LIMITS OF HUMAN INTERACTION IN DYNAMICALLY SIMILAR TELEOPERATION SYSTEMS
Under Unknown Constant Time Delay with Impedance Control

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Abstract: Bilateral teleoperation system are prone to instability coming out from the time-delay introduced by the indeterministic communication channel. This problem has been subject of intensive research under the assumption of non-equal master-slave teleoperators, however, what are the implications of dynamically similar teleoperation system (DSTS), is there simpler stability relationship and trade offs among several involved system and feedback parameters? When we consider a *linear* DSTS system, there arises the question whether there is analytically any advantage, as it was observed heuristically in several experiments (Cho and Park, 2002). In this paper, the stability analysis of such system is reported under an impedance control scheme (Garcia-Valdovinos, 2006) when the delay is considered constant but unknown. by applying the Llewellyn's and Raisbeck's criteria, it is found and explicit and straightforward relationships between the dynamic and kinematic scaling and the stability of the system. This result explicitly suggests clearly guidelines among key factors, such as time delay, desired velocities and feedback gains in terms of the scaling parameters, arises a clear advantage when dealing with dynamically similar systems. This explains why the transparency of the teleoperation system is improved by augmenting/reducing the dynamic/kinematic scaling factor, for given desired frequency, time delay and feedback gains. Simulations and preliminary experimental results illustrate different cases subject to a number of conditions, which can be very useful to design a physical teleoperation system. A preliminary mechatronics design is presented.

1 INTRODUCTION

A bilateral teleoperation system is composed of a master robot and a slave robot, with a human operator commanding the master robot in order to produce the desired position and contact force trajectories[1] for the remotely located slave robot. In turns, the slave robot follows these trajectories so as to produce contact forces to be sent to the master robot as desired force trajectories. In this way, a force/position-force control system is implemented in the master/slave station with a communication channel introducing delayed position and forces signals (Hokayem and Spong, 1984). It is well known that the source of instability of bilateral teleoperation system appears because the time-delay introduced by the indeterministic communication channel is not passive (Q.W. Deng, 2007). Then, the limits to achieve human operator stable interaction with the slave robot, placed at a remote location, through the master robot, becomes an issue, in particular successful teleoperation requires a certain degree of transparency[2] and/or telepresence[3]. Stable interaction is intuitive and easier when mechanical teleoperators are alike? What are the limits of stable interaction for dynamically similar teleoperation system (DSTS) subject to time-delay in the communication channel?

Furthermore, when we consider a *linear* DSTS, there arises the question whether there is analytically any advantage for being the master and slave robot dynamically similar, through the kinematic and dy-

[1] Depending whether is in contact or not.

[2] Manipulation of the slave robot without any dynamics involved in between.

[3] Sensation of being physically in the remote environment.

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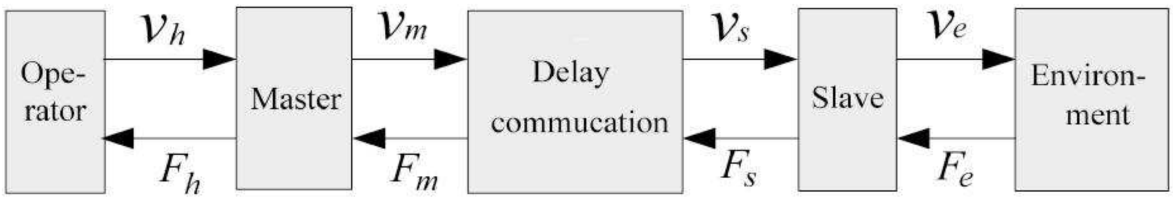

Figure 1: Basic Bilateral Teleoperation Scheme.

namic scaling parameters. It seems DSTS is preferred to carry out over dissimilar teleoperation systems, as it was observed heuristically in several experiments (Cho and Park, 2002).

