Transparency Trade-offs for a 3-channel Controller Revealed by the Bounded Environment Passivity Method

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Abstract—In this paper, the Bounded Environment Passivity method [1] is applied to a 3-channel controller. This method enables the design of teleoperation controllers that show passive behaviour for interactions with a bounded range of environments. The resulting tuning guidelines, derived analytically, provide interesting tuning flexibility, which allows to focus on different aspects of transparency. As telesurgery is the motivation behind this work, the focus lies on correctly reflecting the stiffness properties of the environment. A comparison between the transparency and stability properties of this 3-channel controller and the same properties of the Position-Force controller demonstrates the interesting properties of the 3-channel controller. The theoretical results are verified experimentally on a 1 d.o.f. master-slave setup.

Keywords—Teleoperation; human-robot interaction; transparency; stability

I. INTRODUCTION

A teleoperation system allows a human operator to manipulate a (remote) environment through a master and slave robotic device. The human operator interacts with the master device, while the slave device interacts with the environment. When such system provides haptic feedback to the operator, he/she can also feel the (remote) environment. Teleoperation systems have been used for several applications like handling of radioactive material, operating unmanned underwater vehicles, space robotics and telesurgery [2]. Nowadays, telesurgery is a common practice, although the lack of haptic feedback is often mentioned as a major drawback [3]. The realization of reliable haptic feedback for telesurgery remains a real challenge and is the motivation behind the work presented in this paper.

The design of a teleoperation system with reliable haptic feedback always comes down to finding the right trade-off between transparency and stability for the envisioned application. In order to have a completely transparent system, the teleoperation system should behave as a massless, infinitely stiff connection between the end-effector of the master and the slave [4]. In that case, the human operator feels as if he/she is directly manipulating the remote environment. One should realize that this ideal system is not *strictly* passive, which explains why

designing a real teleoperation system that is both completely transparent and guaranteed stable is unrealistic. In order to obtain full transparency, one depends on ideal conditions, i.e. the exact knowledge of the slave's and master's hardware, as well as exact measurements of force, position, velocity and acceleration. As a consequence, the practical feasibility of this ideal system is limited. Lawrence [5] and Yokokohji and Yoshikawa [6] proposed, independent of each other, a “four-channel” controller realizing full transparency under ideal conditions, but recognized the limited practical feasibility. In theory, full transparency can also be obtained with a three-channel controller [7] and a two-channel controller [8], again under the assumption of ideal conditions. In literature, a lot of attention has been paid to both the transparency properties of the extended Lawrence Architecture [7], [9], [8], [10] and to the stability properties. The detailed stability analysis in [11], [12], [1], however, are restricted to two-channel controllers, while the analyses in [5], [6], [13] are very general. In this paper, task-based tuning guidelines are derived by incorporating knowledge about the environment, which allows a detailed analysis of both transparency and stability.

This paper applies the Bounded Environment Passivity method presented by Willaert et al. [1]. This method studies the passivity of the one-port network Y_{MS} that consists of both the teleoperation system and the environment for a range of environments. As shown in Fig. 1, this is the one-port network with which the human operator interacts. In [1], this method has been applied to the Position-Force two-channel controller and the considered environment, Z_e , was a pure stiffness, K_e , with a *bounded* magnitude:

$$Z_e = \frac{K_e}{s} \quad \text{with} \quad K_e \in [0, K_e^{\max}] \quad (1)$$

Note that from passivity point of view, a pure stiffness and a pure mass are the *worst* case environments [14]. Here, the considered environment will again be a pure stiffness, as the motivation behind this work is telesurgery. One can assume that the inertial properties of the environment the surgeon interacts with, are negligible. Furthermore, it is relatively easy to delineate a range of stiffnesses $[0, K_e^{\max}]$ with which the surgeon typically interacts.

Figure 1: A one-port network $Y_{MS(K_e)}$ representation of a combined teleoperator-environment system.

Here, the Bounded Environment Passivity method is used to study the stability properties of a 3-channel controller originating from the Extended Lawrence Architecture [10]. Compared to the Position-Force controller studied in [1], this 3-channel controller has more interesting properties. Not only does this controller provide better transparency for a wider range of environments, it also provides larger tuning flexibility, which allows to focus on different aspects of transparency. Within this context, the concept of a transparency trade-off is introduced, not to be confused with the stability-transparency trade-off. An example of this trade-off is the possibility to choose for either stiffness transparency, i.e. to focus on the correct reflection of stiffness properties [15] or to focus on free space transparency, i.e. to minimize the admittance felt by the operator when moving in free space.

