2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Stability and Performance Analysis of Three-Channel Teleoperation Control Architectures for Medical Applications

Abdulrahman Albakri*, Chao Liu and Philippe Poignet

***Abstract*— Tele-surgery has been more and more popular in robot-assisted medical intervention. Most existing teleoperation architectures for medical applications adopt 2-channel architectures. The 2-channel architectures have been evaluated in literature and it is shown that some architectures, e.g. position-force (P-F), are able to provide the surgeon a reliable haptic sense of the working environment (transparency). However, stability of these P-F architecture is still a considerable concern especially when physiological disturbances exist in the remote environment. P-PF architecture is proved to provide a convenient alternative. With one more channel 3-channel teleoperation architectures present promising options due to their augmented design flexibility. This paper evaluates stability and transparency of general 3-channel bilateral teleoperation control architectures and provides a design framework guidelines to improve the architectures' stability robustness and optimize the transparency. Simulation evaluations are provided to illustrate how the optimal 3-channel teleoperation architecture is chosen for medical applications given their dedicated requirements.**

***Keywords* :** Bilateral Teleoperation, Haptic feedback, Three-channel architectures, Telesurgery.

I. INTRODUCTION

Teleoperation, telemanipulation and telerobotics are used synonymously to refer to operating on remote environment via connected Master-Slave Network (MSN). Teleoperation has been an active theme of research during past few decades. Since the first trial in nuclear field in mid 1940s, its applications have been extended to explore space, deep ocean and many other not easily reachable environments. The main motivation is to extend operator's capacity to manipulate in hazardous and/or unreachable environments while reserving his/her dexterity, preciseness etc. at the same time [1].

Two main objectives for designing connected master-slave, also called teleoperator, are stability and transparency [2]. Stability of the closed loop teleoperator must be maintained irrespective the behaviour of the operator and the environment. Likewise a transparent system is massless and infinitely stiff [3] and achieves the ideal kinesthetic coupling between master and slave robots. Ideal coupling is realized when the position responses of the master V_m and the slave V_s and the force responses of the master F_m and the slave F_s are respectively identical regardless the operator's and the manipulated environment's dynamics. In other words, to make the impedance felt by the operator and that of the remote environment identical [4].

4-channel control architecture, first proposed by Lawrence [5] and extended by by Hashtrudi-Zaad et al. [6], can be used to design a teleoperator and evaluate it's transparency and stability. The effects of local force feedback is evaluated in [7]. Teleoperation control architectures' stability is investigated using Llewellyn's absolute stability criteria [8], while it's performance is evaluated using "Z_{width}" notion [9] [10]. Furthermore, induced time delay problem inside a teleoperator is handled using passivity theory through scattering approach [5] [11] for constant time delay, or through wave variable technique [12]. Wave variable technique can be extended to handle variable time delays [13]. A global transparency analysis of Extended Lawrence Architecture (ELA) is provided in [14]. So far, most bilateral control architectures adopt 2-channel architectures P-P, P-F or 4-channel PF-PF architectures, where "P" stands for "position" and "F" for "force". The notation A-B (A, B = P, F, PF) used above and hereafter refers A to the signal(s) sent from the master toward the slave. Similarly, the signal(s) fedback from the slave to the master is (are) referred as B. These architectures together with the other two 2-channel architectures F-P and F-F have been evaluated in terms of absolute stability and performance in [6].

In the last decade, due to the advance of robot-assisted medical intervention technology, teleoperation system has found its way into surgical Operation Room (OR) [15]. Nowadays, more and more minimally invasive surgeries (MIS) can be carried out with teleoperated surgical robots, among which the most successful representative is *da Vinci* system by Intuitive Surgery Inc. Nevertheless, *da Vinci* system does not provide the surgeon with haptic feedback. Feeding back the interaction force between the slave (surgical robot) and patient tissues under operation would improve the performance and the success rate of teleoperated MIS [16]. For correct detection of tissue's mechanical properties in MIS for soft tissues during the procedure (transient mode), position/force tracking and impedance matching are most required [17]. To this end, many research works have been introduced to implement and improve the performance of the 2-channel haptic architecture P-F in tele-surgical framework [18] [19]. The effect of position and force scaling on performance and stability during the teleoperation on soft environments has been evaluated in [20].

Introducing the reflection force into a teleoperator will often cause stability problem due to nonlinearity of the human operator and the environment. This problem can interfere the realization of haptic interface when disturbance induced in the remote environment is significant (e.g. beating heart tele-surgery case). Introducing one more channel can enhance system stability as well as stability/transparency trade-off [25] [26] [27] [28]. Sherman et al. [21] confirmed this intuitive reasoning through experimental studies by comparing 2-channel P-P, P-F and 3-channel P-PF architectures.

Despite its encouraging experimental implementation, deeper understanding about stability and performance of the P-PF architecture is yet to be studied. And in literature, systematic analysis of the stability and performance of 3-channel architectures remains an open issue. Furthermore, for a given specific application scenario, how to choose the suitable 3-channel architecture and tune the system parameters to achieve the optimal trade-off between the two main objectives have not been addressed to the best of the authors' knowledge. In this work, general analyses of performance and stability robustness of impedance-impedance 3-channel architectures are carried out for the first time using Z_{width} notion [8] and Llewellyns criterion [9] respectively. A framework for each architectures controller design is provided. As the design guidelines change according to different application tasks, the analysis in

Abdulrahman Albakri*, Chao Liu and Philippe Poignet are with the Department of Robotics, LIRMM (CNRS-UM2), UMR5506, Montpellier, France. albakri, liu, poignet@lirmm.fr

this paper has been targeted for tele-surgery applications on soft-tissue (relatively low frequencies, negligible time delay and low impedances). Simulation studies are carried out to evaluate different architectures and illustrate how an optimal 3-channel architecture is chosen for the soft tissue tele-surgery application scenario.

II. Bilateral teleoperation architectures modelling and evaluation tools

According to the available and exchanged signals between the master and slave sites, 4 types of 3-channel architectures can be distinguished: P-PF, F-PF, PF-P and PF-F. These architectures can be deduced directly from Extended Lawrence Architecture (ELA) [6] Fig.1 by removing one of the communication channels.

A. Teleoperator Modelling

A teleoperator can be modeled as two-port network that exchange power variables as flow (velocity or current) and effort (force or voltage) [29] [2]. At each port the operator (environment) exchanges with the master (slave) the energy represented by force and position information. Single degree of freedom of a teleoperator can be modeled as a connection of cascade 2-port Linear Time Invariant (LTI) (impedance/admittance) blocks [5].

The closed loop dynamics on the master and the slave sites for general teleoperator with 4 communication time delayed channels, as shown in Fig.1, can be expressed as follows:

$$(Z_m + C_m)V_m = (1+C_6)F_m - C_4 e^{-sT_d} V_s - C_2 e^{-sT_d} F_s \quad (1)$$

$$(Z_s + C_s)V_s = -(1+C_5)F_s + C_1 e^{-sT_d} V_m + C_3 e^{-sT_d} F_m, \quad (2)$$

where $Z_i = M_i.s$, $C_i = B_i + K_i/s$ and $Z_{ci} = Z_i + C_i$, $(i = m, s)$ represent impedances and local position controllers of master and slave robot respectively. C_5 and C_6 are the local force controller on the slave and master robots respectively. C_n $(n = 1 \sim 4)$ are the communication layers gains. The gains related to force information (i.e. C_2, C_3, C_5 and C_6) are scalar gains. T_d represents induced time delay inside communication layers.