On one hand, telepresence depends of the degree of transparency, which can be understood as the simultaneous convergence of the position and force error between the master and slave robot. However it also depends on the subjective cognition of the human operator of being there, which depends, among other aspects, on visual aids of the remote environment, kinesthetic coupling, the ability to deal with delayed signals and the man-machine interface. How does these factors are related in DSTS to guarantee stable teleoperation?

In this paper, motivated by the empirical observation that a DSTS is easier to handle, it is argued that dynamic and kinematic similarity introduce a clear trade-off of some of these aspects, so it is reasonable to expect a simpler a trade-off. Analytical results are found based on an impedance control scheme (Garcia-Valdovinos, 2006), when the delay is considered constant but unknown.

1.1 Motivation

When the master and slave teleoperated robots are related linearly by scaling factors of position and force, as well as scaling factors on dynamic and kinematic parameters, a relationship between geometry, power and perception arise to give to the operator a linear relationship behavior. Such scaling factors might give to humans the ability to increase their commanding, perceptual and cognitive skills in different teleoperation tasks, depending on the task undergoing. It has been observed experimentally that by tuning properly these scaling factors a human operator improves his ability to better teleoperate such system (Cho and Park, 2002). Can DSTS yield teleoperation tasks with greater dexterity? What are the trade-offs? It is of interest to understand deeper this phenomena using formal dynamical system tools to analyze properties of stability of dynamically similar teleoperation system.

1.2 Contribution and Organization

Our basic hypothesis is that as long as the human perceives linear correlated variations in both teleoperated robots, he can improve the command of the closed-loop bilateral teleoperation system since spatial and temporal attributes of the visual remote location and kinesthetic coupling will vary linearly without distortion. So cognitively, the human can quickly learn to command the task with greater dexterity. Additionally in this paper we deal with unknown time delay so we design a novel controller to deal with unknown constant time delay (Garcia-Valdovinos, 2006), (Cho and Park, 2002). A computed-torque controller is employed in the master station and a computed torque second order sliding mode controller in the slave station is proposed to produce a desired impedance in closed loop. Then, absolute stability theory and passivity is used to analyze the closed-loop stability properties and therefore the limits of human-teleoperation stability and thus we found the stability trade-offs. To this end, a review is presented in Section 2. Then, in Section 3 the dynamically similar coupled system is presented, while controllers are explained in Section 4. With this result at hand, absolute stability using Llewelyn criteria (Llewellyn, 1952), and passivity using Raisbeck criteria (Raisbeck, 1994), are analyzed in Sections 5 and 6 respectively. The Llewellyn's analysis reveals that a good choice for *dynamic* scaling factors give us the opportunity for greater bounds on position and force scaling to execute tasks of high performance. A quality criterium for transparency analysis is also presented in Section 7. Simulations on a 1 DoF teleoperation systems are shown to illustrate how this dynamic scaling factor improve the performance of the system, shown in Section 8 to better understand the numerical performance. Final conclusions are given in Section 9.

2 DYNAMICALLY SIMILAR DELAYED TELEOPERATION SYSTEM

A dynamically similar teleoperation system has constant scaling factors which relate kinematic and dynamic parameters of the master and slave robots (Goldfarb, 1999). This similarity between the systems is poorly understood so far, since there is not theoretical apparent evident advantage to work out with bilateral system, despite some analysis reported in (Li and Lee, 2003), where the advantages has not been addressed properly in terms of explicit trade-offs of feedback gains, system parameters, desired trajectories and time delay. We surmise in this paper that DSTS improves significantly the ability of humans operating the master teleoperator to carry out efficiently teleoperation tasks at remote environments, when there is an unknown time delay involved in the communication channel.