Section II describes the 3-channel controller. The two-port passivity and the absolute stability of this controller are studied in Section III and Section IV respectively. The Bounded Environment Passivity method is applied in Section V. Section VI describes a comparison between the 3-channel controller and the Position-Force controller. The paper discusses experimental results in Section VII, after which conclusions are drawn in Section VIII.

II. THE 3-CHANNEL CONTROLLER

The controller under study in this paper is a 3-channel controller originating from the extended Lawrence Architecture [7], [10]. This controller will be referred to as the **PD-F-F_h** scheme and the control input forces for the motor of the master, τ_m , and of the slave, τ_s , are:

$$\tau_m = -\lambda \cdot F_e, \quad (2)$$

$$\tau_s = (K_v s + K_p) \cdot (\mu \cdot x_m - x_s) + F_h, \quad (3)$$

with F_h and F_e the interaction forces measured at the end-effector of the master and the slave. The constants μ and λ are a position and force scaling factor. These control inputs correspond to the following parameters for the extended Lawrence Architecture:

$$\begin{aligned} C_s &= (K_v + \frac{K_p}{s}), \quad C_1 = \mu C_s, \quad C_3 = 1, \quad C_5 = 0, \\ C_m &= C_4 = 0, \quad C_2 = \lambda, \quad C_6 = 0. \end{aligned} \quad (4)$$

Table I: Parameters of the teleoperation system

Model	Controller
M_m : 0.64 kg	K_v : 80 Ns/m
B_m : 3.4 Ns/m	K_p : 4000 N/m
M_s : 0.61 kg	μ : 1
B_s : 11 Ns/m	λ : 1

The analysis is based on 1-d.o.f rigid-body models for master and slave, obeying the following equations of motion:

$$F_h + \tau_m = Z_m \cdot v_m, \quad (5)$$

$$\tau_s - F_e = Z_s \cdot v_s, \quad (6)$$

$$Z_m = M_m s + B_m, \quad Z_s = M_s s + B_s, \quad (7)$$

with Z_m and Z_s representing the impedances of the master and the slave robot. All numerical calculations and experiments reported here are based and done on a 1-d.o.f. experimental master-slave setup. The experimental setup consists of two current-driven voice coil motors from hard disk drives as described in [1]. On both devices, one-dimensional force sensors are mounted (resolution: 0.05 N) and linear encoders offer accurate position measurements (resolution: 1 μ m). The structural resonance frequencies of both the master and the slave are above 100 Hz. Table I gives an overview of the parameters used for the rigid-body models and the controller. These parameters, based on a linear model identification of the real setup and on an implementation of the controller on this setup, serve as a starting point for the tuning process. The controller is implemented on a dSpace board, in a real-time loop with a sample frequency of 1 kHz.

III. TWO-PORT PASSIVITY ANALYSIS

To evaluate the Two-port Passivity of the teleoperation system, the *Raisbeck passivity criteria* [16] are used based on the elements h_{ij} of the hybrid matrix [17]. In the case of the **PD-F-F_h** scheme the elements of the hybrid matrix H can be found as:

$$\begin{aligned} h_{11} &= M_m s + B_m, & h_{12} &= \lambda, \\ h_{21} &= -\frac{M_m s^2 + (B_m + \mu K_v)s + \mu K_p}{M_s s^2 + (B_s + K_v)s + K_p}, & h_{22} &= -\frac{(-1 + \lambda)s}{M_s s^2 + (B_s + K_v)s + K_p}. \end{aligned} \quad (8)$$

In the same way as done in [1], it can be proven that not all Raisbeck passivity conditions hold, which allows the formulation of the following theorem:

THEOREM 1 (Active PD-F-F_h scheme): The 3-channel controller given by (2) and (3) forms an active system when applied upon the teleoperator (5), (6) and (7) in all but trivial cases.

However, two-port passivity is a conservative property neglecting the fact that no direct interaction between operator and environment occurs. The next section analyzes the absolute stability property which is a less conservative property incorporating this structural knowledge.

Figure 2: The conditions on M_s in function of the scaling factor λ for absolute stability: three upper boundaries (solid) and two lower boundaries (dashed) define together the region of absolute stability (the gray area).

