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A Passive Force Amplifier

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Abstract— **The proposed robotic system provides the surgeon with an augmented sensation of the interaction forces between the instrument and the organ. Such a system aims at increasing the surgeon's dexterity for tasks requiring that only small forces be applied on the organ (eg. for micro-surgery).**
In the proposed setup, the surgeon manipulates a handle mounted on the instrument. This is a comanipulation system because the surgeon and the robot simultaneously manipulate the instrument.
The proposed control scheme allows an augmented force control: the control law ensures that the instrument applies on the organ the same forces that the surgeon applies on the handle but decreased by a scale factor. As a consequence, the forces sensed by the surgeon are the forces between the instrument and the organ amplified by a scale factor. This control scheme is proved stable thanks to a passivity study. Indeed, passivity analysis is a useful tool for the stability analysis of a robot interacting with the environment.
Experimental results are presented on a robot dedicated to minimally invasive surgery.

I. INTRODUCTION

In the context of robotic surgery, the surgeon and the medical staff have to interact with the robot. Depending on the surgical task, the degree of cooperation can be really different. Simple tasks may be realized by the robot, in an autonomous way, under the surgeon's supervision. For example, the surgeon defines the desired positions via an interface and the robot moves to these positions. However more complex tasks require the surgeon's judgment and, thus, cannot be performed autonomously by the robot. These tasks require that the robot works in cooperation with the surgeon. The surgeon's skills are thus improved as the robot increases his dexterity. To do so, one of the possibilities is robot's force control. For instance, in minimally invasive surgery, a robotic device could be used in order to display manipulation forces back to the surgeon. Indeed, since the instruments are manipulated through a trocar and because of the friction in the trocar, the surgeon looses the sensation of the interaction forces between the instrument and the organ and his dexterity is thus reduced. An other application of force control that could increase the dexterity of the surgeon is force scaling. Indeed, for precise manipulation tasks, a robotic device could provide the surgeon with an augmented sensation of the interaction forces between the instrument and the organ.

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Comanipulation appears to be a good solution to overcome these problems. Comanipulation is a direct interaction between the surgeon and the robot: the instrument is manipulated simultaneously by the surgeon and by the robot. The main difference between comanipulation and teleoperation is that no master arm is needed to impose displacements to the robot. So the complexity and the cost of a comanipulation system may be lower since it involves only one mechanical system. Moreover, the use of a comanipulation system may be more intuitive for the human operator.

Different approaches have been studied concerning the comanipulation. Some systems are able to impose virtual constraints to the surgeon's gesture which restrain the tool into a delimited area of the task-space and forbid the access to critical zones.

In [1], the *Acrobot* system is used to assist the surgeon during an operation of knee replacement. The main feature of this system is to impose virtual constraints on the surgeon when he/she cooperates with the robot. When the task has been defined with the planning software, the manipulator is able to move freely the robot to the operations area. If the surgeon moves the tool outside the defined path, the robot applies forces on the user to modify the current trajectory. It has been clinically proven that the preparation of bones surfaces are more accurate comparing to a classical operation. Once again, no force control is performed with this system.

Moreover, some systems can exploit a measure of forces. Therefore, there is no need to use models of contacts to obtain the measure of distal forces. It is also possible to derive constraints which are directly based on the forces applied by the surgeon on the organs.

In [2], a force controller is used so that the surgeon can guide the robot. The surgical tool is attached below a force sensor mounted on the robot's wrist. The force controller uses the measured forces to provide the reference to an inner velocity control loop. When the desired force is null, any applied force on the instrument causes the robot to move in the direction of this force. So, the surgeon can guide the robot by holding the tool.

In the same manner, the *Surgicobot* system [3] allows the surgeon and the robot to manipulate the same drilling instrument for maxillo-facial interventions. The surgeon can freely move the instrument except in some predefined space where the robot generates restrictive forces in order to

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prevent the surgeon from moving the instrument too close to vital nerves.

In [4], [5] and [6] augmented comanipulation approaches are presented: the surgeon holds a handle mounted on the robot and the robot manipulates the instrument in a way such as it exerts on the organ the same force that the surgeon applies on the handle, but scaled-down. Three different control laws using an inner position/velocity control loop are compared in [6]. The best results are obtained with an adaptive control law involving the estimation of the environment's compliance. However, when the contact with the environment is lost, the estimation becomes problematic. Another disadvantage of this control law is that it requires differentiation of the force applied by the surgeon on the handle which is a noisy signal.

Even if benefits presented in the above references are important (e.g. gesture's accuracy or the increase of system's safety), none of these systems allow the surgeon to feel an amplified version of the distal forces acting between the tool and the organ.

