications, as testified by the large number of applications presented in [4, 5, 6, 7, 8, 9, 10]. In past decades, several different robotic neurosurgical devices have been created. A comprehensive survey can be found in [7]. Today's robot projects focus on three major areas of improvement [7]: increasing the P. Boscariol, A. Gasparetto, R. Vidoni, V. Zanotto A Delayed Force Reflecting Haptic Controller for Master-Slave Neurosurgical Robots Advanced Robotics 29(2), pp.142-156 (2015)

overall accuracy of the classical stereotactic systems, increasing the added-value of the equipment, enhancing the capabilities of the surgeon.

We have developed a master-slave haptic system for neurosurgery [11] which falls into the second area. The surgical robotic system is based on a modified Neuromate robot [12] 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 allows 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, since the surgeon can directly feel if the probe is in contact with tissue with a different stiffness, like blood vessels.

This paper introduces a new force-reflecting controller for master-slave haptic systems. The main feature of the controller is the ability to faithfully reproduce on the master side the force measured by the slave system, allowing at the same time to precisely control the position of the slave device. This controller merges the structures of force-reflecting (FR) controller and Delayed Reference Control (DRC [13, 14, 15, 16]) scheme, which are briefly recalled in Section 2 and 3. In comparison with the FR 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). Such a feature increases by a notable extent the safety of the closed-loop control system. Stability is discussed theoretically in Section 5 and experimentally in Section 6.2. The results of extensive experimental tests are provided in Section 6, where the behavior of the novel control system is tested in several different operative situations. All the results have been obtained using the DAANS master-slave robot [17], 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 (e.g. Phantom [18], or the systems developed in [8, 9]).

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 [19, 20, 21]. 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 tip currently used has a sharp blade. This, in conjunction to the presence of an auxiliary d.o.f. that allows to rotate PRS source around the needle main axis, give the opportunity to treat tumors with irregular (i.e. non spherical) shape. For a more detailed reference on the topic, see [11].

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. Given the evidence that the robotic systems that are suitable for neurosurgical interventions by PRS, besides being very accurate, they must allow real-time measurement of the contact force between the surgical tool and the tissue under treatment. The contact force has then to be fed back to the surgeon through the interface used to guide the tool's insertion [22]. Moreover haptic systems, in connection with virtual reality devices, can be a valuable tool for the training of surgeons [23] and also for the evaluation of the skills of the surgeon [24].

This is the robotic configuration adopted in the robotic system for neurosurgery (named DAANS) developed by our Research Group [11]. Te system includes a haptic master module (Figure 1), operated by the surgeon and a slave module (Figure 2), able to move the PRS along a linear trajectory which can be controlled by rotating the knob of the master device.

A load cell is integrated on the support holding the PRS (Figure 2), 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

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Figure 1: Master haptic knob



Figure 2: DAANS, slave system

feeling. A linear encoder measures the position of the PRS. The master unit is the device on which the surgeon operates by turning 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. 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. 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 Bilateral Force Reflecting Control

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 [25, 26]. 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 [27, 28, 29] schemes.

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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 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. [30, 31, 32, 33, 34]). 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 3 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. f_E represents the environmental force signal, which is due to the exogenous contribution F_E * and the contribution F_E related to the impedance of the environment Z_E .



Figure 3: Direct Force Reflection (DFR) control scheme

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 3). 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) [13, 14, 35, 36] 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. This is a special case of event-based control architectures, where an action reference block is inserted in the loop to change, at run-time, the reference signal, according to the state of the plant.

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. The structure of the DRC scheme differs from that of traditional controllers, as it is shown in Figure 4. 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 respectively. Further details on the DRC control can be found in [14].

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Figure 4: Scheme of a DRC controller

4 A new force-reflecting controller

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.

The master device, represented as Y_M in Figure 5, is a 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 6.

In this work the effects of the operator's hand, represented as Y_H in Figure 5, have been approximated by a simple spring-damper coupling, by using the results and the model proposed in [37, 38]. 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 through 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 5, 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.



Figure 5: Block diagram of the new force-reflecting controller

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 5). By referring at the Figure 5, i.e. the simplified mechanical model of

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Figure 6: Simplified equivalent mechanical model of the overall system

the system, the new control scheme can be easily explained. 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 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 equivalent mechanical model of the closed-loop system system depicted in Figure 6. 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 on the stiffness of the spring, k. The force felt by the operator 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 is 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.