IV. ABSOLUTE STABILITY ANALYSIS

A linear two-port is *absolutely* or *unconditionally* stable if and only if there is no set of passive one-ports for which the coupled system is unstable. Llewellyn's stability criteria provide necessary and sufficient conditions for absolute stability [18]. These criteria are equivalent to the following conditions in terms of the elements of the hybrid matrix H :

- h_{11} and h_{22} have no poles in the open right-half plane (RHP),
- any poles of h_{11} and h_{22} on the imaginary axis are simple and have real and positive residues, and
-

$$\Re(h_{11}) \geq 0, \forall \omega \quad (9)$$

$$\eta(\omega) = -\cos(\angle h_{12}h_{21}) + 2 \frac{\Re(h_{11})\Re(h_{22})}{|h_{12}h_{21}|} \geq 1, \forall \omega. \quad (10)$$

It is relatively straightforward to see that all conditions stated above, except for inequality (10), hold. Further analysis of inequality (10) results in several long conditions on the parameters of the system, that can be expressed as three upper boundaries and two lower boundaries on M_s and one lower boundary on K_v . For reasons of brevity the analytic expressions of the boundaries are not given, but Fig. 2 shows all upper and lower boundaries on M_s in function of λ for the parameters in Table I. It depends on all parameters of the system which of these boundaries define the actual region of absolute stability. The resulting region of absolute stability is shown as the gray area in Fig. 2. The above study of the conditions can be summarized in the following theorem:

THEOREM 2 (Absolutely stable PD-F- F_h scheme):

The 3-channel controller, applied to the teleoperator defined

by (5), (6) and (7), and controlled by control laws (2) and (3) is absolutely stable provided that the mass M_s falls within a specific interval and that K_v is larger than a certain lower boundary.

It is important to note here that for the special case $\mu = \lambda = 1$, the interval on M_s reduces to one point, as can be seen in Fig. 2. This means that the system is absolutely stable only for one specific value of the mass M_s . Moreover, one can prove that if $\lambda \rightarrow 1$ the lower boundary on K_v goes to infinity.

V. ONE-PORT PASSIVITY ANALYSIS

The above derivation showed that for the **PD-F- F_h** scheme, stable interaction with any passive environment can only be achieved for a limited range of M_s , depending on the scaling factor λ . Here, the *Bounded Environment Passivity* method is used in order to derive less restrictive conditions [1]. This method is based on checking the positive realness of the admittance Y_{MS} , which represents the dynamics of the master, the slave, the controller and the environment, as shown in figure 1. As stated before, pure springs and pure masses can be considered as the *worst* case environments since their admittance is not strictly passive. The benefit of the Bounded Environment Passivity method is that the stability properties for a stiffness as an environment and for a mass as an environment can be studied independently. As we assume that the inertial properties of the environment the surgeon interacts with are negligible, the environment considered in this work is a pure spring with stiffness K_e . Through this assumption the admittance $Y_{MS(K_e)}$ can be written as:

$$Y_{MS(K_e)}(s) = \frac{s \cdot x_h}{F_h} = \frac{s(M_s s^2 + (B_s + K_v)s + K_p + (1 - \lambda)K_e))}{(M_m s^2 + B_m s)(M_s s^2 + (B_s + K_v)s + (K_p + K_e)) + \mu \lambda K_e (K_v s + K_p)}. \quad (11)$$

After replacing s by $j\omega$, the $\Re(Y_{MS(K_e)}(j\omega)) \geq 0, \forall \omega$ condition for the **PD-F- F_h** scheme can be written as:

$$A\omega^6 + B\omega^4 + C\omega^2 \geq 0, \forall \omega. \quad (12)$$

with:

$$A = M_s^2 B_m \quad (13)$$

$$B = \lambda K_e B_s M_m + 2K_v B_s B_m + B_s^2 B_m + \lambda K_e M_s B_m - 2K_e M_s B_m - 2K_p M_s B_m + \lambda K_e K_v M_m - M_s K_v \mu \lambda K_e + K_e^2 B_m \quad (14)$$

$$C = -\lambda^2 K_e^2 K_v \mu - \lambda K_e K_p B_m + K_p^2 B_m + 2K_p K_e B_m - B_s K_p \mu \lambda K_e - \lambda K_e^2 B_m + K_e^2 B_m + K_v \mu \lambda K_e^2 \quad (15)$$