Impedance control has been explored in (Cho and Park, 2002) to enforce a desired impedance dynamics in closed loop in order to program arbitrarily the desired impedance parameters. This closed-loop linear dynamic allows to model the entire system as a 2-port network to relate the force and flows of input and output, respectively, by an impedance matrix or an hybrid matrix. This matrix can be used to describe the stability of the entire system using the Absolute Stability Theory (K. Hashtrudi-Zaad, 2000), where a tight relationship between *output* scaling factors and impedance parameters can be found to give sufficient conditions on stability. However, when *dynamic* scaling factors are introduced, the master and slave robot dynamics are related by constants, either in kinematic and/or dynamic parameters, thus, a sort of advantages can emerge from this relation since a single feedback parameter appears. In this paper, we offer an analysis in terms of both the Llewelyn's criteria and Raisbeck's criteria, and verify its real time performance, which demonstrates a clear and intuitive trade off in terms of scaling factors of the DSTS.

3 DYNAMICALLY SIMILAR SYSTEM

Consider the dynamics of a linear teleoperation system consisting of two n-DoF manipulators decoupled systems as follows

$$M_m\ddot{x}_m + B_m\dot{x}_m + K_m x_m = F_{mc} + F_m \quad (1)$$
$$M_s\ddot{x}_s + B_s\dot{x}_s + K_s x_s = F_{sc} + F_s \quad (2)$$

where $\ddot{x}_i$ and $\dot{x}_i$ denote acceleration and velocity of the robot i,respectively; F_{mc}, F_{sc} are the control force inputs and F_m, F_s are external forces to the master and slave systems, respectively; and M_i, B_i and K_i with $i = m, s$ are the inertia, dampness and stiffness positive coefficients of the systems. Let $K > 0$ be the kinematic scaling factor that relates both master and slave configuration spaces such that

$$x_s = \frac{x_m}{K} \quad (3)$$

This system is said dynamically similar after the coordination (3) if there exists a scalar $\zeta > 0$ such that

$$M_m\ddot{x}_m + B_m\dot{x}_m + K_m x_m = \frac{M_s\ddot{x}_s + B_s\dot{x}_s + K_s x_s}{\zeta} \quad (4)$$

Thus, the dynamic parameters of (1)-(2) are related linearly by

$$\zeta M_m = M_s, \quad \zeta B_m = B_s, \quad \zeta K_m = K_s \quad (5)$$

The apparent advantage of this dynamic relationship has not been well explored in the context of teleoperation with unknown constant time delay, though there are a lot of heuristical intuition which leads us to conclude that these systems would allow greater kinesthetic coupling with greater manipulability dexterity as consequence. To this end, it is introduced an impedance control system (Garcia-Valdovinos, 2006) to enforce a 2-port closed-loop desired linear system.

4 IMPEDANCE CONTROL LAW

4.1 1 DoF Teleoperation System

Similarly to (1)-(2), let a 1 DoF master/slave teleoperation system be modeled as a mass-spring-damper system, where external master force F_m on the master is nothing but the human commanding force F_h and the external slave force force F_s stands as the environmental contact force F_e, then (1)-(2) becomes

$$M_m\ddot{x}_m + B_m\dot{x}_m + K_m x_m = F_{mc} + F_h \quad (6)$$
$$M_s\ddot{x}_s + B_s\dot{x}_s + K_s x_s = F_{sc} - F_e \quad (7)$$

where negative sign appears in F_e due to the positive convention of the inertial frame axis.

4.2 Impedance Control Law for the Master

For completeness, the control law (Garcia-Valdovinos, 2006) is introduced here. Consider the following master controller

$$F_{mc} = -F_h + B_m\dot{x}_m + K_m x_m + \frac{M_m}{\bar{M}_m}(F_h - K_f F_e^{dy} - \bar{B}_m\dot{x}_m - \bar{K}_m x_m) \quad (8)$$