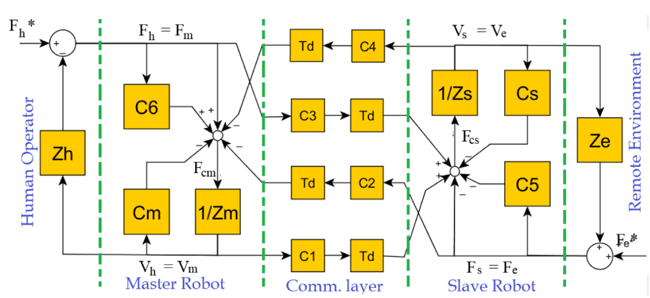

Fig. 1. 4-channel Extended Lawrence Architecture(ELA) [6]

Let $Y = \mathbb{P}\ u$ be the immitance mapping between the input u and the output Y [10], where the immitance matrix $\mathbb{P}$ can be the impedance matrix $\mathbb{Z}$, the admittance matrix $\mathbb{Y}$, the hybrid matrix $\mathbb{H}$ or the alternative hybrid matrix $\mathbb{G}$, where:

$$\begin{bmatrix} F_h \\ F_e \end{bmatrix} = \mathbb{Z} \begin{bmatrix} V_h \\ -V_e \end{bmatrix} \quad \begin{bmatrix} V_h \\ -V_e \end{bmatrix} = \mathbb{Y} \begin{bmatrix} F_h \\ F_e \end{bmatrix}$$
$$\begin{bmatrix} F_h \\ -V_e \end{bmatrix} = \mathbb{H} \begin{bmatrix} V_h \\ F_e \end{bmatrix} \quad \begin{bmatrix} V_h \\ F_e \end{bmatrix} = \mathbb{G} \begin{bmatrix} F_h \\ -V_e \end{bmatrix}. \quad (3)$$

Hybrid modeling has been widely employed to represent tele-operators. Based on ELA, H-matrix elements take the following form:

$$\mathbb{H} = \begin{bmatrix} \frac{Z_{cm}Z_{cs}+C_1C_4e^{-2sT_d}}{(1+C_6)Z_{cs}-C_3C_4e^{-2sT_d}} & \frac{C_2Z_{cs}e^{-sT_d}-C_4(1+C_5)e^{-sT_d}}{(1+C_6)Z_{cs}-C_3C_4e^{-2sT_d}} \\ -\frac{C_3Z_{cm}e^{-sT_d}+C_1(1+C_6)e^{-sT_d}}{(1+C_6)Z_{cs}-C_3C_4e^{-2sT_d}} & \frac{(1+C_5)(1+C_6)-C_2C_3e^{-2sT_d}}{(1+C_6)Z_{cs}-C_3C_4e^{-2sT_d}} \end{bmatrix}$$

and its interpretation is:

$$\mathbb{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = \begin{bmatrix} Z_{in} & \frac{1}{force\ scale} \\ velocity\ scale & Z_{out} \end{bmatrix}. \quad (4)$$

B. Stability

Passivity theory has been employed to design a stable teleoperator [5]. According to passivity theorem, teleoperation system is passive and stable if it is terminated by strictly passive operator and environment dynamics. Using immittance mapping representation $Y = \mathbb{P}u$, a 2-port network is passive if and only if its input and output satisfy:

$$\int_0^t Y^T(\tau)u(\tau)\ d\tau\ \geq\ 0\ \forall\ t\ \geq\ 0. \quad (5)$$

Necessary and sufficient conditions for unconditional stability of a LTI 2-port network are provided by Llewellyns absolute stability conditions [6], [8] and [10]. A LTI two-port network is absolutely stable if and only if:

$$\begin{aligned} &\Re\{p_{11}\}\ \geq\ 0 \\ &\Re\{p_{22}\}\ \geq\ 0 \\ &\eta_p(\omega) = -cos(\angle p_{12}p_{21}) + 2\frac{\Re\{p_{11}\}\Re\{p_{22}\}}{|p_{12}p_{21}|}\ \geq\ 1, \end{aligned} \quad (6)$$

where $p_{ij}, (i, j = 1, 2)$ are the elements of the immitance matrix $\mathbb{P}$. $\Re\{\chi\}$ is the real part of any complex χ and $\cos(\angle\chi) = \frac{\Re\{\chi\}}{|\chi|}$.

The first two conditions imply the passivity of the master and slave when there is no coupling between them i.e. when $p_{12} = p_{21} = 0$, while the third condition incorporates the effect of coupling. Llewellyns criterion is valid for any immittance matrix, and the value of the stability parameter is independent of the immittance matrix employed, that is, $\eta_z = \eta_y = \eta_h = \eta_g$. Absolute stability depends on the network parameters alone and is not subject to operator or environment linearity. This characteristic will be used to simplify the calculation of absolute stability criterion by using the simplest matrix representing the structure under consideration.

C. Performance evaluation

The performance of two port network teleoperator can be described in terms of transparency. Transparency is the match between the environment impedance and the impedance transmitted to the operator [5]. A teleoperator is said to be transparent when the kinematic correspondence condition $V_h = V_e$, the impedance matching condition $Z_{to} = Z_e$ and $Z_{te} = Z_h$ are valid all times for all frequencies, where Z_{to} is the impedance transmitted to the operator, Z_e the impedance of the remote environment, Z_{te} the impedance transmitted to the environment and Z_h human operator impedance. Considering $\triangle h = h_{11}h_{22} - h_{12}h_{21}$, Z_{te} and Z_{to} are defined as:

$$Z_{te} = \frac{F_h}{V_h} = \frac{h_{11} + Z_h}{\triangle h + h_{22}\ Z_h}, \quad Z_{to} = \frac{F_e}{V_e} = \frac{h_{11} + \triangle h\ .\ Z_e}{1 + h_{22}\ Z_e}. \quad (7)$$

A perfect trancparency, called also optimized transparency, is achieved when $h_{11} = h_{22} = 0$ and $h_{12}.h_{21} = -1$ hold. Accordingly, the communication layer gains in transparency optimized system were defined as:

$$\begin{aligned} C_1 &= Z_{cs} = Z_s + C_s \\ C_2 &= (1 + C_6) \\ C_3 &= (1 + C_5) \\ C_4 &= -Z_{cm} = -(Z_m + C_m). \end{aligned} \quad (8)$$