Condition (12) holds in case that $(A \geq 0)$ and $(B \geq 0 \text{ or } B^2 - 4AC \leq 0)$ and $(C \geq 0)$. The condition $A \geq 0$ is trivial. The condition $B \geq 0$, can be written as an upper boundary on M_s :

$$ub_1 : M_s \leq \frac{\lambda K_e B_s M_m + 2K_v B_s B_m + B_s^2 B_m + K_v^2 B_m + \lambda K_e K_v M_m}{-\lambda K_e B_m + 2K_p B_m + K_v \mu \lambda K_e + 2K_e B_m} \quad (16)$$

$$lb: M_s \geq -\frac{(B_m B_s + \lambda K_e M_m + B_m K_v)(K_v + B_s)}{\lambda K_e (\lambda K_e (B_m + \mu K_v)^2 + 4 K_p B_m (K_v + B_s))} \left(\lambda K_e (B_m - \mu K_v) - 2 B_m (K_e + K_p) + 2 \sqrt{-B_m (-B_m (K_e + K_p)^2 + \mu \lambda K_e^2 + K_v (\lambda - 1) + \lambda K_e B_m (K_e + K_p) + \mu \lambda B_s K_p K_e)} \right) \quad (17)$$

$$ub_2: M_s \leq -\frac{(B_m B_s + \lambda K_e M_m + B_m K_v)(K_v + B_s)}{\lambda K_e (\lambda K_e (B_m + \mu K_v)^2 + 4 K_p B_m (K_v + B_s))} \left(\lambda K_e (B_m - \mu K_v) - 2 B_m (K_e + K_p) - 2 \sqrt{-B_m (-B_m (K_e + K_p)^2 + \mu \lambda K_e^2 + K_v (\lambda - 1) + \lambda K_e B_m (K_e + K_p) + \mu \lambda B_s K_p K_e)} \right) \quad (18)$$

Figure 3: The three conditions on M_s for bounded environment passivity as a function of K_e ($\lambda = 0.85$), with ub_2 as determining boundary. The points a and b show the upper and lower boundary for M_s based on absolute stability also appearing in Fig. 2)

The condition $B^2 - 4AC \leq 0$ can be written as a lower and upper boundary on M_s as can be seen in respectively (17) and (18). For the parameters of Table I, M_s obeying (16) or (17) and (18) comes down to M_s obeying (18) as shown in Fig. 3. Thus, the conditions $B \geq 0$ and $B^2 - 4AC \leq 0$ result in one upper boundary on M_s . Lastly, the condition $C \geq 0$ can be expressed as a lower boundary on K_v :

$$K_v \geq \frac{(\lambda - 1)K_e^2 B_m + \lambda K_p K_e (\mu B_s + B_m) - K_p B_m (2K_e + K_p)}{\mu \lambda (-\lambda + 1) K_e^2} \quad (19)$$

In the special case that $\mu = \lambda = 1$ and $B_m < B_s$, the condition $C \geq 0$ can be expressed as a condition on K_e :

$$K_e \leq \frac{K_p B_m}{B_s - B_m} \quad (20)$$

If $B_m \geq B_s$ however, the condition $C \geq 0$ holds for all K_e . Fig. 4 shows the lower boundary on K_v as a function of K_e for three different values of λ and the parameters of Table I. This figure also shows that for the special case $\mu = \lambda = 1$ and $B_m < B_s$, there is a maximum value for K_e defined by (20).

Note that, so far, conditions (16), (17), (18) and (19) are expressed in function of a *fixed* environment stiffness, K_e , and not in function of the maximum value of the *bounded* range of stiffnesses, K_e^{max} . This is done to not further complicate the mathematical representation. Nevertheless

Figure 4: The lower boundary on K_v for bounded environment passivity as a function of K_e for different values of λ (solid). For the special case $\lambda = 1$, the lower boundary on K_v can be interpreted as an upper boundary on K_e

the bounded environment passivity properties can be deduced from these conditions. For example, in Fig. 4, the solid lines show the bounded environment passivity properties, while the dot-dashed lines show the fixed environment passivity properties. For bounded environment passivity, a lower boundary should be monotonically rising in function of K_e , while an upper boundary has to be monotonically falling.

Based on the analytic conditions (16), (17), (18) and (19) and their representations in Fig. 3 and 4, one can see that there are several practically feasible ways to make the system passive for all K_e starting from the parameters of Table I, i.e. with $\mu = \lambda = 1$. Two of them are discussed here, i.e. (i) to lower λ , or (ii) to increase the master damping. For example:

- for $\lambda = 0.85$, the one-port admittance $Y_{MS(K_e)}$ is passive based on the above conditions. Experimentally, the human operator feels no instability when contacting multiple environments with different stiffnesses (100-27000 N/m). However, the human operator does not feel the correct environment stiffness.
- for $B_m = B_{m,h} + B_{m,c} = 13.4$, again the one-port admittance $Y_{MS(K_e)}$ is passive and the human operator feels no instability. Here, $B_{m,h}$ is the inherently present hardware damping (i.e. 3.4 Ns/m) and $B_{m,c}$ is extra added control

damping through negative velocity feedback at the master. Now, perfect stiffness transparency is reached at the cost of extra damping which decreases the free-space transparency.