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. The transfer function between the displacements of the operator and the master, $G_p(s)$, can be obtained as:

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

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where:

$$b_{1,2} = b_H b_{1,1} = b_H k k_V + k_H b_{1,0} = k k_V k_H a_{1,3} = J_M a_{1,2} = b_M + b_H + J_M k k_V a_{1,1} = k + a_M k k_V + k_H + k k_V b_H a_{1,0} = k k_V k_H$$
(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 :

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

where:

$$b_{2,3} = b_H J_M b_{2,2} = b_H b_M + J_M k_H + b_H J_M k k_V b_{2,1} = b_M k_H + b_H b_M k k_V + J_M k k_V k_H + h_H k b_{2,0} = k k_H + b_M k k_H k_V$$
(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.

Therefore, it can be pointed out that the kinestetic sensation, i.e. the torque returned to the haptic knob, depends only on the k_V parameter.

4.2 Tuning of the system gains

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:

$$f_H(t) = J_M \ddot{x}_M(t) + k(x_{M,ref}(t) - x_M(t))$$
(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 5), the simplified relation between the haptic force f_H and the position x_M can be computed as:

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

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

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

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 [39, 40], 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 devlop a suitable ratio between the real force and the applied resistance to movement at the master side.

The velocity reference for the master $\dot{x}_{M,ref}$ (Figure 5), 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 (f_e) . According to Eq. 5, k_V has to be proportional to the velocity signal to have a suitable force sensation. 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).

5 Stability

In this work, the stability analysis have been carried out by considering constant or slowly variable external forces. In such cases the k_V parameter, that depends on f_e , can be treated as a constant and the master can be considered decoupled from the slave device. Thus, the stability of the new haptic control scheme can be analyzed by using the Colgate's Theorem [41]. The operator is modeled as a passive two-port element. Therefore, no further hypothesis on the value of the operator's parameters (b_H and k_H) must be formulated.

The first step consists on redrawing the control structure in a more useful form, able to account for the nature (continuous or sampled) of all the signals in the control loop. Therefore, the control scheme can be redrawn as in Figure 7. In such a figure, the master position x_M , provided by the optical encoder, is sampled by the controller every T seconds. Therefore, x_M^* is the sampled version of x_M . The block M(s) represents the transfer function between the force applied to the knob and its speed. F_P and F_A represent the passive and active forces applied to the knob by the operator, respectively. The position controller C(z) and the reference governor W(z) are two discrete transfer functions defined as follows:

$$C(z) = k W(z) = \frac{T}{2} \frac{z+1}{z-1} k_V$$
(10)

Therefore, the transfer function between the sampled master displacement and the torque command is:

$$H(z) = \frac{\tau_z}{x_M^*} = \frac{2k(z-1)}{kk_V T z + kk_V T + 2z - 2}$$
(11)

The holder (H_0) makes piecewise continuous the controller's action. Now, the overall system takes the form of the Colgate's Theorem [41]. The Theorem states that, with the mentioned hypothesis about the operator's impedance Z, the necessary and sufficient condition for the stability is:

$$b_M > \frac{T}{2} \frac{1}{1 - \cos(\omega T)} \operatorname{Re}\left[(1 - z^{-1}) H(z) \right]$$
 (12)

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Figure 7: Control scheme redrawn for applying the Colgate's Theorem

for all $0 \le \omega \le \frac{\pi}{T}$, where $z = e^{i\omega T}$. By rewriting this condition for our problem, the constraint is:

$$\frac{kT}{\sqrt{c_1^2 + c_2^2}} < 1 \tag{13}$$

for all $0 \le \omega \le \frac{\pi}{T}$, and where:

$$c_{1} = b_{M}(kk_{V}T + 2)\sin\omega T$$

$$c_{2} = b_{M}(kk_{V}T + 2)\cos\omega T + b_{M}(kk_{V}T - 2) + kT$$
(14)

Straightforward manipulation leads to the following condition:

$$\frac{1}{k_V} < 2\frac{b_M T_i}{T} = f_{H,\max} \tag{15}$$

Since $1/k_V$ modulates the force felt by the operator, the condition sets an upper bound for the reflected force. This bound can be increased by adjusting the sample frequency and/or the rise time T_i . The smaller the sampling time T, the greater the upper bound. In the same way, the slower the system response, the greater the upper bound. The existence of an upper bound for f_H will be experimentally shown in Section 6.2.

6 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.

6.1 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

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Figure 8: Experimental setup

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. Environmental force is reproduced on the master side only when opposing the direction of motion, in order to render the resistance to penetration. In Figure 9 the signals recorded during an experimental test are reported. x_M represents the angular position of the master knob. The value of τ (i.e. the fed 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. Here the knob is operated at a comfortable speed, at around 1 rad/s, but as it will be shown later, the performance of the controller is almost not affected by the speed of x_M .