Nevertheless, transparency optimized system is marginally absolutely stable. To improve the architecture's stability robustness, perfect transparency has to be compromised [6]. The transparency can also be expressed using the notion of Z_{width} [9]. The impedance transmitted to the operator Z_{to} can be characterized by Z_{tomin} and $Z_{towidth}$. Z_{tomin} represents the impedance transmitted to the operator when the slave is in free space motion ($Z_e = 0$), and $Z_{towidth}$ represents the dynamic range of impedances transmitted to the operator when the environment impedance changes from zero to infinity ($Z_e = \infty$). System performance is optimized when $|Z_{tomin}| \to 0$, and $|Z_{towidth}| \to \infty$. From (7), Z_{tomin} and $Z_{towidth}$ can be written as:

$$Z_{tomin} = Z_{to} \mid_{Z_e=0} = h_{11} \tag{9}$$

$$Z_{towidth} = Z_{to}\mid_{Z_e\to\infty} = -h_{12}\, h_{21} / h_{22}. \tag{10}$$

III. Stability and Performance Analysis of 3-Channel Architectures

Telesurgery employed P-P architecture at the very beginning. P-P architecture is simple and accessible but non-transparent. Transparency and haptic sense represent major concerns in telesurgery. To perform a transparent teleoperation, two different types of information need to be exchanged between the two remote sites. Providing haptic sensation during telesurgical intervention improves remarkably quality of the procedure. P-F architecture appears as a promising alternative but also suffers the stability problem. The P-PF architecture has been proved to have more fidelity in comparison with P-P and P-F architectures. However, there is no analysis of this architecture compared with other 3-channel architectures.

The target application of this study is haptic teleoperation on soft tissues which are subject to motion disturbance (e.g. thoracic telesurgery). The architecture's stability has to be guaranteed for a relatively wide range of frequencies where the physiological motion disturbances include fast heart beating and relatively slow respiration. To maximize transparency of teleoperation on soft tissues, good performance values Z_{tomin} and $Z_{towidth}$ are expected. Despite that, enough range of impedances $Z_{towidth}$ that can be reflected to the operator is necessary, to achieve $|Z_{tomin}| \to 0$ is still a priority in medical telesurgery context since most operations are in contact with soft tissue or in free space.

3-channel architectures have been used in literature to perform teleoperation [16] [25] [26] [27] [28]. Hereafter the analysis in terms of stability and transparency of 3-channel architectures is addressed. Moreover, a design framework after each analysis is proposed to provide some useful guidelines to achieve the stability/-transparency trade-off. This paper employs the typical conception of the local position and force controllers C_m, C_s, C_5 and C_6 together with comunication layers' gains C_1, C_2, C_3 and C_4 where C_2, C_3, C_5, and C_6 assumed to be scalar gains.

A. Position-Position Force Control Architecture (Flow forward, Flow backward, Effort backward)

Position-position force (P-PF) architecture has already been used in medical context [23]. It can be deduced from ELA by setting direct effort forward gain to zero, i.e. $C_3 = 0$. Sherman et al. [21] showed through experiments that this architecture has better fidelity over P-P and P-F architectures. Nevertheless, no explicit evaluation of its stability and performance has been provided in literature.

Since $\eta_h = \eta_z = \eta_g = \eta_y$, the matrix that provides the simplest representation, here impedance matrix $\mathbb{Z}$, will be used to evaluate the absolute stability of P-PF architecture:

$$\begin{array}{ll} z_{11} = \frac{(1+C_5)Z_{cm}+C_1C_2e^{-2sT_d}}{(1+C_5)(1+C_6)} & z_{12} = \frac{C_2Z_{cs}-C_4(1+C_5)}{(1+C_5)(1+C_6)}e^{-sT_d} \\ z_{21} = \frac{C_1}{(1+C_5)}e^{-sT_d} & z_{22} = \frac{Z_{cs}}{(1+C_5)}. \end{array} \tag{11}$$

The positive realness of $\Re\{z_{11}\}$ and $\Re\{z_{22}\}$ implies the passivity of the master and slave robots when they are not coupled, that is when $C_i = 0$ $(i = 1,...,4)$. The passivity of the uncoupled master (z_{11}) and slave (z_{22}) is guaranteed since Z_{cm} and Z_{cs} are passive. Stability of coupled master-slave via P-PF teleoperation control architecture can be evaluated through the third condition of (6) :

$$\begin{aligned} \eta_{p.pf}(\omega) &= \eta_{1p.pf}(\omega) + \eta_{2p.pf}(\omega) \\ &= -cos(\angle z_{12}z_{21}) + 2\frac{\Re\{z_{11}\}\Re\{z_{22}\}}{|z_{12}z_{21}|} \\ &= -cos(\angle \frac{C_1}{(1+C_5)}\frac{C_2Z_{cs}-C_4(1+C_5)}{(1+C_5)(1+C_6)}e^{-2\omega jT_d}) \\ &\quad +2\frac{\Re\{\frac{(1+C_5)Z_{cm}+C_1C_2e^{-2\omega jT_d}}{(1+C_5)(1+C_6)}\}\Re\{\frac{Z_{cs}}{(1+C_5)}\}}{|\frac{C_1}{(1+C_5)}\frac{C_2Z_{cs}-C_4(1+C_5)}{(1+C_5)(1+C_6)}e^{-2\omega jT_d}|} \\ &= sgn(1+C_6)[-cos(\angle C_1(C_2Z_{cs}-C_4(1+C_5))\ e^{-2\omega jT_d}) + \\ &\quad 2\frac{\Re\{(1+C_5)Z_{cm}+C_1C_2e^{-2\omega jT_d}\}\Re\{Z_{cs}\}}{|C_1(C_2Z_{cs}-C_4(1+C_5))|}] \geq 1. \end{aligned}$$

To avoid the effect of time delay on $\eta_{1p.pf}(\omega)$, the architecture's absolute stability is guaranteed if $\eta_{2p.pf}(\omega) \geq 2$ because $\eta_{1p.pf(\omega)} = -cos(\angle\chi) \in [-1,+1]$ for any complex χ. Moreover, $|e^{-2\omega jT_d}| = 1$ limits time delay effect only to the numerator of $\eta_{2p.pf}$. Thus, stability of time delayed P-PF is guaranteed when the following condition holds:

$$\begin{aligned} \Re\{Z_{cm}\} \geq &-\frac{C_2}{(1+C_5)}\Re\{C_1e^{-2\omega jT_d}\} + \\ &\frac{sgn(1+C_6)|C_1|}{(1+C_5)\Re\{Z_{cs}\}}|(C_2Z_{cs}-C_4(1+C_5)|. \end{aligned} \tag{12}$$

This equation shows clearly that master damping $\Re\{Z_{cm}\}$ has a significant effect on the system's stability and has to be greater than a minimum amount regulated by (12). Time delay effect can be studied through numerical analysis. For example, if C_1 is designed to take the form $C_1 = a + \frac{b}{s}$, then $R\{C_1e^{-2\omega jT_d}\} \in [-a,\ a]$ when $\omega \gg 10$ rad/s can be approved through simulation. Otherwise, $|C_1|$ has a dominant effect. In Operating Room (OR), time delay induced in the telesurgical system is very small and hence negligible. Therefore, the absolute stability condition can be simplified to:

$$\begin{aligned} \eta_{p.pf}(\omega) = sgn(1+C_6)[-cos(\angle C_1(C_2Z_{cs}-C_4(1+C_5))) \\ +2\frac{\Re\{(1+C_5)Z_{cm}+C_1C_2\}\Re\{Z_{cs}\}}{|C_1(C_2Z_{cs}-C_4(1+C_5))|}] \geq 1. \end{aligned} \tag{13}$$