This tuning flexibility is a good example of the concept of a transparency trade-off: the stability properties of both tuning settings are sufficient but they differ in the kind of transparency that is reached. For the above example, one has to choose for either stiffness transparency or free space transparency. Depending on the envisioned application one should select the appropriate transparency. For the application of telesurgery, the reflection of the correct stiffnesses properties is typically most important. Moreover, manipulation velocities are low, which means that some extra damping at the master will not deteriorate the free-space transparency too much. The stiffness transparency property and the passivity boundary for the two control settings above are shown in respectively Fig. 5 and Fig. 6. These figures are explained in the following section.

VI. THE **PD-F-F_h** SCHEME VERSUS THE **PD-F** SCHEME

This section compares the transparency and stability properties of the 3-channel controller, i.e. the **PD-F-F_h** scheme, to an implementation of the basic Position-Force controller studied in [1], namely the **PD-F** scheme. The control inputs for the motors of the master and the slave for the latter controller are very similar to (2) and (3), except for the force-feedforward term F_h :

$$\tau_m = -\lambda \cdot F_e, \quad (21)$$

$$\tau_s = (K_v s + K_p) \cdot (\mu \cdot x_m - x_s). \quad (22)$$

Under the assumption that the environment is a pure stiffness, the admittance $Y_{MS(K_e)}$ for the **PD-F** scheme can be written as:

$$Y_{MS(K_e)} = \frac{s(M_s s^2 + (B_s + K_v)s + (K_p + K_e))}{(M_m s^2 + B_m s)(M_s s^2 + (B_s + K_v)s + (K_p + K_e)) + \mu \lambda K_e (K_v s + K_p)}. \quad (23)$$

A. Comparison of transparency properties

As a measure for stiffness transparency, the stiffness felt by the human operator when manipulating the master quasi-statically can be used. For the **PD-F-F_h** scheme, this is:

$$\lim_{s \rightarrow 0} \frac{1}{s} \cdot Y_{MS(K_e)}(s) = \frac{K_p + (1 - \lambda)K_e}{\mu \lambda K_e K_p}. \quad (24)$$

In the case $\mu = \lambda = 1$, this is the exact environment stiffness. For the **PD-F** scheme however, this is

$$\lim_{s \rightarrow 0} \frac{1}{s} \cdot Y_{MS(K_e)}(s) = \frac{K_p + K_e}{\mu \lambda K_e K_p}, \quad (25)$$

which means that even for $\mu = \lambda = 1$, the human operator does not feel the correct environment stiffness, but a series

connection of K_p and K_e . As K_p is practically limited, this is a stiffness lower than the real environment stiffness. Based on (24) and (25), Fig. 5 shows the stiffness K_{th} felt by the human operator when manipulating the master quasi-statically in function of K_e , for the two controllers and different parameter settings. Note that the free-space admittance felt by the human operator is the same for both controllers:

$$Y_{MS(Z_e=0)} = \frac{1}{M_m s + B_m}. \quad (26)$$

B. Comparison of stability properties

Next to these transparency properties, also the stability properties are compared. The Bounded Environment Passivity method applied to the **PD-F-F_h** scheme resulted in several conditions of which (18) and (19) are the most determining ones for the parameters of Table I, i.e. an upper boundary on M_s and a lower boundary on K_v . For the **PD-F** scheme, there is only one determining condition resulting from the Bounded Environment Passivity method. In [1], this condition is written as an upper boundary on $\mu \lambda$, but this same condition can also be written as an upper boundary on M_s :

$$M_s \leq \frac{B_m(K_v + B_s)^2(\mu \lambda K_v K_e + 2B_m(K_e + K_p)) + 2\sqrt{B_m(B_m(K_e + K_p)^2 + \mu \lambda K_v K_e^2 - \mu \lambda B_s K_p K_e)}}{\mu \lambda K_e(\mu \lambda K_v^2 K_e + 4K_p B_m(K_v + B_s))}. \quad (27)$$

Fig. 6 shows these conditions for the two controllers and different parameter settings. The major differences are:

- The **PD-F** scheme cannot be tuned such that $Y_{MS(K_e)}$ is passive for all environment stiffnesses. This corresponds to the fact, proven in [1], that the **PD-F** scheme is never absolutely stable. The **PD-F-F_h** scheme, however, can be absolutely stable and there are parameter settings, even for $\mu = \lambda = 1$, for which $Y_{MS(K_e)}$ is passive for all environment stiffnesses.
- For the **PD-F** scheme, there is a very restrictive condition on M_s , independent of M_m . For the **PD-F-F_h**, the condition on M_s does depend on M_m and is clearly less restrictive for the parameters of the system described in this paper.