Eq. (8) into (6) gives rise to the following desired impedance equation for the master robot

$$\bar{M}_m\ddot{x}_m + \bar{B}_m\dot{x}_m + \bar{K}_m x_m = F_h - K_f F_e^{dy} \quad (9)$$

where positive $\bar{M}_m, \bar{B}_m, \bar{K}_m$ are the desired inertia, dampness and stiffness for the master robot, respectively, and $F_e^{dy} = F_e(t - T_s)$, being T_s the delay from the slave to the master station. That is, the *master* impedance control law enforces a desired impedance (9) in closed-loop, whose parameters are chosen by the user depending of a specific task, such that:

- when the slave robot *is not* touching the environment, $F_e^{dy} = 0$, then (9) becomes a mass-spring-damper system driven solely by the human force F_h, notice that in this case the controller is in *position* impedance mode..
- when the slave robot *is* touching the environment, $F_e^{dy} > 0$, then (9) becomes a mass-spring-damper system driven by force error $F_h - K_f F_e^{dy}$. In this case, actuators in the master station makes the human perceives a contact force equal to $K_f F_e^{dy}$, while the human virtually recreates, cognitively, the surface of the object according to this vector, through kinesthetic sensations of the scaled and delayed slave contact force, which arise normal at the contact slave point and the visual image coming from the slave station. Notice that when the slave is contact, the master control is in impedance *force* control mode.

To achieve such effects, it is necessary to control the slave robot in impedance position and force control modes, according to the contact regime.

4.3 Impedance Control Law for the Slave (Garcia-Valdovinos, 2006)

Similarly to the master controller, the objective in the slave station is to impose a desired impedance to the slave robot

$$\bar{M}_s\ddot{\tilde{x}}_s + \bar{B}_s\dot{\tilde{x}}_s + \bar{K}_s\tilde{x}_s = -F_e \quad (10)$$

where positive $\bar{M}_s, \bar{B}_s, \bar{K}_s$ are the desired inertia, dampness and stiffness for the slave robot, respectively. The position tracking error $\tilde{x}_s$ is expressed as follows

$$\tilde{x}_s = x_s - K_p x_m^{dy} \quad (11)$$

where $x_m^{dy} = x_m(t - T_m)$, being T_m the delay from the master to the slave station. Now, let the following control law for the slave robot be

$$\begin{aligned} F_{sc} &= -\frac{M_s}{\bar{M}_s}(\bar{B}_s\dot{x}_s + \bar{K}_s x_s + F_e + K_i\sigma) \\ &\quad + M_s K_p \bar{M}_m^{-1}\left(F_h^{dy} - K_f F_e^{dy} - \bar{B}_m\dot{x}_m^{dy} \right. \\ &\quad \left. - \bar{K}_m x_m^{dy}\right) + F_e + B_s\dot{x}_s - K_g\Omega \quad (12) \\ \sigma &= \int_0^t \mathrm{sgn}(I_e(\tau))\, d\tau \quad (13) \end{aligned}$$

where $F_h^{dy} = F_h(t - T_m)$. Notice that the feedforward term F_e^{dy} allows control without any measurement of the time delay. In any case, notice that F_e^{dy} is available for measurement at any time.

Notice that the gain K_g is a new control variable that weights the extended error variable Ω. The proposed sliding surface I_e is proposed naturally out of (10), that is we want (10) to be the attractive convergent manifold, then the extended error manifold is

$$I_e = \bar{M}_s\ddot{x}_s + \bar{B}_s\dot{x}_s + \bar{K}_s x_s + F_e \quad (14)$$

Then we can build a high order sliding surface Ω as a function of the sliding surface I_e as follows[4]

$$\Omega = \frac{1}{M_m}\left(\int_0^t I_e(\tau)d\tau + \int_0^t\int_0^t \mathrm{sgn}(I_e(\tau))d\sigma d\tau\right) \quad (15)$$

Finally, substituting (12)-(13) into (7) gives rise to the closed-loop error equation for the slave robot:

$$\dot{\Omega} = -\beta\Omega \quad (16)$$

where $\beta = \frac{K_g}{M_s} > 0$ is Lipschitz. Consequently, all closed-loop signals in the slave station are bounded, enforcing exponential convergence of $\Omega \to 0$. Therefore, this chain of implications means that a second order sliding mode is enforced, and a sliding mode arises, at $I_e = 0$, which means that (10) arises in finite-time.