In this paper, we present a control scheme for augmented comanipulation with force feedback. The main advantages of this control law is that it does not require any knowledge of the environment nor differentiation of a noisy signal. This approach is an extension of previous works [7] realized in our laboratory.

The first part of this paper is devoted to the proposed control law for augmented comanipulation. This control scheme is proven stable thanks to a passivity study in the second part. Experimental results with a robot dedicated to minimally invasive surgery are presented in the last part.

II. Augmented Comanipulation

A. Principle of the Approach

We present hereafter a robotic device in order to assist the surgeon for accurate manipulation tasks requiring human judgment and involving small interaction forces between the surgical tool and the organ. Therefore, the proposed device allows an augmented comanipulation. It is a comanipulation system because the surgical instrument is held simultaneously both by the surgeon and by the robot. We call it augmented because the robot is controlled in such a way that the surgeon is provided with an amplified sensation of the interaction forces between the instrument and the organ. As a consequence, the instrument applies on the organ the same forces that the surgeon would apply in a transparent mode but decreased by a scale factor. This device can also filter the surgeon's tremor in order to increase the accuracy of the task. This approach supposes that the reference forces provided by the surgeon and the interaction forces between the instrument and the organ may be measured separately. Therefore a handle equipped with a force sensor (force sensor 2) is mounted on the instrument (see figure 1). The surgeon manipulates this handle and the force sensor 2 measures the forces applied by the surgeon on the instrument at point O_2. Note that w_e and w_s are respectively the wrench applied by the instrument on the organ at point O_1 and the wrench applied by the instrument on the surgeon at point O_2. Assuming that the transformation between the frame $\mathcal{F}_1$ and the frame $\mathcal{F}_2$ is known, we can compute the wrench $-w_u$ applied by the surgeon on the instrument at point O_1 in $\mathcal{F}_r$ linked to the fixed robot base frame: $-w_u = \mathbf{T_{12}}(-w_s)$.

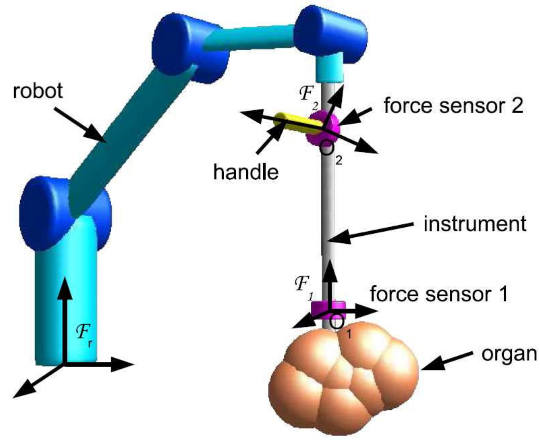

Fig. 1. Setup for augmented comanipulation

$$\text{with:} \quad \mathbf{T_{12}} = \begin{bmatrix} \mathbf{I_3} & \mathbf{0_3} \\ -[O_2O_1]_\times & \mathbf{I_3} \end{bmatrix}$$

where $[O_2O_1]_\times$ denotes the skew symmetric matrix associated with the vector from O_2 to O_1 expressed in the basis of frame $\mathcal{F}_r$.

With these notations, as detailed in subsection II-C, the aim of the proposed approach is to control the robot such that $w_u = -\frac{1}{\beta} w_e$ where $\beta \in]0;1]$ i.e. the surgeon feels the forces applied by the organ on the instrument, $-w_e$, amplified by a scale factor $\frac{1}{\beta} \geq 1$. The proposed control scheme is presented in the following subsection.

B. Proposed Control Scheme

The robot dynamics is modeled by the general form:

$$\mathbf{M}(q)\ddot{q} + C(q,\dot{q})\dot{q} + \Gamma_v\dot{q} + G_g(q) = \tau - \tau_e - \tau_u \qquad (1)$$

where $q \in \mathbb{R}^n$ denotes the joint positions, $\mathbf{M}(q)$ is the positive definite symmetric inertia matrix, $C(q,\dot{q})\dot{q}$ is a vector grouping the Coriolis and centrifugal joint torques, $\Gamma_v\dot{q}$ is a vector grouping the dissipative joint torques, $G_g(q)$ is a vector grouping the gravity joint torques, τ is the command vector for joint torques. $-\tau_e$ and $-\tau_u$ are the joint torques corresponding respectively to $-w_e$ and $-w_u$ i.e. $-\tau_e = \mathbf{J^t}(q)\,(-w_e)$ and $-\tau_u = \mathbf{J^t}(q)\,(-w_u)$ where $\mathbf{J}(q)$ is the Jacobian matrix of the robot at point O_1, expressed in the basis of $\mathcal{F}_r$.

