Bilateral controllers for teleoperated percutaneous interventions : evaluation and improvements

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***Abstract*— This paper presents two teleoperation control schemes developed in the context of percutaneous procedures in interventional radiology. The teleoperation task is characterized by a nonlinear interaction with the environment. The whole force feedback teleoperation structure is modeled to derive a practical, stable and transparent force feedback. The proposed control approach is based on the adaptation of standard force feedback teleoperation controllers. Position-position and force-position structures are improved by local compensation loops that include an a priori knowledge of the interactions between the slave robot and the environment made of soft tissues. This contribution allows to improve position tracking capabilities in spite of the nonlinearity of the interaction.**

I. Introduction

Teleoperation systems are composed of two connected manipulators that enable human operators to perform different tasks in remote, hazardous or delicate environments. Since the first teleoperation systems in the 1950's [1], the number and diversity of teleoperation applications have considerably increased. Today, such systems are used in underwater exploration, manufacturing, chemical and biological industry, and, more recently, in the medical field.

In the medical field, the first commercial teleoperation systems were ZEUS, from Computer Motion and DaVinci from Intuitive Surgical. These systems are dedicated to minimally-invasive surgery (MIS) and specially to laparoscopic interventions. They allow the surgeon to perform surgical interventions from a remote location, as illustrated during the Lindberg operation, when Pr. Jacques Marescaux carried out the first long distance surgical intervention between New York and Strasbourg on a real patient with a Zeus system [2], [3].

Unfortunately, such teleoperation systems are unilateral and the surgeon only has a visual feedback of the operation field during a teleoperated intervention. In particular, these systems do not provide to feel the interaction forces between the surgical tool and the organs. Yet, it is a critical information for the safety of the patient.

Robotic teleoperation is also very promising for interventional radiology procedures that requires the protection from X-rays. This is the case of CT-guided percutaneous interventions during which the practitioner performs local treatments directly through the skin of the patient with specific needles. The workflow of such an intervention starts with the planning of the needle trajectory using pre-operative imaging. Even though different imaging techniques are used, we will only consider computed tomography (CT) in this paper. Indeed, in the case of the CT-scan, the quality of the anatomical images is far better than images from Ultrasound probe (US). Additionally this technique is more convenient and less expensive than Magnetic Resonance Imaging (MRI). During the intervention, the radiologist uses intra-operative CT-scan images to obtain the expected needle trajectory. Since images acquisition is not realtime, the radiologist uses haptic feeling to guide the needle through the anatomical layers, between two CT-scan acquisitions. The success of the intervention mainly relies on the accuracy of the insertion. This requires an intense use of the CT-scan and the radiologist is exposed to a great amount of hermful X-rays.

As this technique offers very interesting possibilities for diagnosis and treatment and since there exists no efficient force feedback teleoperation system for percutaneous treatments, we proposed to develop a teleoperated needle driver with force feedback [4]. Its principle is described in figure 1. Unlike previous teleoperation systems with only visual feedback, this new device will also allow force feedback.

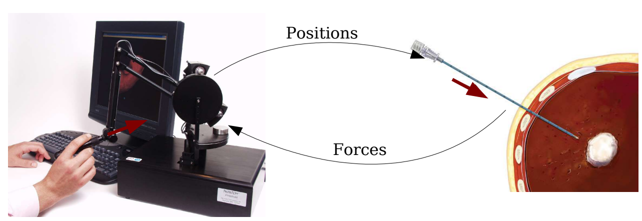

Fig. 1. Teleoperated needle driver scheme

The main problem in force feedback teleoperation consists in the design of the controller that has to be stable and transparent. This paper proposes an evaluation of classical controllers structures in the case of a teleoperated needle insertion in a liver. In the first part of the paper, we address the problem of modeling a teleoperation system in contact with a human operator and an unknown environment. The second part is dedicated to the description of the two main classical control schemes. The third part presents teleoperation simulations were the slave manipulator interacts with a nonlinear environment, identified from force measurements of in vivo needle insertions. We will then conclude on the performance of the evaluated controllers in a teleoperated system dedicated to percutaneous interventions.