In this case, it should be noticed that $\eta_{1p.pf}(\omega) = -cos(\angle T(\omega j))$, where $T(\omega j)$ is a transfer function that can be assigned by the designer and written under the form $T(s) = a_t s + b_t + \frac{c_t}{s}$. This characteristic enables the designer to improve the stability margin of the architecture using $\eta_{1p.pf}(\omega)$ by assigning suitable parameters to $T(s)$. The architecture's stability investigation is performed using the condition $\eta_{2p.pf}(\omega) \geq 2$ and has:

$$\begin{aligned} \Re\{Z_{cm}\} \quad \geq \quad &-\frac{C_2\Re\{C_1\}}{(1+C_5)} \\ &+\ \frac{sgn(1+C_6)|C_1|}{(1+C_5)\Re\{Z_{cs}\}}|C_2Z_{cs}-C_4(1+C_5)|. \end{aligned} \tag{14}$$

Increasing the damping on the master/slave robots i.e $\Re\{Z_{cs}\}$, $\Re\{Z_{cm}\}$ and/or decreasing $|C_1|$ especially $\Re\{C_1\}$ improve the architecture's stability. Moreover, because $\frac{|C_1|}{\Re\{Z_{cs}\}}|C_2 Z_{cs} - C_4(1+C_5)| \geq 0$ for $0 < \omega < \infty$, designing $-C_2\Re\{C_1\}$ and $sgn(1+C_6)$ in a way to have counteractive signs will improve the stability. Because C_2 is frequency independent, the stability robustness can be enhanced by scaling down the slave-environment interaction force before feedback it to the master with $0 \leq C_2 \leq 1$. Nevertheless, this tuning has a counteractive effect on architecture's transparency where it reduces the range of impedances that can be reflected to the teleoperator. The performance is analysed using (9) and(10):

$$Z_{tomin} = h_{11} = \frac{Z_{cm}}{(1+C_6)} + \frac{C_1 \ C_4 e^{-2sT_d}}{(1+C_6)Z_{cs}}$$
$$Z_{towidth} = -\frac{h_{12} \ h_{21}}{h_{22}} = \frac{C_1 e^{-2sT_d}}{(1+C_5)(1+C_6)Z_{cs}}[Z_{cs}C_2 - C_4(1+C_5)]. \quad (15)$$

Because Transparency evaluation is characterized by the study of $|Z_{tomin}|$ and $|Z_{towidth}|$ and considering $|e^{-2\omega j T_d}| = 1$, the role of time delay is reduced to only affect $|Z_{tomin}|$. As it is already mentioned, good performance can be achieved if $|Z_{tomin}| \rightarrow 0$ and $|Z_{towidth}| \rightarrow \infty$. $|Z_{tomin}| = 0$ is achieved for non-delayed system when $C_1 = Z_{cs}$ and $C_4 = -Z_{cm}$. However, since mass in Z_{cm}, and Z_{cs} can't be zero, perfect transparency can't be achieved and needs to be compromised with absolute stability margin. This can be easily seen by substituting these two conditions in the original stability condition of non-delayed system. Indeed, using a, b in C_1, C_2 as $C_1 = a.Z_{cs}$ and $C_4 = -b.Z_{cm}$ may help to obtain better trade-off between stability and transparency. $|Z_{tomin}|$ can also be improved by decreasing $|C_1|$ which will reduce the range of impedances that can be reflected to the teleoperator $|Z_{towidth}|$. Increasing $\Re\{Z_{cs}\}$ will improve simultaneously performance and absolute stability of the architecture. Increasing $(1+C_6)$ has no effect on the stability parameter, but it reduces $|Z_{tomin}|$ and at the same time the range of the reflected impedances $|Z_{towidth}|$. Finally C_2 can be used to achieve the trade-off between $|Z_{towidth}|$ and $\eta_{p.pf}$ depending on specific system setup without affecting $|Z_{tomin}|$.

It can be seen that stability and performance analysis of 3-channel architecture is much more complicated than 2-channel architectures. Except few parameters whose roles are easy to identify, other parameters need to be tuned carefully to achieve good trade-off of absolute stability and performance depending on specific application requirements and system setup.

B. Force-Position Force Control Architecture (F-PF) (Effort forward, Flow backward, Effort backward)

To the authors' knowledge, this work is the first time for the architecture F-PF to be analysed in terms of absolute stability and transparency. This architecture can be deduced from ELA by setting master coordinating force feedforward controller to zero, that is $C_1 = 0$. Stability is investigated depending on alternative hybrid matrix $\mathbb{G}$:

$$g_{11} = \frac{(1+C_5)(1+C_6) - C_2C_3e^{-2sT_d}}{(1+C_5)Z_{cm}} \qquad g_{12} = -\frac{C_2Z_{cs} - C_4(1+C_5)}{(1+C_5)Z_{cm}}e^{-sT_d}$$
$$g_{21} = \frac{C_3}{(1+C_5)}e^{-sT_d} \qquad g_{22} = \frac{Z_{cs}}{(1+C_5)}. \quad (16)$$

First two conditions in Llewellyn's criterions are guaranteed due to the passivity of non-connected master and slave. Third condition evaluates the stability of F-PF control architecture:

$$\begin{aligned}\eta_{f.pf}(\omega) &= \eta_{1f.pf}(\omega) + \eta_{2f.pf}(\omega)\\ &= -cos(\angle g_{12}g_{21}) + 2\frac{\Re\{g_{11}\}\Re\{g_{22}\}}{|g_{12}g_{21}|}\\ &= -cos(\angle - \frac{C_3}{Z_{cm}}(C_2Z_{cs} - C_4(1+C_5))e^{-2\omega T_d j})\\ &+ 2\frac{\Re\{(1+C_5)(1+C_6) - C_2C_3e^{-2\omega T_d j}\}\Re\{Z_{cs}\}}{\frac{\Re\{Z_{cm}\}}{|Z_{cm}|}|C_3||C_2Z_{cs} - C_4(1+C_5)|}] \geq 1.\end{aligned}$$

Because $\eta_{1f.pf} \in [-1,+1]$ and includes $e^{-2\omega T_d j}$, the absolute stability of the system can be guaranteed only when $\eta_{2f.pf} \geq 2$. To guarantee absolute stability, the following condition must hold:

$$\Re\{Z_{cs}\} \geq \frac{cos(\angle Z_{cm})|C_3|.|C_2Z_{cs} - C_4(1+C_5)|}{\Re\{(1+C_5)(1+C_6) - C_2C_3e^{-2\omega T_d j}\}}. \quad (17)$$