A closer analysis shows that the slave impedance control law enforces a desired impedance in closed-loop whose parameters are chosen by the user depending of a specific task, such that:

- when the slave robot *is not* touching the environment, $F_h^{dy} = 0, F_e = 0$ and (10) becomes an unforced mass-spring-damper system such that $\tilde{x}_s \to 0$ and the slave tracks the desired delayed position and velocities of the master. Notice that when the slave is not in contact, the slave control is in position impedance control mode.

[4]Notice that if (14) converge to zero, then (9) appears and the human would perceive the desired impedance to control at will the slave robot.

- when the slave robot *is* touching the environment, $F_e > 0$ and (10) becomes a mass-spring-damper system driven by the slave contact force F_e. In this case, actuators in the slave station make that the slave robot maintains contact ($|\tilde{x}_s| > 0$) while F_e stays around F_h^{dy}. Notice that when the slave is in contact, the slave control is in impedance *force-position* control mode.

With this result, it is now important to analyze the absolute stability properties to find the conditions under which this result is valid.

5 ABSOLUTE STABILITY ANALYSIS

With the desired impedance imposed by the controllers (8) and (12)-(13), the closed-loop dynamics (9) and (10) can be modeled as a 2-port network. Transforming this dynamic into the frequency domain and doing some algebra, closed-loop system can be represented as

$$\begin{bmatrix} F_h \\ V_s \end{bmatrix} = H \begin{bmatrix} V_m \\ -F_e \end{bmatrix} \tag{17}$$

where H is the so called Hybrid Matrix. Using the relationship (5) the hybrid matrix is built from elements depending of function of the desired master impedance parameter as follows

$$H = \begin{bmatrix} \frac{\bar{M}_m s^2 + \bar{B}_m s + \bar{K}_m}{s} & K_f e^{-T_s s} \\ K_p e^{-T_m s} & \zeta \frac{s}{\bar{M}_m s^2 + \bar{B}_m s + \bar{K}_m} \end{bmatrix} \tag{18}$$

which is fundamental to carry out the implications of a unique dynamic scaling factor. To proceed, it is useful to give the following definition on 2-port systems:

Definition: Absolute Stability Criteria for 2-port Systems: *A two-port system (17)-(18) is absolute stable if it does not exist a set of impedances for which the entire system become unstable. If the network is not absolutely stable, it is potentially unstable. By the conditions of the llewellyn's criteria a 2-port network is absolutely stable if and only if*

1. *h_{11} and h_{22} have no poles in the right half plane*
2. *Any poles of h_{11} and h_{22} on the imaginary axis are simple with real and positives residues*
3. *For all real values of* ω

- $\mathrm{Re}\{h_{11}\} \geq 0$
- $\mathrm{Re}\{h_{22}\} \geq 0$
- $2\mathrm{Re}\{h_{11}\}\mathrm{Re}\{h_{22}\} - \mathrm{Re}\{h_{12}h_{21}\} - |h_{12}h_{21}| \geq 0$

Notice that since the human operator is physically holding with his hand the master robot, it is imperative to ensure stable behavior, thus it is required to guarantee the fulfillment of previous Definition. To this end, notice that conditions 1. and 2. are trivially satisfied with positive impedance parameters. The third condition, when using (18), becomes:

$$\begin{array}{ll} \textbf{A.} & [\cos(T_m + T_s)\omega - 1] K_p K_f + 2\zeta\nu \geq 0 \\ \textbf{B.} & K_p K_f \leq \zeta\nu \end{array} \tag{19}$$

where

$$\nu = \frac{(\bar{B}_m\omega)^2}{(\bar{K}_m - \bar{M}_m\omega^2)^2 + (\bar{B}_m\omega)^2} \tag{20}$$

Inequality (19), necessary for the absolute stability of the system, shows that the scaling factors of position, force, and dynamical similarity ζ are critical for the design and performance of the teleoperation system.