II. SYSTEM MODELING

The most general model to represent a teleoperation system is made up of five blocks: the user, the master manipulator, the bilateral controller, the slave manipulator and the remote environment. This scheme, adapted from [5], is represented in figure 2.

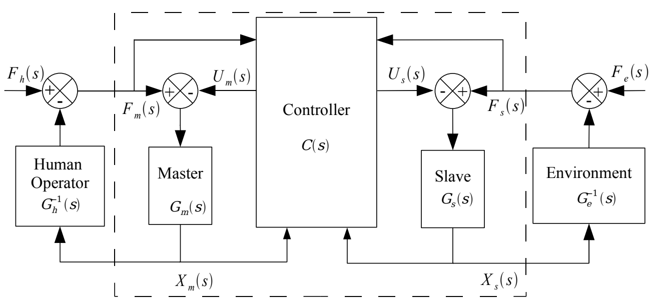

Fig. 2. General model for telemanipulation

The central block (dashed) represents the master-slave system which interacts with the human operator and the environment.

If we focus on needle insertion tasks, the manipulation requires two degrees of freedom: a translation in the insertion direction and a rotation to orientate the bevel of the needle. However, force feedback is mainly useful for the insertion and the withdrawal of the needle. The orientation of the bevel is useful to bend the needle on a bone, or to remove the needle when some tissue or skin stick to it. So, from now on, we will assume that the interaction forces between the needle and the skin are along the needle shaft and so that the problem has only one degree of freedom.

A. Master and slave manipulators models

We assume that the actuator nonlinear dynamical effects and the dry friction forces can both be neglected. The dynamic model of the master and the slave manipulators can respectively be expressed in the Laplace domain as:

$$G_m(s) = \frac{X_m(s)}{F_m(s)-U_m(s)} = \frac{1}{m_m s^2+b_m s}, \quad (1)$$

$$G_s(s) = \frac{X_s(s)}{F_s(s)-U_s(s)} = \frac{1}{m_s s^2+b_s s}, \quad (2)$$

with $G_m(s)$ (resp. $G_s(s)$) the transfer function of the master (resp. the slave) manipulator. The dynamic parameters of the master (resp. the slave) manipulator are its mass m_m (resp. m_s), and its viscous coefficient b_m (resp. b_s). $X_m(s)$ (resp. $X_s(s)$) represents the position of the master (resp. the slave) manipulator. $F_m(s)$ is the force that the human operator applies on the master manipulator and $F_s(s)$ the force that the slave manipulator applies on the environment. Finally, $U_m(s)$ (resp. $U_s(s)$) are the forces applied by the actuator driving the master (resp. the slave) manipulator.

B. Human operator model

The modeling of the human operator is by far the hardest task. The influence of the human operator during a telemanipulation task is very complex. Its modeling requires to take into account:

- the influence of the nervous system responsible for the reflex effects and the time delay to respond to a stimulus;
- the dynamic behavior of the arm.

A meaningful model of the human operator proposed by [6] is shown in figure 3. On this scheme, $M(s)$ is the neural

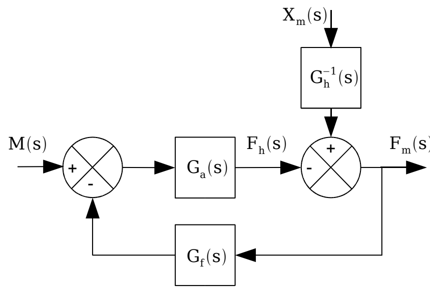

Fig. 3. Human operator model

command. It represents the position of the end-effector of the slave manipulator, as it is desired by the human operator. This information is sent to the muscles by the nervous system, that induces a time lag T_d. The signal $F_h(s)$ is the intended muscle force of the human operator. The transfer function which represents the muscle activation dynamics with the time lag T_d is denoted as $G_a(s)$ [7]. The transfer function $G_h(s)$ corresponds the muscular contraction and to the dynamics of the passive tissues surrounding the joint. It is generally modeled by a second order transfer function. Note that the parameters of all these transfer functions are difficult to obtain because they are different from a human operator to another, and from an application to another. According to the previous notations, the model of the human operator represented in figure 3 is given by:

$$F_m(s) = G_h^{-1}(s)X_m(s) - F_h(s), \quad (3)$$

$$F_h(s) = G_a(s)(M(s) - G_f(s)F_m(s)), \quad (4)$$

with:

$$G_h(s) = \frac{1}{m_h s^2 + b_h s + k_h}, \quad (5)$$

$$G_a(s) = \frac{K_a e^{-sT_d}}{1+\tau_a s}, \quad (6)$$

$$G_f(s) = \frac{K_f}{1+\tau_f s}, \quad (7)$$

where the parameters of the human operator arm are the mass m_h, the friction constant b_h, and the stiffness coefficient k_h. The time constant for the muscle activation dynamics is τ_a. For the neural feedback due to the interaction with the master manipulator, the time constant is denoted as τ_f. In this model, it is assumed that the master manipulator end-effector and the human operator hand are linked during the manipulation.

For the simulation purpose, typical numerical values of the dynamic models of a human operator were chosen:

$$\begin{aligned} G_h(s) &= \frac{1}{4.04s^2 + 34.76s + 176.58}, \\ G_a(s) &= \frac{176.58e^{-0.110s}}{0.025s+1}, \\ G_f(s) &= \frac{0.015}{0.0167s+1}. \end{aligned}$$

C. Environment model

Most studies on the design of bilateral controllers are based on a linear model of the environment. In medical applications and particularly in the case of percutaneous interventions, the slave manipulator interacts with a nonlinear environment: the organs, the skin and the bones of the patient. In this paper, we use a realistic nonlinear model that relates forces along the needle shaft direction to the depth of the needle in the organs. It corresponds to a needle insertion in the liver of a pig, at a constant speed, according to the results presented in [8]. Figure 4 presents the in vivo data and the model identified from these data. This model is based

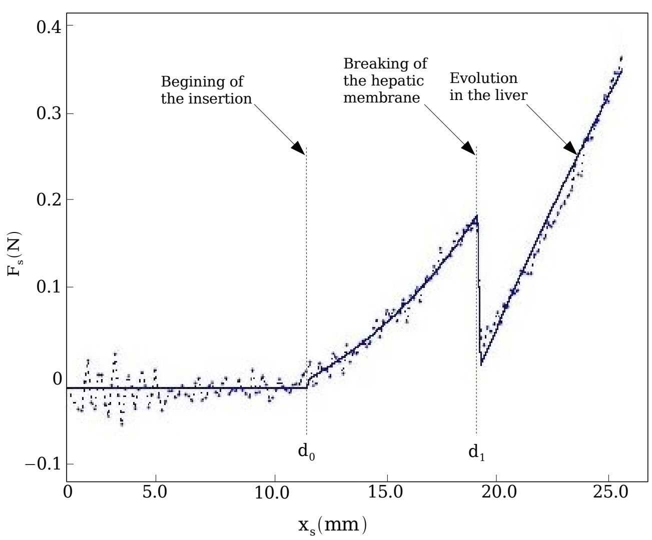

Fig. 4. Needle insertion into a pig liver : measurements and identified model

on the work of Fung [9] for the identification of soft tissues deformations. Besides being nonlinear, it is not continuous, what can be observed at the rupture of the hepatic membrane. So, during the needle insertion phase the data are identified to a set of disjoint functions:

$$F_s(x_s) = \begin{cases} 0, & x_s < d_0, \\ (f_0 + b_0)e^{a_0(x_s - d_0)} + b_0, & d_0 < x_s < d_1, \\ (f_1 + b_1)e^{a_1(x_s - d_1)} + b_1, & x_s > d_1 \end{cases} \tag{8}$$

where d_0 represents the initial position of the skin, assumed to be constant, and d_1 represents the position of the needle when it breaks the hepatic membrane. The parameters of the model, denoted as f_0, f_1, a_0, a_1, b_0 and b_1 depend on the mechanical properties of the tissue. For the insertion presented in figure 4 the identified values are $[f_0; a_0; b_0; d_0] = [0.2; 0.121; -0.098; 11.45]$ and $[f_1; a_1; b_1; d_1] = [-3.39; -0.031; 1.7; 19.65]$.

III. Teleoperation controllers

A. Prior works

The fundamental requirement for any control system is stability. Nevertheless, one of the main objectives of force feedback teleoperation systems is to provide the human operator the feeling that he is directly touching the environment: this property is known as transparency [10]. The bilateral controller which transmits the signals between the master and the slave manipulators has to be designed in order to make the system stable and to offer the optimal transparency performance in spite of time delays, plant disturbances, measurements noise and modeling uncertainties.

Hannaford [11] and Raju [12] works introduced the two-port network representation, based on linear network theory, to analyze the transparency of teleoperation systems and to design specific transparent controllers. In the two-port network context, different representations of the system are possible: hybrid matrix [11], scattering matrix [13] or impedance matrix [14]. To achieve perfect transparency, the hybrid parameters of the two-port teleoperation system have to yield approximatively the identity. Concerning the stability of the two-port network, the problem has often been addressed with the tools of passivity theory [15].

Passivity methods have been extensively applied on systems with time delays [13]. Nevertheless, this criterion is conservative, since it assumes that the human operator and the environment are both passive. To reduce this drawback, some authors used μ-synthesis [16] or unconditional stability to design a stable controller. Recent works on time-domain passivity control [17] have been used to provide stability for a wide variety of environments or human operator motions. These methods, based on an estimate of the dissipation, are still conservative. Indeed, these controllers design techniques do not use models of the human operator or the environment, that should allow to design less conservative controllers.

In the medical field dedicated force feedback teleoperation systems already exist. Most of them are used in laparoscopic MIS [18], [19], [20], [21]. In spite of the lack of realism it may cause, these systems use linear control techniques. As already explained, in the case of needle insertion procedures, the interactions are clearly nonlinear: stiffness may be variable, breaking of membranes occur when the needle is inserted or the needle may touch bones, etc. So, in the rest of this paper, we will introduce interaction nonlinearities in the problem of bilateral control of a teleoperation system using two standard controllers schemes : the Position-Position scheme and the Force-Position scheme.

B. Position-Position controller

In this extensively studied control scheme [11], [10], [22], [19], the master position serves as a reference for the slave position controller and, reciprocally, the slave position serves as a reference for the master position controller. This architecture implies that the position controllers of both the master and the slave have good tracking capabilities, since the manipulators have to follow exactly each other.

The Position-Position control scheme corresponding to the general structure of figure 2 is presented in figure 5. It has a symmetrical structure, except for the k_p parameter, that is a position scale factor allowing to change the rate of motion between the master and the slave manipulators.

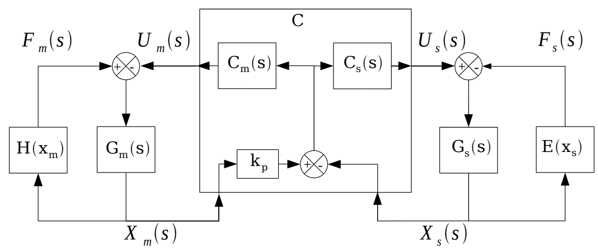

Fig. 5. Block diagram of the Position-Position controller

Force feedback on the master manipulator is the result of the force generated by the master controller, due to the position error tracking when the slave manipulator is in contact with the environment. This control scheme does not require any force sensor. In the literature [10], the position controllers of both the master and the slave manipulators are generally PD controllers. Since there is no integral effect, it is necessary to have high values for the gains of the PD controllers to achieve good tracking. They are tuned once for all, for a given type of environment. If the environment properties vary, this structure may not be adapted. For instance, a sudden contact between the slave manipulator and a hard environment will cause an unstable behavior of the whole system. Therefore, it is impossible to have perfect transparency and robust stability at the same time with this structure.