Since C_2, C_3, C_5 and C_6 are considered as scalar gains, The role of time delay is obvious by inspecting the most critical case of $\Re\{e^{-2\omega T_d j}\} = cos(2\omega T_d) \in [-1 \ 1]$, and when: $\Re\{(1+C_5)(1+C_6) - C_2C_3e^{-2\omega T_d j}\} = (1+C_5)(1+C_6) - C_2C_3\Re\{e^{-2\omega T_d j}\} = 0$. This means that time delay may cause the system to lose absolute stability for certain frequencies. When time delay is negligible ($T_d = 0$), absolute stability parameter takes the form:

$$\begin{aligned}\eta_{f.pf}(\omega) = &-cos(\angle - \frac{C_3}{Z_{cm}}(C_2Z_{cs} - C_4(1+C_5)))\\ &+2\frac{((1+C_5)(1+C_6) - C_2C_3)\Re\{Z_{cs}\}}{\frac{\Re\{Z_{cm}\}}{|Z_{cm}|}|C_3||C_2Z_{cs} - C_4(1+C_5)|}] \geq 1 \ .\end{aligned} \quad (18)$$

The absolute stability criterion is reduced to:

$$\Re\{Z_{cs}\}cos(\angle Z_{cm}) \geq \frac{|C_3||C_2Z_{cs} - C_4(1+C_5)|}{(1+C_5)(1+C_6) - C_2C_3} \ . \quad (19)$$

Because $\Re\{Z_{cm}\} = B_m \geq 0$, $-\frac{\pi}{2} \leq \angle Z_{cm} \leq \frac{\pi}{2}$ holds and hence $cos(\angle Z_{cm}) = \frac{\Re\{Z_{cm}\}}{|Z_{cm}|} \in [0,1]$. Accordingly, Increasing M_m (for high frequencies) and K_m (for low frequencies) in the imaginary part of Z_{cm} and decreasing master damping B_m, so that $cos(\angle Z_{cm}) \rightarrow 0$, and improves architecture's stability. The formula (19) shows that force controller gains C_2, C_3, C_5 and C_6 have a dominant role on the stability of the architecture. This conclusion can be justified easily because the two remote sites are exchanging basically force signals in addition to the position information received from slave side. However, optimized transparency architecture can't be realized because applying $(1+C_5)(1+C_6) - C_2C_3 \rightarrow 0$ implies extremely high damping on slave robot. It is also worthy to note that increasing the damping $\Re\{Z_{cs}\}$ on slave part and decreasing $|Z_{cs}|$ by reducing its imaginary part improve the architecture's stability.

Performance investigation is accomplished by applying the equations (9) and (10) on F-PF hybrid matrix to get:

$$Z_{tomin} = \frac{Z_{cm}Z_{cs}}{(1+C_6)Z_{cs} - C_3C_4e^{-2sT_d}}$$
$$Z_{towidth} = \frac{(C_2Z_{cs} - C_4(1+C_5))C_3Z_{cm}e^{-2sT_d}}{((1+C_6)Z_{cs} - C_3C_4e^{-2sT_d})((1+C_5)(1+C_6) - C_2C_3e^{-2sT_d})}. \quad (20)$$

The role of time delay is very complicated and needs numerical analysis to evaluate its effect on a specific teleoperator. On the other hand, it can be remarked that $|Z_{towidth}| = T(\omega)|Z_{tomin}|$. This means that minimizing $|Z_{tomin}|$ will lead to reduced range of impedances that can be reflected and the parameters need to be compromised.

Comparing (19) and (20) shows clearly the necessity of compromising the stability margin to improve the architecture's performance. $|Z_{tomin}|$ can be minimized by minimizing $|Z_{cm}Z_{cs}|$ and/or increasing $|(1+C_6)Z_{cs} - C_3C_4e^{-2sT_d}|$. The latter can be done by increasing C_6. Increasing the range of impedances that can be reflected through the teleoperator demands to decrease force controller gains C_5 and C_6. $|Z_{cm}|$ plays an important role to improve and compromize $|Z_{towidth}|$.

C. Position Force-Position Control Architecture (PF-P) (Flow forward, Effort forward, Flow backward)

Hashtrudi-Zaad et al. discussed in [7] this architecture's transparency as a special case realized from optimized Extended Lawrence Architecture (ELA) by applying $C_6 = -1$, this requires C_2 to be zero. However, stability analysis of this architecture has not been reported yet. Stability evaluation is performed based on ELA using alternative hybrid matrix ($\mathbb{G}$) by removing the direct force feedforward from slave to master i.e. $C_2 = 0$:

$$\begin{aligned} g_{11} &= \frac{(1+C_6)}{Z_{cm}} & g_{12} &= \frac{C_4 e^{-sT_d}}{Z_{cm}} \\ g_{21} &= \frac{C_3 Z_{cm} + C_1(1+C_6)}{(1+C_5)Z_{cm}} e^{-sT_d} & g_{22} &= \frac{Z_{cm}Z_{cs} + C_1 C_4 e^{-2sT_d}}{(1+C_5)Z_{cm}} \end{aligned} \quad (21)$$

First two conditions of Llewellyn's stability criterions (6) hold because non-coupled master and slave are passive. Teleoperator stability is evaluated using 3^{rd} condition of (6):

$$\begin{aligned} \eta_{pf.p}(\omega) &= \eta_{1pf.p}(\omega) + \eta_{2pf.p}(\omega) \\ &= -cos(\angle g_{12}g_{21}) + 2\frac{\Re\{g_{11}\}\Re\{g_{22}\}}{|g_{12}g_{21}|} \\ &= sgn(1+C_5)[-cos(\angle C_4 \frac{C_3 Z_{cm} + C_1(1+C_6)}{Z_{cm}^2 \ e^{2\omega j T_d}}) \\ &+ 2\frac{(1+C_6)}{cos^2(\angle Z_{cm})} \frac{\Re\{Z_{cm}Z_{cs} + C_1 C_4 e^{-2\omega j T_d}\}}{|C_4||C_3 Z_{cm} + C_1(1+C_6)|} \geq 1 \end{aligned}$$

The absolute stability is guaranteed when $\eta_{2pf.p} \geq 2$:

$$\begin{aligned} &\Re\{Z_{cm}Z_{cs}\} \geq -\Re\{C_1 C_4 e^{-2\omega j T_d}\} \ + \\ &\frac{sgn(1+C_5)}{(1+C_6)} cos^2(\angle Z_{cm})|C_4||C_3 Z_{cm} + C_1(1+C_6)| \end{aligned} \quad (22)$$