At the lowest level of the controller, a proportional velocity feedback is used in order to partially linearize the robot dynamics:

$$\tau = -\mathbf{B}\dot{q} + \widehat{G}_g(q) + \widehat{C}(q,\dot{q})\dot{q} + \tau_c$$

where $\mathbf{B}$ is a symmetric positive definite matrix of feedback gains, τ_c is the new command vector for the joint torques,

$\widehat{G_g}(q)$ and $\widehat{C}(q,\dot{q})\dot{q}$ are estimated values of $G_g(q)$ and $C(q,\dot{q})\dot{q}$. Therefore, the model (1) becomes:

$$\mathbf{M}(q)\ddot{q} + \mathbf{B}\dot{q} = \tau_c - \tau_e - \tau_u \tag{2}$$

The proposed control scheme is presented on figure 2.

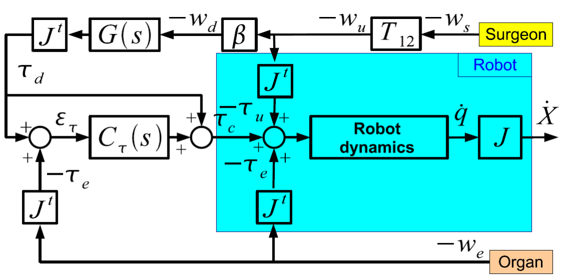

Fig. 2. Augmented Comanipulation force control scheme in joint space.

In this figure the Jacobian matrix $\mathbf{J}(q)$ is noted $\mathbf{J}$. This control scheme introduces notations defined as follow:

- $\mathbf{G}(s)$, where s is the Laplace complex variable, is a low-pass filter that we introduce in order to filter the surgeon's tremor. It is chosen as follow:

$$\mathbf{G}(s) = \frac{1}{\alpha s + 1}\mathbf{I_6} \in \mathbb{C} \tag{3}$$

  We choose the same cut-off frequency $\frac{1}{\alpha} > 0$ for each component of the wrench w_d. Let's remark that by choosing $\alpha = 0$, we have $\mathbf{G}(s) = \mathbf{I_6}$ and thus we do not filter the surgeon's tremor.
- $C_\tau(s)$ is a Proportional-Integral torque compensator at the joint level such that:

$$\mathbf{C}_\tau(s) = \mathbf{K_p} + \frac{\mathbf{K_i}}{s} \tag{4}$$

  where $\mathbf{K_p} \in \mathbb{R}^{n \times n}$ and $\mathbf{K_i} \in \mathbb{R}^{n \times n}$ are symmetric, positive definite matrices.
- $\dot{X}$ is the 6-component vector grouping the coordinates of the rotational and linear velocity of the instrument at point O_1 with respect to frame $\mathcal{F}_r$, expressed in the basis of $\mathcal{F}_r$.

In the sequel the following assumption will be used :

Assumption 1: The matrix $\mathbf{J}(q)$ is of full rank n

This assumption means that the robot is not in a singular configuration.

C. Equilibrium

The stability of the control scheme 2 will be proved in the following section. So, assuming that this control scheme is stable, as the controller $\mathbf{C}_\tau(s)$ involves an integral term, the torque error ε_τ will be null at the equilibrium. So, at the equilibrium:

$$\tau_d - \tau_e = 0 \tag{5}$$

As the stable low-pass filter $G(s)$ has a steady-state gain equal to 1, at the equilibrium, $\tau_d = \mathbf{J}(q)^t\beta(-w_u)$. Thus (5) leads to :

$$\mathbf{J}(q)^t\left((-w_u) + \frac{1}{\beta}(-w_e)\right) = 0 \tag{6}$$

If $n = 6$ i.e. if we consider a 6 joints robot, the matrix $\mathbf{J}(q)$ is square. Moreover, according to assumption (1), this matrix is of full rank. Therefore, it can be deduced from equation (6) that:

$$w_u = \frac{1}{\beta}(-w_e) \tag{7}$$

Suppose that we choose $\beta = 1$. Then, equation (7) can be written:

$$w_u = (-w_e) \tag{8}$$

It means that the wrench w_s sensed by the surgeon at point O_2 is such that its expression at point O_1, w_u, is equal to the wrench $-w_e$ applied by the organ on the instrument expressed at point O_1. Thus the surgeon manipulates the instrument in a transparent way i.e. the surgeon senses the wrench w_s as if he/she were manipulating a zero mass instrument without any friction.

Similarly, if $\beta \in]0;1[$, equation (7) means that the wrench w_s sensed by the surgeon is an amplified version, by the scale factor $\frac{1}{\beta} > 1$, of the wrench that he would sense in a transparent manipulation. Let's remark that (7) can be written $w_e = \beta(-w_u)$. It means that the wrench applied by the instrument on the organ at point O_1 is the wrench applied by the surgeon at the same point, reduced by the scale factor β.