In Figure 10 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 master knob position x_M . As it is visible in Figure 10, 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 10 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. Here the DAANS end-effector is moved towards an elastic element, in this case a sponge rubber sheet. This material can give a faithful emulation of the elastic behavior of cerebral tissue. The results of this test are presented in Figure 11. Three signals are shown: the measured position of the master knob x_M , the force command given to the actuator of the master for creating the haptic sensation (τ) and the scaled force (f_e) that, in this case, is measured by means of the load cell mounted on the end-effector of the slave. The position of the slave system is governed by a fast PID control loop. Master knob position x_M acts as the

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Figure 9: Experimental test with constant f_e

position reference signal $x_{S,ref}$ for this loop. In this way, the slave position can track faithfully the knob position. This is the configuration used during surgical operations, since it allows to control the position of the slave system and also to feel the resistance force encountered by the probe.

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. The ratio between the perceived force τ and the measured force f_e can be suitably modified in order to adjust the perceived stiffness on the master side.

Again, the feedback torque τ can track the force measured by the load cell (through a scaling

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Figure 10: Experimental test with virtual elastic wall

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 influenced by the noise which affects the force measure f_e .

6.2 Experimental evaluation of stability limits

Further results are presented in this section to provide an experimental evaluation of the stability limits of the proposed control systems. The stability condition in Eq. 15 states that for a given force f_e , the unstable operation is encountered if the ratio T_i/T is set too small. To give an approximative evaluation of this limit, a large number of experimental tests has been performed. A summary of the most significant results is provided in Figure 12. The graph indicates if the closed-loop control has shown to be stable or not for different values of the reference force f_e and of the time constant T_i . The stable operative point are indicated with a circle, while the unstable ones are shown with a square marker. The tests have been performed in this way: first the master knob is rotated at a constant speed, so that the haptic force is felt by the operator. Then, the knob is quickly released. Stability is considered to be reached if the haptic torque τ falls to zero quickly and x_m is steady. In all the other cases, the operative point must be considered as unstable. It can be seen that the stability limit is well represented by a straight line that passes from the origin of the (T_i, f_e) plane, in agreement with the stability condition of Eq. 15. Clearly this evaluation is not meant as a true experimental validation of Eq. 15, but is meant to show that, given two fixed values for f_e and T, there is a lower limit on T_i with regard to the stability of the closed-loop system.

The measure of the torque produced by the haptic knob τ and of the master knob position x_M are shown in Figures 13, 14, 15 as well as the reference force f_e for three different operative points. The first test, whose results are presented in Figure 13, shows a clearly unstable behavior. Such a test, which is shown in Figure 12 with the letter A, has been performed with $f_e = 200$ mNm and $T_i = 0.01$ s.

As it is clear form Eq. 15, stability can be reached by either (or both) lowering the value of f_e or increasing the time constant T_i . The test B, reported in Figure 14, shows how a stable operation can be obtained simply by halving f_e , i.e. with $f_e = 100$ mNm and $T_i = 10$ ms. Otherwise, stability can be reached from the operative point of test A by doubling T_i , i.e. with $T_i = 20$ ms and $f_e = 200$ mNm. This is indicated as the operative point C in Figure 12. For this test, the plot of τ and x_M with respect to time are shown in Figure 15.

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Figure 11: Experimental test in master-slave operation: interaction with an elastic wall. Comparison of measured external force f_e and feedback torque τ

7 Conclusion

In this paper an innovative Delayed Force Reflection control system for master-slave haptic devices has been presented. The proposed solution merges the structure of DRC control and FR control. This controller has been developed in order to improve the performance of intervention in minimally invasive robot-assisted surgery. Indeed, the proposed system has been studied and tuned to provide a good haptic sensation, stability and, in the meantime, a high degree of safety. In particular, by implementing the proposed innovative controller on the neuro-surgical master-slave robotic devices developed by our Research Group, the stability limits and the haptic performance have been investigated. Experimental tests show the effectiveness of the system both in case of simulated clinical procedures and of neuro-surgical interventions. Analytic results show that the stability of the closed-loop system is guarantee if a proper ratio between the measured contact force and the closed-loop sampling frequency is ensured. Future work will cover an extensive evaluation of the performances of the system in a clinical environment.

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Figure 12: Experimental validation of stability region

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Figure 13: Experimental validation of stability region: test with $f_e = 200$ mNm, $T_i = 0.01$ s - Test A

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Figure 14: Experimental validation of stability region: test with $f_e = 200$ mNm, $T_i = 0.02$ s - Test B

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Figure 15: Experimental validation of stability region: test with $f_e = 100$ mNm, $T_i = 0.01$ s - Test C

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