Time delay effect on stability evaluation is reduced to $\Re\{C_1 C_4 e^{-2\omega j T_d}\}$. Significant effect of time delay can be handseled by decreasing $|C_1 C_4|$ and especially $|C_4|$. Condition (22) shows that minimum amount of $\Re\{Z_{cm}Z_{cs}\}$ is necessary to guaranty the stability. Moreover, it's noted that $\angle Z_{cm}$ has a significant effect on system's stability. If a certain design of a teleoperator is imposed, stability margin can be improved when $\angle Z_{cm} \rightarrow \pm\frac{\pi}{2}$. Because two remote sites are exchanging basically position informations supported by force information sent from master site toward slave one, position feedforward gains C_1, C_4 and position controllers on each site C_m, C_s has major effect to achieve a stable architecture and to compromise stability robustness with architecture transparency. However, decreasing C_3 or increasing $|1+C_6|$ may also improve the stability. Performance evaluation is carried out by applying (9) and (10) on PF-P's hybrid representation:

$$\begin{aligned} Z_{tomin} &= h_{11} = \frac{Z_{cm}Z_{cs} + C_1 C_4 e^{-2sT_d}}{(1+C_6)Z_{cs} - C_3 C_4 e^{-2sT_d}} \\ Z_{towidth} &= -\frac{h_{12}h_{21}}{h_{22}} = -\frac{C_4}{(1+C_6)} \frac{C_3 Z_{cm} + C_1(1+C_6)}{(1+C_6)Z_{cs} - C_3 C_4 e^{-2sT_d}} e^{-2sT_d}. \end{aligned} \quad (23)$$

Time delay affects clearly the performance of this architecture, especially the minimum impedance reflected to the operator. Nevertheless, this effect can be reduced by decreasing $|C_4|$ mainly and/or decreasing $|C_1|$, $|C_3|$. Examining performance parameters shows an opposition between them and their assignment subjects to specific application requirements.

In tele-surgery on soft tissues, low $|Z_{tomine}|$ and high sensitivity are most demanded in a teleoperator. Therefore, after designing a stable teleoperator, minimum reflected impedance characteristic is first of all to be compromised and achieved. Then additional margin can be used to improve impedance bandwidth. $|Z_{tomine}|$ can be decreased by increasing $|Z_{cs}|$ and $|C_3|$ or decreasing $|Z_{cm}|$, $|C_1|$ and $|C_6|$. On the other hand, bigger $|Z_{towith}|$ needs increasing $|Z_{cm}|$, $|C_1|$ and $|C_3|$ and/or decreasing $|Z_{cs}|$ and $|C_6|$. As consequence, bigger $|C_3|$ and smaller $|C_6|$ are preferred to achieve better performance.

D. Position Force-Force Control Architecture (PF-F) (Flow forward, Effort forward, Effort backward)

To the authors' knowledge, the analysis of PF-F in terms of stability and transparency has not yet been addressed in the literature. To derive this architecture from Extended Lawrence Architecture, coordinating force feedforward from slave to mater needs to be removed by setting C_4 to zero. Stability evaluation is performed by applying Llewellyn's criterions (6) on hybrid matrix ($\mathbb{H}$):

$$\begin{aligned} h_{11} &= \frac{Z_{cm}}{(1+C_6)} & h_{12} &= \frac{C_2}{(1+C_6)} e^{-sT_d} \\ h_{21} &= -\frac{C_3 Z_{cm} + C_1(1+C_6)}{(1+C_6)Z_{cs} \ e^{sT_d}} & h_{22} &= \frac{(1+C_5)(1+C_6) - C_2 C_3 e^{-2sT_d}}{(1+C_6)Z_{cs}} \end{aligned} \quad (24)$$

Uncoupled master-slave passivity is guaranteed because Z_{cm} and Z_{cs} are passive. (PF-F) teleoperator's stability is evaluated depending on the 3^{rd} condition of Llewellyn's criterions (6):

$$\begin{aligned} \eta_{pf.f}(\omega) &= \eta_{1pf.f}(\omega) + \eta_{2pf.f}(\omega) \\ &= -cos(\angle h_{12}h_{21}) + 2\frac{\Re\{h_{11}\}\Re\{h_{22}\}}{|h_{12}h_{21}|} \\ &= -cos(\angle -\frac{C_2}{Z_{cs}}(C_3 Z_{cm} + C_1(1+C_6))e^{-2\omega j T_d}) \\ &+ 2\frac{\Re\{Z_{cm}\}\Re\{(1+C_5)(1+C_6) - C_2 C_3 e^{-2\omega j T_d}\}}{cos(\angle Z_{cs})|C_2||C_3 Z_{cm} + C_1(1+C_6)|} \geq 1. \end{aligned}$$

To circumvent time delay effect inside $\eta_{1pf.f}$, absolute stability of the system can be guaranteed only when $\eta_{2pf.f}(\omega) \geq 2$. To realize a stable PF-F architecture for certain range of frequencies, the following condition must hold:

$$\Re\{Z_{cm}\} \geq \frac{cos(\angle Z_{cs})|C_2||C_3 Z_{cm} + C_1(1+C_6)|}{(1+C_5)(1+C_6) - C_2 C_3 cos(-2\omega T_d)} \quad (25)$$

To satisfy (25), small $|C_2|$ and $cos(\angle Z_{cs})$ are preferred. Minimizing $|C_2|$ leads to reduce time delay effect and improve simultaneously architecture's stability. However, condition (25) shows clearly the necessity of minimum amount of damping on master to guarantee system's stability. Increasing local force controllers on each sites and/or adjusting $\angle Z_{cs}$ in a way so that $\angle Z_{cs} \rightarrow \pm\frac{\pi}{2}$ will also improve architecture's stability. When time delay is negligible, $\eta_{1pf.f}(\omega)$ can be used to improve stability margin for certain range of frequencies by adjusting the transfer function appeared inside the cosine function. Following (9) and (10) gives:

$$\begin{aligned} Z_{tomin} &= h_{11} = \frac{Z_{cm}}{(1+C_6)} \\ Z_{towidth} &= -\frac{h_{12}h_{21}}{h_{22}} = \frac{C_2}{(1+C_6)} \frac{C_3 Z_{cm} + C_1(1+C_6)}{(1+C_5)(1+C_6) - C_2 C_3 e^{-2sT_d}} e^{-2sT_d}. \end{aligned} \quad (26)$$

$|Z_{tomin}|$ can be minimized by decreasing $\Im m\{Z_{cm}\}$ and thus $|Z_{cm}|$ without affecting (25) or by increasing $|C_6|$. Note that reducing $\angle Z_{cm}$ won't affect system's stability. Moreover, time delay doesn't affect $|Z_{tomin}|$. On the other hand, increasing $|Z_{towidth}|$ requires decreasing C_3, C_5, C_6 and/or increasing $|C_1|$, C_2 and $|Z_{cm}|$. Again, as trade-off, smaller $|Z_{cm}|$, $|C_5|$ and bigger $|C_1|$, C_2 are preferred for better transparency.

IV. Simulation Studies and Discussions

In this section, two simulation studies are carried out to analyze the performance and the absolute stability of different 3-channel architectures and illustrate how an optimal 3-channel architecture is selected according to the analysis and given application specifications to achieve a good trade-off between stability and transparency.