If $n < 6$, $\mathbf{J}^t(q) \in \mathbb{R}^{n\times 6}$ is not square. Thus it cannot be deduced from (6) that the wrench error $\varepsilon_w = (-w_u) + \frac{1}{\beta}(-w_e)$ is zero. The wrench error ε_w is not necessarily zero but belongs to the null space of $\mathbf{J^t}(q)$. An equilibrium is obtained between w_u and $\frac{1}{\beta}(-w_e)$.

III. Passivity

In the proposed approach, the robot interacts with its environment. The stability of the control loop depends not only on the robot dynamics but also on the environment dynamics. However we cannot assume for a known model for the environment. Therefore, a useful tool for the stability analysis of the proposed control loop is passivity analysis since this study does not require any environments model. Thus, whatever could be the contacts (robot-organ / robot-surgeon), the passivity analysis ensures that the system remains stable. This principle is presented in the following subsection

A. Principle

Let consider an LTI system with an input u, an output y, such that $y = \mathbf{T}(s)\,u$ with $\mathbf{T}(s)$ a real rational transfer matrix. This system is passive if and only if $\mathbf{T}(s)$ is positive real. In turn, positive realness can be checked by the following property [8]:

Property 1: Let $s_k = \sigma_k + j\omega_k$, $k \in \{1..m\}$, denote the m poles of all the elements $T_{ij}(s)$ of $\mathbf{T}(s)$, and let $j\omega_l$,

$l \in \{1..p\}$, denote the $p \le m$ pure imaginary poles of all the elements $T_{ij}(s)$ of $\mathbf{T}(s)$. The transfer $\mathbf{T}(s)$ is Positive Real if, and only if:

1) $\forall k \in \{1..m\}, \sigma_k < 0$;
2) $\forall l \in \{1..p\}$, $j\omega_l$ is of multiplicity 1, and the associated residue matrix $\mathbf{K}_l$ is hermitian, positive semidefinite (PSD). The matrix $\mathbf{K}_l$ can be computed as:

$$\mathbf{K}_l = \lim_{s \to j\omega_l} (s - j\omega_l)\mathbf{T}(s) \text{ , if } \omega_l \text{ is finite}$$

$$\text{and:} \quad \mathbf{K}_l = \lim_{s \to \infty} \frac{\mathbf{T}(s)}{s} \text{ , if } \omega_l \text{ is infinite}$$

Note that a zero of $T_{ij}(s)$ is considered as a pole at the infinity.

3) $\mathbf{T}^t(-j\omega) + \mathbf{T}(j\omega) = \mathbf{T}^*(j\omega) + \mathbf{T}(j\omega)$ is PSD, for any $\omega \in \mathbb{R} - \{\omega_l, l \in \{1..p\}\}$. ■

Property 2: Let now consider an LTI system with two different inputs u_1 and u_2 provided by two different environments, and assume that this system is described by: $y = \mathbf{T_1}(s)u_1 + \mathbf{T_2}(s)\, u_2$. This system is passive if and only if $\mathbf{T_1}(s)$ is positive real and $\mathbf{T_2}(s)$ is positive real. ■

B. Passivity of the Modified Force Control Scheme

1) Modeling, Linearized Robot Dynamics: The robot controlled by the control scheme depicted on figure 2 is a system whose output is $\dot{X}$. This system has two inputs $-w_u$ and $-w_e$ provided by two different environments, respectively the surgeon and the organ. So, in order to study the passivity of this system we first have to compute the transfer matrix $\mathbf{Y_u}(s)$ between $-w_u$ and $\dot{X}$ and the transfer matrix $\mathbf{Y_e}(s)$ between $-w_e$ and $\dot{X}$. This computation supposes that the system is linear. Therefore, we linearize the robot dynamics (2) by assuming that the robot evolves in a neighborhood of a given joint configuration q_0 so that we can set $\mathbf{M} = \mathbf{M}(q_0)$ constant. The resulting linearized model writes:

$$\dot{q} = \mathbf{Y_r}(s)(\tau_c - \tau_u - \tau_e) \quad \text{with} \quad \mathbf{Y_r}(s) = (\mathbf{M}\, s + \mathbf{B})^{-1} \tag{9}$$

where s is the Laplace complex variable. Moreover, under the assumption that the robot evolves in a neighborhood of a given joint configuration q_0, we can set $\mathbf{J} = \mathbf{J}(q_0)$ constant. Then, we get the following model:

$$\dot{X} = \mathbf{Y_u}(s)\,(-w_u) + \mathbf{Y_e}(s)\,(-w_e) \tag{10}$$

where:

$$\left\{ \begin{array}{lcl} \mathbf{Y_u}(s) & = & \mathbf{J}\mathbf{Y_r}(s)\; [\mathbf{I_n} + \beta\, \mathbf{G}(s)(\mathbf{C}_\tau(s) + \mathbf{I_n})]\, \mathbf{J^t} \\ \mathbf{Y_e}(s) & = & \mathbf{J}\mathbf{Y_r}(s)\; [\mathbf{I_n} + \mathbf{C}_\tau(s)]\, \mathbf{J^t} \end{array} \right.$$