Therefore, the consequences of introducing a dynamic similar system in teleoperation, from the point of view of Absolute Stability, are:

1. A unique similarity factor ζ is introduced, which offers a simpler analysis and easy to tune system.
2. The similarity factor ζ allows to derive simpler conditions of absolute stability.
3. The similarity factor ζ improves the design methodology of teleoperators based in impedance controllers. That is, there is a clear trade-off of all important parameters of the system, depending on the desired performance (ω), impedance parameters $\bar{M}_m, \bar{B}_m \bar{K}_m$, position scaling K_p and force scaling K_f and time delays, a ζ can be found.
4. From (18), the scaling factor ζ allows bigger margin on other parameters, thus the opportunity to improve performance based on the physical structure of the teleoperation system.
5. Due to the fact that both master and slave impedance parameters are related by this factor, the whole set of parameters can be expressed in terms of each other, which minimize the number of parameters implied in the design process making it easier to establish a performance limit.

6 PASSIVITY ANALYSIS

Passivity is a powerful criteria to analysis the energetic coupling of a closed loop system, a more conservative implication in comparison to Lyapunov stability criteria, however since the human operator is physically coupled with a typically mechanical system in closed-loop, it is important to analyze the passivity of the closed-loop system.

A two-port network is said to be passive if for all inputs of energy, the output energy is equal or less than the input energy. If the network is not passive, it is active. Raisbeck's passivity criterion is used to determine the passivity of the system.

Definition: Raisbeck Passivity Criterion for 2-port Systems: *It is said that a 2 port-network is passive if and only if*

1. *The parameters of the hybrid matrix H have no poles in the right half plane*
2. *Any poles of the elements of the hybrid matrix on the imaginary axis are simple and their residues satisfy the following conditions, for all real values of* ω,

- $r_{11} \geq 0, \quad r_{22} \geq 0$
- $r_{11}r_{22} - r_{12}r_{21} \geq 0$
- $4\mathrm{Re}\{h_{11}\}\mathrm{Re}\{h_{22}\} - [\mathrm{Re}\{h_{12}\} + \mathrm{Re}\{h_{21}\}]^2 - [\mathrm{Im}\{h_{12}\} - \mathrm{Im}\{h_{21}\}]^2 \geq 0$

where r_{ij} *denotes the residue of* h_{ij}.

In a similar way, the first two items are satisfied with positive impedance parameters, and the third is satisfied if the following inequality is fulfilled

$$K_p^2 + K_f^2 - 2K_pK_f\cos(T_1 + T_2)\omega \leq 4\zeta\nu \tag{21}$$

Then absolute stability is a more relaxed stability criteria than passivity. The passivity condition is necessary to assure a complete energetic stability performance of the closed loop system. Thus, we can choose the dynamic scaling factor in order to have a greater upper and lower bounds to vary the other factors of position and force without affect passivity, because it is of primary interest to maintain passivity since the human is physically holding the mechanical master robot.

7 TRANSPARENCY ANALYSIS

In order to determine the transparency of the system, a quality criterion in teleoperation systems based on the impedance matrix is derived from equations (9) and (10),

$$\begin{bmatrix} F_h \\ F_e \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} V_m \\ V_s \end{bmatrix} \tag{22}$$