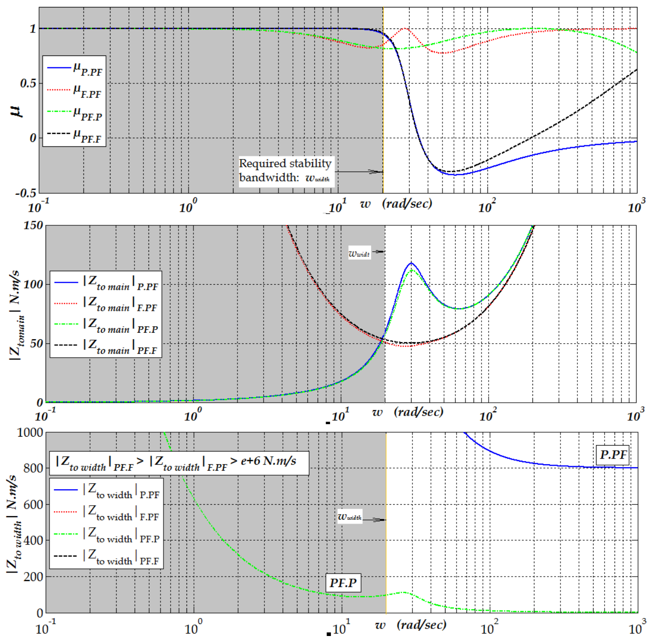

Fig. 2. 1st Example: Absolute stability parameter (upper), Performance parameters $|Z_{tomin}|$ (middle) and $|Z_{towidth}|$ (lower).

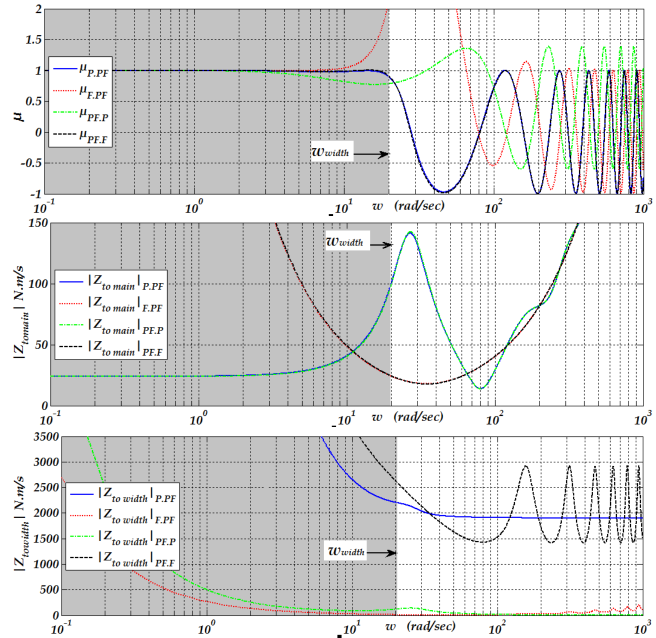

Fig. 3. 2st Example: Absolute stability parameter (upper), Performance parameters $|Z_{tomin}|$ (middle) and $|Z_{towidth}|$ (lower).

Beating heart is a very challenging environment and its movement frequency is up to 2 Hz. Thus, the motion disturbance frequencies in thoracic telesurgery lie in the range 0 $\sim$ 2 Hz (0 $\sim$ 12.6 rad/s) [31]. In this simulations, the target range of frequencies for stable teleoperation is set to 20 rad/sec. Because soft tissues has usually low impedances, $|Z_{tomin}| \rightarrow 0$ is a more important characteristic to consider for transparency. However, enough range of $Z_{towidth}$ still has to guaranteed. Teleoperator sensitivity as another measurement for soft tissue MIS is beyond the scope of this paper and hence is not discussed.

TABLE I

SIMULATION PARAMETERS OF TELEOPERATOR'S CONTROLLER GAINS

		1st Simulation	2nd Simulation
$Z_m = 0.7s$ & $Z_s = 50s$			
Local Controllers	C_m	$50 + \frac{630}{s}$	$30 + \frac{850}{s}$
	C_s	$800 + \frac{40000}{s}$	$1100 + \frac{50000}{s}$
	C_5	0	0.7
	C_6	0	0.7
Communication Layer	C_1	$800 + \frac{40000}{s}$	$5500 + \frac{50000}{s}$
	C_2	1	1
	C_3	1	1
	C_4	$-(50 + \frac{630}{s})$	$-(30 + \frac{850}{s})$
Time delay	T_d	0 ms	20 ms

A specific teleoperator has been used in both of these simulations with two different sets of bilateral controllers. The master and the slave were modeled as impedance instruments. Operator-master and slave-environment interaction forces are communicated with no scaling. In practice, the acceleration measurements are noisy and not always available, so they are neglected. Therefore, the communication channels C_1 and C_4, of the optimized transparency architecture, take the form $C_1 = C_s$ and $C_4 = -C_m$ rather than $C_1 = Z_{cs}$ and $C_4 = -Z_{cm}$. Simulation parameters are shown in TableI. Simulation results are shown in Fig.2 and Fig.3. Except different controller gains used, 20 ms time delay is introduced in the 2nd simulation.

The upper part of each figure introduces the absolute stability parameter η. An architecture is said to be absolutely stable when $\eta \geq 1$ as in (6). In fact, each architecture can be tuned to be absolutely stable for certain range of frequencies but then the architecture's performance will degrade. The middle part of each figure shows the minimum impedance that can be felt through the teleoperator i.e. when $Z_e = 0$. $|Z_{tomin}|$ as a performance measurement has to be very small and its value depends on target application. The lower part provides the range of impedances that can be reflected through the teleoperator. This range is expected be as wide as possible to enable the teleoperator to reflect a big variety of environments.

The first simulation is performed based on optimized transparency architectures without time delay mimicking the case as in OR. The teleoperator's controllers can be tuned to guaranty the architectures' stability in the target range of frequencies (as indicated by the dark region). The middle part of Fig.2 shows that low $|Z_{tomin}|$ can be achieved by P-PF and PF-P architectures while F-PF and PF-F give poor performance. In the lower figure PF-P and F-PF are not shown since they possess high enough $|Z_{towidth}|$ over large range of frequencies. P-PF architecture is shown to have enough reflected impedance range. Comparatively, PF-P architecture offers very low $|Z_{towidth}|$. This simulation study shows that P-PF architecture presents the optimal choice for our targeted application. In fact, this conclusion won't be changed using different control parameters. Fig.3 shows a non-optimized transparency case with time delay. The above discussions and conclusions are shown to still stand valid. Hence, P-PF presents the most suitable architecture for our application (soft tissues MIS).

Nevertheless, it can be noticed that if $|Z_{tomin}| \rightarrow a$ instead of $|Z_{tomin}| \rightarrow 0$ is expected (e.g. applications that use hydraulic teleoperator) where a is a small enough impedance, then PF-F architecture (black line) may be the suitable option. In fact PF-F architecture is more suitable for heavy environment and big impedances. Actually, P-PF and PF-F architecture are based on P-F architecture (which mimics the ideal teleoperator) supported by position information from slave side in P-PF and by force information from master side in PF-F. The additional information channel provides more freedom to achieve stability/transparency trade-off, which again justify the use of 3-channel architectures.