2) Passivity Study: The system (10) is passive if and only if the matrices $\mathbf{Y_u}(s)$ and $\mathbf{Y_e}(s)$ are positive real. As $\mathbf{J}$ is supposed to be of full rank (Assumption 1), this condition is equivalent to the positive realness of the matrices $\mathbf{Y_{u,2}}$ and $\mathbf{Y_{e,2}}$ defined as follow:

$$\left\{ \begin{array}{lcl} \mathbf{Y_{u,2}} & = & \mathbf{Y_r}(s)\; [\mathbf{I_n} + \beta\, \mathbf{G}(s)(\mathbf{C}_\tau(s) + \mathbf{I_n})] \\ \mathbf{Y_{e,2}} & = & \mathbf{Y_r}(s)\, [\mathbf{I_n} + \mathbf{C}_\tau(s)] \end{array} \right. \tag{11}$$

Equations (11), (9), (4) and (3) lead to :

$$\left\{ \begin{array}{l} \mathbf{Y_{u,2}} = (\mathbf{M}\, s + \mathbf{B})^{-1} \left[\mathbf{I_n} + \frac{\beta \mathbf{K'_p}}{\alpha\, s+1} + \frac{\beta \mathbf{K_i}}{s\,(\alpha\, s+1)} \right] \\ \mathbf{Y_{e,2}} = (\mathbf{M}\, s + \mathbf{B})^{-1} \left[\mathbf{I_n} + \mathbf{K_p} + \frac{\mathbf{K_i}}{s} \right] \end{array} \right. \tag{12}$$

where $\mathbf{K'_p} = \mathbf{K_p} + \mathbf{I_n}$.

We first derive conditions ensuring the positive realness of $\mathbf{Y_{u,2}}(s)$. The poles of $\mathbf{Y_{u,2}}(s)$ are $s_1 = 0$, $s_2 = -\frac{1}{\alpha}$ and the poles of $\mathbf{Y_r}(s)$. We defined $G(s)$ such that $s_2 = -\frac{1}{\alpha} < 0$. The poles associated to $\mathbf{Y_r}(s)$ are the solutions of $\det(\mathbf{M}\, s + \mathbf{B}) = 0$ i.e. the eigenvalues of $-\mathbf{M}^{-1}\mathbf{B}$. As far as $\mathbf{M}$ and $\mathbf{B}$ are symmetric positive definite matrices, the eigenvalues of $-\mathbf{M}^{-1}\mathbf{B}$ are negative real.

In order to check the second condition of property 1, we compute the residue $\mathbf{K_1}$ associated to pole $s_1 = 0$. We get:

$$\mathbf{K_1} = \lim_{s \to s_1} s\mathbf{Y_{u,2}} = \beta \mathbf{B}^{-1}\mathbf{K_i}$$

As $\beta > 0$, we deduce the following condition for the passivity of the control scheme:

$$\mathbf{B}^{-1}\mathbf{K_i} \ge 0 \tag{13}$$

The third condition of property 1 consists in checking, for any $\omega \in \mathbb{R} - \{0\}$, the positive semidefiniteness of the matrix $\mathbf{H_1}(j\omega)$ defined as follow:

$$\begin{array}{l} \mathbf{H_1}(j\omega) = \mathbf{Y_{u,2}}(j\omega) + \mathbf{Y_{u,2}}^t(-j\omega) \\ = (j\omega\mathbf{M} + \mathbf{B})^{-1} \left[\mathbf{I_n} + \frac{\beta \mathbf{K'_p}}{j\alpha\,\omega+1} + \frac{\beta \mathbf{K_i}}{j\omega\,(j\alpha\,\omega+1)} \right] \\ + \left[\mathbf{I_n} + \frac{\beta \mathbf{K'_p}}{-j\alpha\,\omega+1} + \frac{\beta \mathbf{K_i}}{-j\omega\,(-j\alpha\,\omega+1)} \right] (-j\omega\mathbf{M} + \mathbf{B})^{-1} \end{array} \tag{14}$$

because $\mathbf{K'_p}$, $\mathbf{K_i}$, $\mathbf{M}$ and $\mathbf{B}$ are symmetric.