To reduce the effect of the environment nonlinearity when the hepatic membrane tears, we propose to take an a priori model of the environment into account (see previous section II-C). The model, $\hat{E}$, described by equations (8), allows to estimate the interaction force between the slave manipulator and the environment. From this estimation, we designed a specific controller structure that exhibits a compensation of the nonlinear effects of the environment (see figure 6). This control structure reduces the position error between the master and the slave manipulators, especially during nonlinear phases. The proposed scheme is based on the use of an internal model [23] to increase stability robustness and performances. Indeed, the environment model acts as a feedforward term into the control loop on the slave side and provides a faster force feedback on the master side.

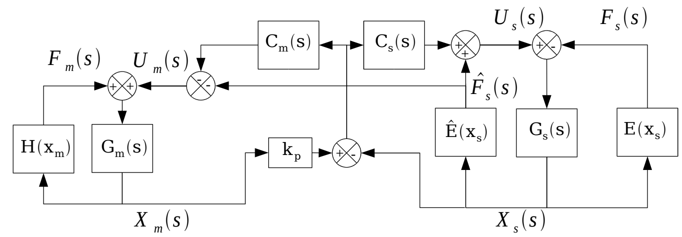

Fig. 6. Block diagram of the modified Position-Position controller, with environment interaction compensation

C. Force-Position controller

The Force-Position controller is certainly the most intuitive structure. As illustrated in figure 7, the position of the master manipulator, scaled by a factor k_p, is used as the reference position for the slave manipulator. The measured forces when the slave is in contact with the environment, scaled by a factor k_f, are fed-back to the human operator through the master manipulator. Unlike the Position-Position structure,

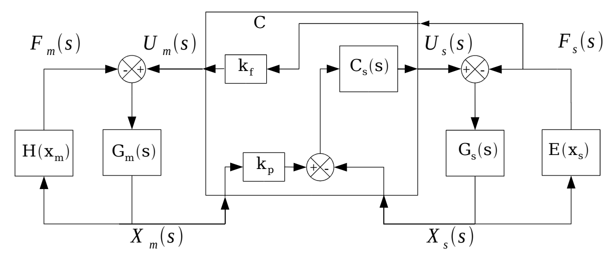

Fig. 7. Block diagram of the Force-Position controller

the Force-Position controller requires a force sensor mounted on the end-effector of the slave manipulator.

It was shown in [24] that this controller is stable for any linear environment if k_f is smaller than a critical value. This value is the ratio of the masses of the master and the slave manipulators. The force sensor on the slave manipulator adds noise in the loop that has to be filtered. It usually results a limitation of the servoing bandwidth.

Again, many references in the literature deals with this structure. Most of them are interested in the design of an optimal controller for specific applications such as [19] for medical telesurgery.

Generally, the classical force-position controller does not provide an efficient position tracking. So, again, we propose to use an a priori model of the environment in the control law to reduce this disturbance and increase the position tracking capabilities of the controller, in a similar way as we did for the position-position scheme (see figure 8). This a priori model reduces the disturbance resulting from the environment nonlinearities.