To understand the beneficial properties of the **PD-F-F_h** scheme one can rewrite equation (5) as follows:

$$F_h = (M_m s + B_m)v_m - \tau_m \quad (28)$$

and introduce the control input (2) to obtain:

$$F_h = (M_m s + B_m)v_m + \lambda F_e. \quad (29)$$

This expression shows that the force feedforward of F_h , i.e. the third channel, is equivalent to the combination of a model feedforward term, $(M_m s + B_m)v_m$ and a local force feedback, λF_e . The stability problems of the Position-Force controller can be intuitively explained by the phase lag

introduced by the position controller. The model feedforward term $(M_ms + B_m)v_m$ decreases the phase lag of the position controlled slave, and improves as such the stability when contacting spring-like environments [19], [1]. As mentioned above, for the Position-Force controller, the stiffness the human operator feels is the series connection of the environment stiffness and the stiffness of the position controller. The local force feedback term λF_e makes the position controller more stiff with respect to static interaction forces. For $\lambda = 1$, the position controller is theoretically infinitely stiff, as a consequence the human operator feels the correct environment stiffness when manipulating the master quasi-statically.

VII. EXPERIMENTS

Using the master-slave setup described in Section II, the correctness of the proposed analytic conditions is exper-

Figure 5: **PD-F** versus **PD-F-F_h**: stiffness transparency (the ideal case is the straight line under 45°)

Figure 6: **PD-F** versus **PD-F-F_h**: the condition on M_s based on Bounded Environment Passivity.

Figure 7: Interaction with a hard contact (± 41000 N/m) and a soft object (1100 N/m) for (a) the **PD-F** scheme and (b) the **PD-F-F_h** scheme.

imentally verified. The interactions with a hard environment (± 41000 N/m) and a soft environment (1100 N/m) are described here for two different controllers. The first controller is the **PD-F** scheme with the parameters of Table I. The second controller is the **PD-F-F_h** scheme with the parameters of Table I but $B_m = 13.4$.

For both the soft and the hard environment, $Y_{MS(K_e)}$ is active with the **PD-F** scheme. Although it is difficult for a human operator, it is possible to realize stable interaction, depending on his/her posture and behaviour. With the **PD-F-F_h** scheme, as $Y_{MS(K_e)}$ is passive for both environments, all human operators easily realize stable interaction with both environments independent of his/her posture or behaviour. Two of these experiments are shown in a force-position plot, as such plots allow to see the stiffness transparency. Fig. 7(a) and (b) show these plots for respectively the **PD-F** scheme and the **PD-F-F_h** scheme. As described in Section VI, the stiffness perceived with the **PD-F** scheme is clearly lower than the real environment stiffness, while with the **PD-F-F_h** scheme, the correct environment stiffness is perceived. This is an illustration of the interesting properties of the 3-channel controller under study in this paper, i.e. achieving stiffness transparency while guaranteeing stable interaction.

VIII. CONCLUSIONS

In this paper, a detailed stability analysis of a 3-channel controller is presented. The analysis is based on two traditional methods, i.e. *Two-port Passivity* and *Absolute Stability* and the more recent method of *Bounded Environment Passivity*. The latter analyzes the passivity of Y_{MS} , i.e. the one-port network with which the human operator interacts. The environment is considered to be a pure stiffness. The resulting analytic passivity conditions show an interesting tuning flexibility, which reveal the concept of transparency trade-offs. This means that one can choose between different control settings, while maintaining, for the same range of environments, the passivity of Y_{MS} . Depending on the selected control settings, there is a focus on a different aspect of transparency. The example detailed here, is the trade-off

between focussing on stiffness transparency and focussing on free-space transparency.

A detailed comparison of the transparency properties and the stability properties of the 3-channel controller under study in this paper and the classical position-force controller shows the beneficial properties of the 3-channel controller. This is confirmed by experimental results.

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