Positive semidefiniteness of $\mathbf{H_1}(j\omega)$ is equivalent to positive semidefiniteness of $\mathbf{H_2}(j\omega)$ defined as follow:

$$\begin{array}{l} \mathbf{H_2}(j\omega) = \frac{1}{\beta}(j\omega\mathbf{M} + \mathbf{B})\mathbf{H_1}(j\omega)(-j\omega\mathbf{M} + \mathbf{B}) \\ = \left[\frac{1}{\beta}\mathbf{I_n} + \frac{\mathbf{K'_p}}{j\alpha\,\omega+1} + \frac{\mathbf{K_i}}{j\omega\,(j\alpha\,\omega+1)} \right] (-j\omega\mathbf{M} + \mathbf{B}) \\ +(j\omega\mathbf{M} + \mathbf{B}) \left[\frac{1}{\beta}\mathbf{I_n} + \frac{\mathbf{K'_p}}{-j\alpha\,\omega+1} + \frac{\mathbf{K_i}}{-j\omega\,(-j\alpha\,\omega+1)} \right] \end{array} \tag{15}$$

We get:

$$\begin{array}{rcl} \mathbf{H_2}(j\omega) & = & \mathbf{R_1} - \frac{\alpha\,\omega^2}{\alpha^2\omega^2+1}\mathbf{R_2} + \frac{1}{\alpha^2\omega^2+1}\mathbf{R_3} + \\ & & +j\frac{\omega}{\alpha^2\omega^2+1}\mathbf{Im_1} + j\frac{1}{\omega(\alpha^2\omega^2+1)}\mathbf{Im_2} \end{array} \tag{16}$$

where:

$$\begin{array}{l} \mathbf{R_1} = (2/\beta)\mathbf{B} \\ \mathbf{R_2} = \mathbf{K'_p}\mathbf{M} + \mathbf{M}\mathbf{K'_p} \\ \mathbf{R_3} = \mathbf{K'_p}\mathbf{B} + \mathbf{B}\mathbf{K'_p} - (\mathbf{K_i}\mathbf{M} + \mathbf{M}\mathbf{K_i}) - \alpha(\mathbf{K_i}\mathbf{B} + \mathbf{B}\mathbf{K_i}) \\ \mathbf{Im_1} = \mathbf{M}\mathbf{K'_p} - \mathbf{K'_p}\mathbf{M} + \alpha(\mathbf{B}\mathbf{K'_p} - \mathbf{K'_p}\mathbf{B}) - \\ \qquad\qquad \alpha(\mathbf{M}\mathbf{K_i} - \mathbf{K_i}\mathbf{M}) \\ \mathbf{Im_2} = \mathbf{K_i}\mathbf{B} - \mathbf{B}\mathbf{K_i} \end{array}$$

The hermitian matrix $\mathbf{H_2}(j\omega)$ must be PSD to ensure passivity. Thus its real part has to be PSD and its imaginary part has to be null (see [7] for details). Therefore, the following conditions have to be satisfied for any $\omega \in \mathbb{R}\backslash\{0\}$:

$$\mathbf{R_1} - \frac{\alpha\,\omega^2}{\alpha^2\omega^2+1}\mathbf{R_2} + \frac{1}{\alpha^2\omega^2+1}\mathbf{R_3} \ge 0 \tag{17}$$

$$\frac{\omega}{\alpha^2\omega^2+1}\mathbf{Im_1} + \frac{1}{\omega(\alpha^2\omega^2+1)}\mathbf{Im_2} = 0 \tag{18}$$

As $\lim_{\omega \to 0} \frac{\omega}{\alpha^2\omega^2+1} = 0$ and $\lim_{\omega \to 0} \frac{1}{\omega(\alpha^2\omega^2+1)} = \infty$, condition (18) leads to $\mathbf{Im_2} = 0$. Then, we deduce from equation (18) that $\mathbf{Im_1} = 0$. Thus, condition (18) is equivalent to:

$$\begin{cases} \mathbf{Im_1} = 0 \\ \mathbf{Im_2} = 0 \end{cases} \quad (19)$$

Equation (17) can be re-written:

$$\frac{\alpha\,\omega^2}{\alpha^2\omega^2+1}(\alpha\mathbf{R_1} - \mathbf{R_2}) + \frac{1}{\alpha^2\omega^2+1}(\mathbf{R_1} + \mathbf{R_3}) \geq 0 \quad (20)$$