IV. Simulations

A. System description

In this section, we evaluate the effectiveness of the modified Position-Position and Force-Position architectures in the

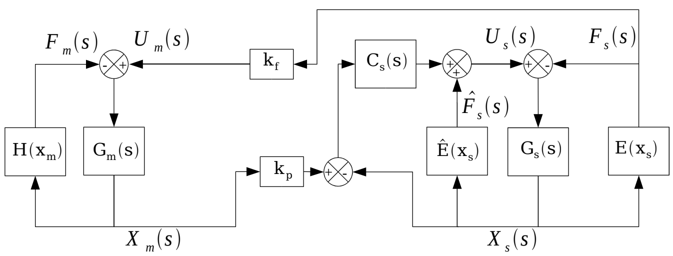

Fig. 8. Block diagram of the modified Force-Position controller

case of needle insertions, *i.e.* in the case of the nonlinear interaction described by equation (8).

The teleoperation system model for these simulations is the same as Cavusoglu [19]. It is composed of two identical PHANToM™1.5 haptic interfaces, from Sensable Technologies. These device are mechanically constrained so that their end-effector has only one degree of freedom. It moves along the vertical direction orthogonally to the skin. The dynamic models of the master and the slave robots are:

$$G_m(s) \ = \ G_s(s) \ = \ \frac{1}{0.09641s^2 + 2.665s}$$

if we suppose that local position control loops compensate the gravity effects.

B. Simulations

We consider the idealized following task : a human operator wants to reach a point in the liver 35 mm away from the origin of the needle tip, with a constant velocity of 17.5 mm/s. The entry point on the liver is reached after 11.45 mm, from the initial position of the needle.

1) Position-Position structure: The PD position controllers are designed to reach a stability margin of 60° with natural pulsation of $\omega_0 = 60.3$ rad/s, and $k_p = 1$, we obtain:

$$C_m(s) = C_s(s) = 3.7(s + 85.0);$$

The effects of the nonlinearities compensation can be observed in figure 9 for the position tracking error and in figure 10 for the force tracking error. In figure 9, the position tracking error between the master and the slave manipulators is measured in the case of the classical position-position controller and the modified position-position controller.When the needle tip is not in contact with the skin, the slave manipulator exactly follows the master manipulator. After the insertion, the controller with the nonlinearity compensation provides a better position tracking than the classical controller. After the hepatic membrane puncture, the position error of the classical controller drifts whereas the position error of the modified controller converges to a value below 0.2 mm. Furthermore the modified controller reduces the transient duration of the force tracking error.

2) Force-Position structure: The slave position controller is the same as the one proposed in the previous scheme, and $k_f = 1$.

The modified force-position structure provides a better position tracking error than the classical controller (see figure

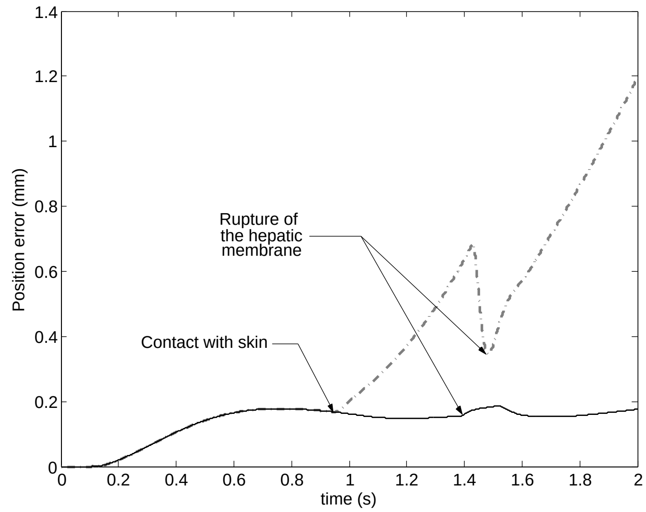

Fig. 9. Position tracking error for the classical position-position scheme (dash) and for the modified scheme (solid)