The elements of the impedance matrix are in function of desired impedance parameters and scaling factors as follows

$$\begin{aligned} Z_{11} &= \frac{\xi}{s}\left(1 + \zeta K_pK_f e^{-(T_m+T_s)s}\right) \\ Z_{12} &= -\frac{\xi}{s}K_f e^{-T_s s} \\ Z_{21} &= \frac{\xi}{s}K_p e^{-T_m s} \\ Z_{22} &= -\frac{\xi}{s} \end{aligned}$$

where

$$\xi = \bar{M}_m s^2 + \bar{B}_m s + \bar{K}_m$$

The ideal transparency is reached by the system when the (input) environmental impedance Z_e is equal to the output human impedance Z_h, so that, we have

$$Z_h = Z_e \tag{23}$$

From (22), we have

$$Z_h = Z_{11} + \frac{Z_{12}Z_{21}}{Z_e + Z_{22}} \tag{24}$$

where Z_{11}, Z_{22}, Z_{12}, Z_{21} are the elements of the impedance matrix Z. Expressing the elements of Z in terms of the master impedance and substituting them in (24), it gives

$$\begin{aligned} Z_h &= \xi\left(1 + \zeta K_pK_f e^{-(T_m+T_s)s}\right) + \\ & \xi^2 \frac{\left(K_pK_f e^{-(T_m+T_s)s}\right)}{Z_e s^2 - \xi s} \end{aligned} \tag{25}$$

Now, we can analyze the transparency of the system in terms of free motion regime, which means that $Z_e = 0$ ideally, and constrained motion regime $Z_e = \infty$, in the worst case, then we have the following:

1. When $Z_e \to 0$, Z_h becomes (25), such that when the dynamic scaling factor ζ is greater, $Z_h \to 0$, or smaller desired impedance parameters is tuned, the higher transparency is obtained in free motion due to
$$Z_e \to 0 \Rightarrow Z_h \to \frac{1}{\zeta}\frac{\xi}{s}$$
2. In contact tasks $Z_e \to \infty$, ideally so does the output impedance. In this case, the transparency relation (24) becomes
$$Z_h \to Z_{11} = \frac{\xi}{s}\left(1 + \zeta K_pK_f e^{-(T_m+T_s)s}\right)$$

Notice that the dynamic scaling factor ζ is directly proportional to Z_h, hence, the greater it is the better the transparency is.

8 SIMULATION

In this section the effect of the dynamic scaling is shown for a 1 DoF teleoperation system. Simulations were made in 3 cases:

1. All dynamic, kinematic and force scaling factors are the unit.
2. The scaling factors of position and force are $K_p = 2$ and $K_f = 0.01$, respectively, and the dynamic scaling factor is $\zeta = 0.1$.
3. $zeta$ is increased to 10 and the rest of the parameters are preserved as in case 2.

A smooth force profile was introduced arbitrarily as the force exerted by the human. This force trajectory was designed in such a way that the teleoperator goes from an initial position to the contact point arriving softly with null velocity. This is in order to avoid large spikes due to hard contact. Once the slave robot is in the contact point, the human begin to apply an intermittently force on the constraint 3.

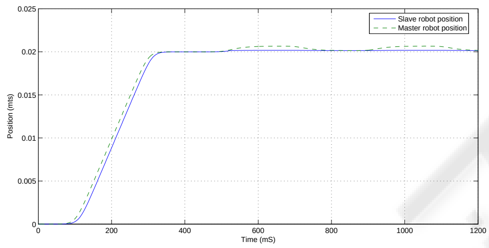

Figure 2: Position error of the master (dashed line) and slave (dotted line) for Case 1.

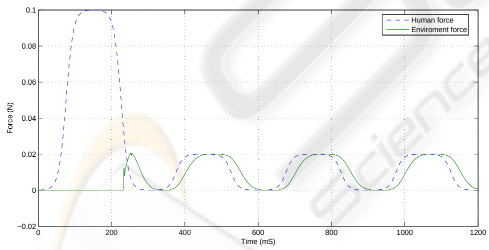

Figure 3: Human force error (master/dashed line) and constraint force error (slave/dotted line) for Case 1.