As $\lim_{\omega \to 0} \frac{\alpha\,\omega^2}{\alpha^2\omega^2+1} = 0$ and $\lim_{\omega \to 0} \frac{1}{\alpha^2\omega^2+1} = 1$, we deduce the following necessary condition for (20):

$$\mathbf{R_1} + \mathbf{R_3} \geq 0 \quad (21)$$

If $\alpha \neq 0$, $\lim_{\omega \to \infty} \frac{\alpha\,\omega^2}{\alpha^2\omega^2+1} = \frac{1}{\alpha}$ and $\lim_{\omega \to \infty} \frac{1}{\alpha^2\omega^2+1} = 0$. Thus, for $\alpha \neq 0$, we deduce the following necessary condition for (20):

$$\alpha\mathbf{R_1} - \mathbf{R_2} \geq 0 \quad (22)$$

For any ω, $\frac{\alpha\,\omega^2}{\alpha^2\omega^2+1} \geq 0$ and $\frac{1}{\alpha^2\omega^2+1} \geq 0$. Therefore, equations (21) and (22) are also sufficient conditions for (20). Let's remark that if we chose $\alpha = 0$ i.e. if we do not filter the surgeon's tremor, the equation (20) is equivalent to (21). To summarize, the matrix $\mathbf{Y_{u,2}}(s)$ and thus $Y_u(s)$ is positive real if and only if the following conditions are satisfied:

$$\begin{cases} \mathbf{B}^{-1}\mathbf{K_i} \geq 0 \\ \mathbf{Im_1} = 0 \\ \mathbf{Im_2} = 0 \\ \mathbf{R_1} + \mathbf{R_3} \geq 0 \\ \alpha\mathbf{R_1} - \mathbf{R_2} \geq 0 \qquad \text{if } \alpha \neq 0 \end{cases} \quad (23)$$

As far as positive realness of $\mathbf{Y_{e,2}}(s)$ is concerned, with a similar reasoning we deduce that the first and the second condition of property 1 are satisfied if and only if $\mathbf{M}^{-1}\mathbf{B} > 0$ and $\mathbf{B}^{-1}\mathbf{K_i} \geq 0$. It can be noticed in equations (12) that the expression of $\mathbf{Y_{e,2}}(s)$ is similar to the expression of $\mathbf{Y_{u,2}}(s)$ when $\beta = 1$, $\alpha = 0$ and $\mathbf{K'_p}$ is replaced by $\mathbf{K_p}$. Therefore, we deduce from equations (19) and (17) that the third condition ensuring the positive realness of $\mathbf{Y_{e,2}}(s)$ is satisfied if and only if:

$$\begin{cases} \mathbf{MK_p} - \mathbf{K_pM} = 0 & (a) \\ \mathbf{K_iB} - \mathbf{BK_i} = 0 & (b) \\ \mathbf{B} + \mathbf{K_pB} - \mathbf{K_iM} \geq 0 & (c) \end{cases} \quad (24)$$

The equations (23) and (24) lead to the following conditions for the passivity of the proposed control scheme:

$$\begin{cases} \mathbf{B}^{-1}\mathbf{K_i} \geq 0 & (a) \\ \mathbf{MK_p} - \mathbf{K_pM} = 0 & (b) \\ \alpha\left[(\mathbf{BK_p} - \mathbf{K_pB}) - (\mathbf{MK_i} - \mathbf{K_iM})\right] = 0 & (c) \\ \mathbf{K_iB} - \mathbf{BK_i} = 0 & (d) \\ (\frac{1}{\beta}\mathbf{I_n} + \mathbf{K'_p})\mathbf{B} - \mathbf{K_iM} \geq 0 & (e) \\ \mathbf{B} + \mathbf{K_pB} - \mathbf{K_iM} \geq 0 & (f) \\ (\alpha/\beta)\mathbf{B} - \mathbf{K'_pM} \geq 0 \qquad \text{if } \alpha \neq 0 & (g) \end{cases} \quad (25)$$

with $\mathbf{K'_p} = \mathbf{K_p} + \mathbf{I_n}$.

IV. EXPERIMENTS

The aim of these experiments is to show that it is possible to provide force feedback to the surgeon thanks to the proposed control scheme. Furthermore, for different values of the gain β, we will verify that the system remains stable. Experimental setup will be briefly described and benefits of augmented comanipulation will be evaluated experimentally. Note that, in the rest of the paper, the used joint torque compensator gains and the values of $\mathbf{B}$, α and β were chosen in such a way that the conditions given in 25 are verified.

A. Experimental Setup

The robot MC^2E (French acronym for *compact manipulator for endoscopic surgery*) is depicted on the Figure 3. It is a Kinematically Defective Manipulator (KDM) which means that it has fewer joints than the dimension of the space in which its end-effector evolves. It is specially suited for minimally invasive robotic surgery applications [9]. With $n = 4$ joints and a spherical structure, this robot provides 4 degrees of freedom (DOFs) at the instrument tip.