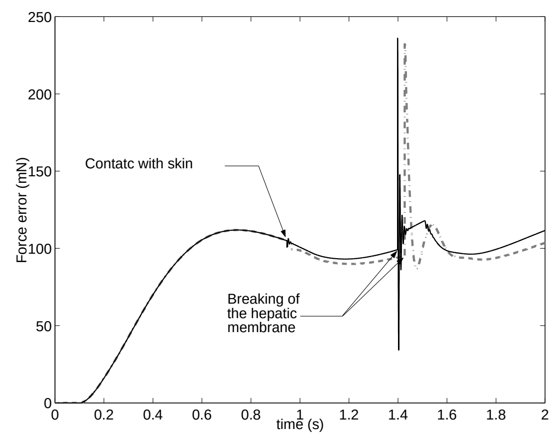

Fig. 10. Force tracking error for the classical position-position scheme (dash) and for the modified scheme (solid)

11). Although the position tracking error of the classical controller drifts when the interaction forces increase, the modified scheme allows to reach a constant position error without reducing the force tracking performance (see figure 12).

V. Conclusion

Classical bilateral teleoperation controllers with Position-Position and Force-Position structures have seldom been studied in interaction with a nonlinear environment. In the context of robotized needle insertions, nonlinear interactions are frequent because of membrane ruptures. To derive an efficient structure to cope with this problem, we based our study on the use of an interaction model, which was derived from previous experiments. In this paper, we illustrated the efficiency of a model based compensation of the nonlinear

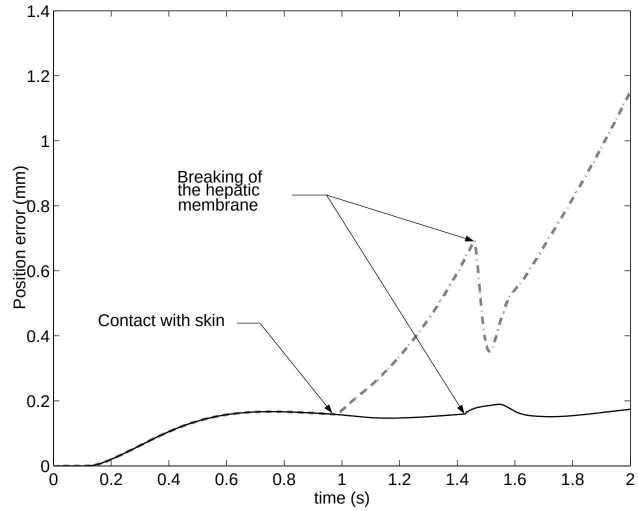

Fig. 11. Position tracking error for the classical force-position scheme (dash) and for the modified scheme (solid)

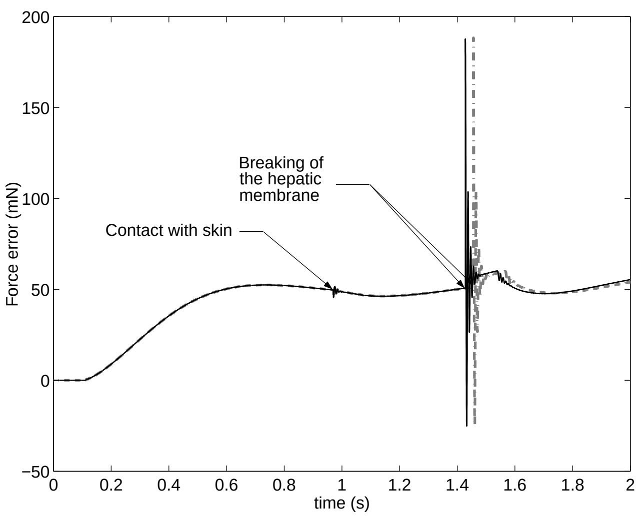

Fig. 12. Force tracking error for the classical force-position scheme (dash) and for the modified scheme (solid)

effects of the environment. Noticeable improvements in position tracking were obtained without decreasing force feedback performance. These results are interesting from an application point of view since position tracking is critical for percutaneous interventions to reach a precise targets in the liver.

VI. ACKNOWLEDGMENTS

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