V. Conclusions

In this work, a general evaluation procedure for 3-channel architecture is established based on Llewellyns absolute stability criterions and Z_{width} notion for transparency. All possible 3-channel architectures have been evaluated using these tools in an uniformed manner and design guidelines are provided after each evaluation considering the specific concerns of medical applications. Simulation studies have been carried out to evaluate the stability and performance of each 3-channel architecture. The P-PF architecture is recommended based on analysis of simulation evaluation results.

References

[1] B. Siciliano, O. Khatib (Eds.): *Springer Handbook of Robotics* (Parts D and F), Springer, 2008.

[2] P.F. Hokayem, M.W. Spong, "Bilateral teleoperation:An historical survey", *Automatica*, v.42, n.12, pp.2035-2057, 2006.

[3] M. Handlykken, T. Turner, "Control system analysis and synthesis for a six degree-of-freedom universal force-reflecting hand controller", *IEEE Conference on Decision and Control including the Symposium on Adaptive Processes*, v.19, pp. 1197-1205, 1980.

[4] Y. Yokokohji, T. Yoshikawa, "Bilateral control of masterslave manipulators for ideal kinesthetic couplingformulation and experiment", *IEEE Trans. on Robotics and Automation*, v.10, n.5, pp. 605-620, 1994.

[5] D. A. Lawrence,"Stability and transparency in bilateral teleoperation", *IEEE Trans. on Robotics and Automation*, v.9, n.5, pp. 625-637, 1993.

[6] K. Hashtrudi-Zaad and S. E. Salcudean, "Analysis of control architectures for teleoperation systems with impedance/admittance master and slave manipulators", *Int. J. Rob. Res.*, v.20, n.6, pp. 419-445, 2001.

[7] K. Hashtrudi-Zaad and S. E. Salcudean, "Transparency in Time-Delayed Systems and the Effect of Local Force Feedback for Transparent Teleoperation," *IEEE Trans. on Robotics and Automation*, vol. 18, no. 1, pp. 108-114, Feb. 2002.

[8] S.S. Haykin, *Active Network Theory*. Addison-Wesley, 1970.

[9] J.E. Colgate, J. M. Brown, "Factors Affecting the Z-Width of a Haptic Display", *Proc. of the IEEE ICRA* , pp. 3205-10, 1994.

[10] R.J. Adams and B. Hannaford, "Stable Haptic Interaction wit Virtual Environments", *IEEE Trans. on Robotics and Automation*, v.15, pp.465-474, 1999.

[11] R.J. Anderson, M.W. Spong, " Bilateral control of teleoperators with time delay ", *IEEE Trans. on Auto. Cont.*, v.34, n.5, pp. 494-501, 1989.

[12] G. Niemeyer, J.E. Slotine, "Stable adaptive teleoperation",*IEEE Journal of Oceanic Engineering*, v.16, n.1, pp. 152-162, 1991.

[13] E. Nuno, L. Basanez, R. Ortega, M.W. Spong, "Position Tracking for Non-linear Teleoperators with Variable Time Delay", *The Int. Journal Of Robotics Research*, v.28, n.7, pp.895-910, July 2009

[14] E. Naerum, B. Hannaford, "Global Transparency Analysis of the Lawrence Teleoperator Architecture", *ICRA'09*, pp. 3866-71, 2009.

[15] A. Suliman, H. Ashrafian, T. Athanasiou, "Current Trends and Future Developments in Robotic Cardiac Surgery", *Hospital Chronicles*, v.5, n.1, pp.151-156, 2010.

[16] A.M. Okamura: "Methods for haptic feedback in teleoperated robot-assisted surgery", *Industrial Robot* v.31, n.6, pp. 499-508, 2004.

[17] M.Tavakoli, A.Aziminejad, R.V.Patel, M.Moallem, "High-Fidelity Bilateral Teleoperation Systems and the Effect of Multimodal Haptics". *IEEE Trans. on Sys., Man, and Cyber.*, v.37, n.6, pp.1512-28, 2007.

[18] J. Rosen, B. Hannaford, R.M. Satava, (Eds.): *Surgical Robotics*, 1st Ed., Springer, 2011.

[19] L.A. Sanchez, M.Q. Le, K. Rabenorosoa, et al. "A Case Study of Safety in the Design of Surgical Robots : The ARAKNES platform", in Proceeding of 12th International Conference on Intelligent Autonomous Systems (IAS'12), Jeju, Korea, 2012.

[20] H.I. Son, T. Bhattacharjee, and H. Hashimoto, "Effect of Scaling on the Performance and Stability of Teleoperation Systems Interacting with Soft Environments", Advanced Robotics, pp.1577-1601, 2011.

[21] A. Sherman, M. C. Cavusoglu, "Comparison of Teleoperator Cconrol Architectures for Palpation Task", *Proc. IMECE00*, pp. 1261-68, 2000.

[22] M.C. Cavusoglu, A. Sherman, F. Tendick, "Design of bilateral teleoperation controllers for haptic exploration and telemanipulation of soft environments", *IEEE Trans. Rob. and Aut.*, v.18, pp.641-647, 2002.

[23] J.J. Abbott and A.M. Okamura, "Stable forbidden-region virtual fixtures for bilateral telemanipulation", *Journal of Dynamic Systems, Measurement and Control*, v. 128, n. 1, pp. 53-64, 2006.

[24] H.I. Son, T. Bhattacharjee, D.Y. Lee, "Estimation of environmental force for the haptic interface of robotic surgery", *Int J Med Robot.*, v.6 n.2 pp.221-230, 2010.

[25] H. Flemmer, J. Wikander : "Transparency and Stability Analysis of a Surgical Teleoperator System", HAPTICS, pp. 605-620, 2003.

[26] R. Kubo, N. Iiyama, K. Natori et al. : "Performance Analysis of a Three-Channel Control Architecture for Bilateral Teleoperation with Time Delay," *IEEE Trans. on Industry Applications*, vo.127, n.12, pp.1224-30, 2007.

[27] S. Susa, K. Natori, K. Ohnishi,"Three-Channel Micro-Macro Bilateral Control System with Scaling of Control Gains", *34th IEEE Ann. Conf. on Industrial Electronics,IECON*, pp. 2598- 2603, 2008.

[28] C.J. Zandsteeg, D.J.H. Bruijnen, M.J.G. van de Molengraft,"Haptic tele-operation system control design for the ultrasound task: A loop-shaping approach", *Mechatronics*, v.20, pp.767-777, 2010.

[29] B. Hannaford, "A Design Framework for Teleoperators with Kinesthetic Feedback", *IEEE Trans. Rob. Aut.*, v.5, n.4, pp.426-434, 1989.

[30] T. L. Brooks, "Telerobotic response requirements". *IEEE Inter. Conf. on Sys., Man and Cybernetics*, pp. 113-120, 1990.

[31] W. Bachta, P. Renaud, L. Cuvillon, E. Laroche, A. Forgione, J. Gangloff,"Motion Prediction for Computer-Assisted BeatingHeart Surgery", *IEEE Trans. Biom. Eng.*, v.56, n.11, pp. 2551-63, 2009.