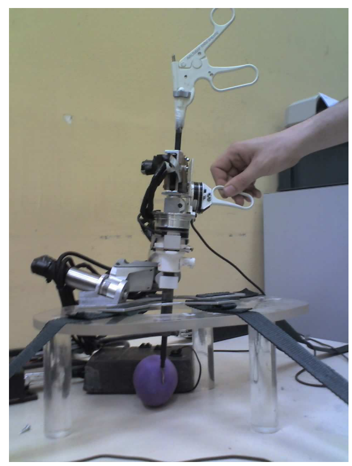

Fig. 3. Experimental Setup.

Apart from its compactness, the main feature of this robot is that it offers a possibility for force measurement in MIS. Namely, MC^2E can measure the distal organ-instrument interaction with a 6-axis force-torque sensor placed outside the patient. Thus, it is subject to much less sterilization constraints. Remarkably, due to the special mounting of the force sensor, these measurements are not affected by the disturbance forces and torques arising from the interaction between the trocar and the instrument.

The new control scheme presented in section II indicates that the robot interacts with two different environments (the organ and the surgeon). It needs a second force sensor to measure forces between the robot and the surgeon. Therefore to measure forces applied by the surgeon, a second force sensor has been added on the robot. Due to difficulties to fix it directly on the handle, it has been deported on the second axis of MC^2E. This particular disposition was the quickest way to provide force feedback to the manipulator. However, the same disposition is not adapted to transmit forces along instrument's axis. In order to overcome this problem, next step will be to modify existing experimental setup to exploit each of the robot's DOF.

B. Experimental Results

The figure 4 shows how the gain β has been modified during the experiment. $\beta = 1$ is a particular value for which

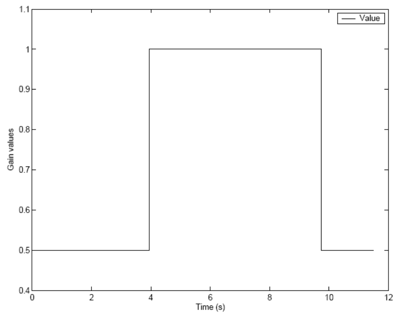

Fig. 4. Gain values vs. time.

torques measured on the organ are equal to torques applied by the manipulator. When setting $\beta = 0.5$, torques applied on the organ should be decreased by a factor 2.

The figure 5 depicts torque measurements. It allows to compare torques applied on the organ, torques provided to the controller and torques applied on the manipulator. This

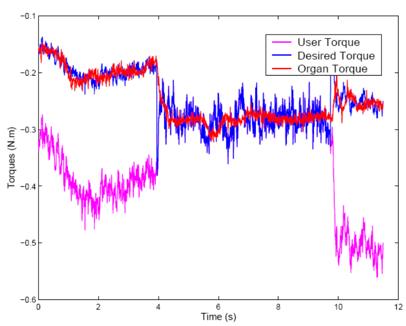

Fig. 5. Torque values vs. time.

result demonstrates that the proposed control scheme allows a reduction of the torques applied on the organ. At $t = 10s$, β is switched from 1.0 to 0.5. One can notify that torques applied on the organ almost remain the same but torques applied by the surgeon are amplified. Therefore, to apply the same efforts on the organ, the surgeon must amplify forces acting on the robot. This result satisfies equation (7).

The figure 6 shows that the system remains stable for different values of gains. Furthermore, it demonstrates that

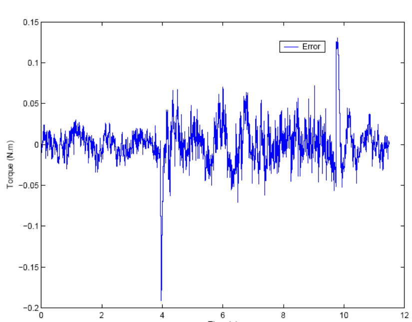

Fig. 6. Torque error vs. time.

good performances can be achieved with the controller which has been proposed in section II. Error appearing on Figure 6 is mainly due to noise on measurement. However, one can notice that there are some error peaks on this plot. This phenomenon is due to the modification of the force feedback gain during experiments. In practice, if a fixed value of β is used, these peaks would not appear.

V. CONCLUSIONS

This paper presents a modified version of a force control scheme. In the context of comanipulation, it is possible to provide force feedback to the manipulator by modifying torques reference. In order to obtain such results, a second force sensor is necessary to distinguish manipulator and environment forces.

Robots kinematic has been used to deal with torques equilibrium. In other words, using a gains matrix allows reduction of forces acting on the environment and amplification of forces acting on the manipulator. Experiments have been conducted to show efficiency of the proposed control scheme. Moreover, a formal proof of passivity has been established. It ensures stability of the system whatever could be contacts between the robot and its environment.

In future work, in-vivo experiments will be conduced. Even if experiments are satisfying with actual experimental setup, it should be modified to exploit the last 2 DOFS. A new handle seems to be the easiest way to use existing robot.

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