In Case 1, the chosen scaling factors and the impedance parameters give us an acceptable performance and a stable behavior. The position error between master and slave in Figure 2 shows that both robots follow the same constrained trajectory. Due to the impedance programmed for the master robot a slight movement toward the constraint is allowed. However, the slave robot stands along the physical constraint. With this stable response under constrained operation, the scaling factor of position is increased to obtain a larger workspace with slave robot and the force scaling factor is tuned in order to apply a greater force profile on the constraint and protect the human to receive a large reflected force that could be potentially dangerous.

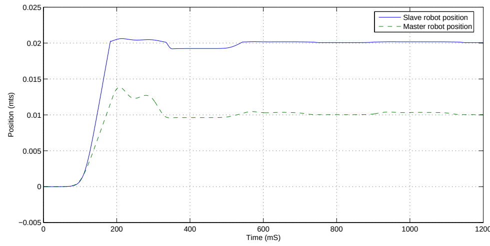

Figure 4: Position error of the master (dashed line) and slave (dotted line) for Case 2.

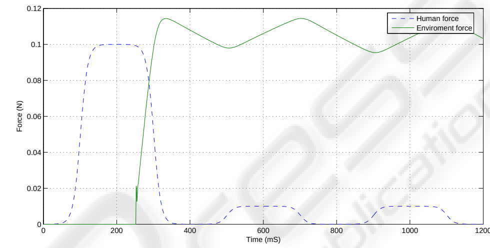

Figure 5: Human force error (master/dashed line) and constraint force error (slave/dotted line) for Case 2.

In Case 2, the change described in the scaling factors make the system unstable. The slave robot go away from its position as can be seen in Figure 4, while the force at the constraint (see Figure 5) disappears.

In order to handle this behavior, the dynamic scaling factor is increased (Case 3). Then the slave robot can reach the scaled position and force as shown in Figures 6 and 7.

The results in simulation show that in case 1, we obtain a acceptable performance and a stable behavior in the system but when we try to increase the performance changing the values of the others factors the

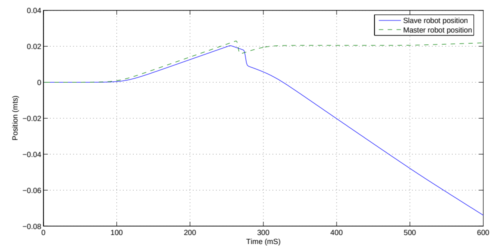

Figure 6: Position error of the master (dashed line) and slave (dotted line) for Case 3.

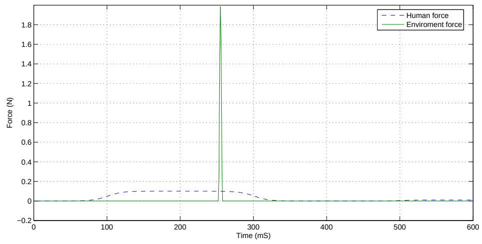

Figure 7: Human force error (master/dashed line) and constraint force error (slave/dotted line) for Case 3.

stability of the system is affected (Case 2). By making a new choice on this dynamic scaling factor we can preserve the scaling factors already chosen for an specific task without affect the stability

9 CONCLUSIONS

Using a novel impedance controller and advanced stability tools, precise conditions to guarantee stability, even in harsh conditions, is proposed for dynamically similar bilateral teleoperation robotic system. In this case, this system depends on a constant parameter, which relates explicitly and clearly a trade off between stability, passivity and transparency. The controller enforces convergence in finite time due to the sliding surface, which is nothing but the impedance equation, thus the closed-loop system dynamics is entirely governed by the desired controlled equation. This yields useful boundaries to vary impedance, scaling parameters and frequency, in terms of the bounded ime delay, which in turn allows to introduce a desired performance criteria in terms of surrounding physical conditions. This result seemingly allows to establish a simpler methodology to design dynamically similar teleoperators with a given desired performance in realistic conditions.

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