

Reset Control for Passive Bilateral Teleoperation

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Abstract—Communication delays are problematic for teleoperated systems. They give rise to a trade-off between speed and robustness, which cannot be overcome by means of linear controllers. In order to solve this problem, in this paper we present a novel approach that combines passivity-based techniques and reset control principles. In this way, it is possible to obtain simultaneously the robust stability properties of passive control and the performance improvement enabled by reset strategies. Experimental and simulation results are presented which confirm the good behavior achieved with this method.

Index Terms—Nonlinear control, passivity, reset control, teleoperation.

I. INTRODUCTION

The main advantage of reset control is the possibility of overcoming linear fundamental limitations [8] by means of a simple strategy. It is well known that many control problems are subject to fundamental, unsolvable trade-offs between competing design objectives; for example, bandwidth versus robust stability [2]. These limitations are particularly severe for plants having right-half-plane poles or zeros, or time-delays such as those appearing in teleoperation. Most of these trade-offs hold for every possible linear controller but, in principle, it might happen that nonlinear or hybrid controllers perform better and improve simultaneously speed of response and robustness. This is the purpose of reset control, which is based on a very simple idea: in a standard tracking problem it consists of resetting to zero (or, more generally, to other value) the state of the controller at certain instants, for example when the tracking error is zero.

The idea of reset control dates back to the Clegg Integrator [13] and to the first order reset element (FORE)[17]. Since then it has been clear that reset control may improve performance, but its design has to be done with care, as it might also introduce instability. In [9] a certain stability condition (the H_β condition) was introduced for finite-dimensional systems, which was later extended to time-delay systems [7]. New

techniques for reset stability can be found in [23], and a recent performance analysis in [1].

On the other hand, bilateral teleoperation is an area that has motivated an enormous amount of research in the last two decades [16]. Modern teleoperation is usually based on applying passivity-based control techniques [28] to teleoperated systems. Using passivity tools has a number of advantages: they provide a multi-domain and modular approach to modeling, and transparent control principles based on energy and power concepts. The passivity ideas can be adapted to the teleoperation framework, where a human operator (actuating a master device) manipulates a remote machine (slave device) which is possibly interacting with the environment. If some time delay exists, a communication channel transmitting velocity and force (which provides the operator with a feeling of telepresence that is essential in applications [21], [18], [20], [22]) is no longer passive. As an alternative, wave variables – which are obtained from velocities and forces via the scattering transformation, see [3], [24]– should be transmitted, thus making the delayed line behave like an analog lossless LC line. This is called line-passivation.

It turns out that after line passivation, and with passive controllers at the master and slave sides, the overall teleoperation system becomes passive. Since it is assumed that the external elements –human operator and environment– behave in a passive way, this means that the system is stable for all possible constant values of the time delay. This delay-independent stability property can also be extended to time-varying delays [11], and therefore it is possible to use internet as the communication channel, as has already been shown in several applications [25], [26], [27], [30].

Delay-independent stability can be interpreted partly as an advantage and partly as a drawback: on the one hand, it is an advantage because the designer does not have to worry about the delay. On the other hand, it is a drawback because, if the passive controllers are stable for very large delay values, they tend to provide worse performance than other (non passive) controllers, which are unstable for large delays but stable for small nominal delays.

Realizing that the source of the problem is the time-delay, which introduces a linear trade-off between speed and robustness, it becomes clear that using the reset-control principle in teleoperation might enable us to combine the robustness of the passive solutions with the fast position tracking performance provided by a proper design of the reset action. This is the basic idea of this paper, which is based on the authors' previous work in the fields of reset control [4], [5], [6], [7], [10], [29] and teleoperation [14].

A preliminary version of this paper [15] was presented at the IECON'08 conference. Many substantial modifications

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have been included in this new version: first, a theoretic justification of the use of reset in teleoperation is provided. Second, a PI+CI reset strategy [6], [29] is chosen instead of the previous simple full reset, thus enabling an additional tuning of the reset action in order to obtain a good transient response while simultaneously eliminating the steady state error. Third, contact with the environment has now been taken into consideration in the simulations; and fourth, experimental results with a real plant are provided.

As a consequence, the paper is organized as follows. Section II provides an overview of the system, summarizing what was already explained in [15] about passive teleoperation. Then, section III shows how the use of reset is capable of overcoming the fundamental limitations of linear controllers, namely when time delays are present. In section IV the proposed reset strategy is presented, and experimental results are provided in section V. Finally, conclusions are given in section VI.

II. PASSIVE TELEOPERATION AND SYSTEM OVERVIEW

The block diagram that describes the overall system is plotted in Fig.1. It consists of the following subsystems: a master device commanded by an operator, a master impedance controller (represented as the parallel of a spring K_m and a damper B_m), the scattering transformations corresponding to master and slave sides, the communication channel, a slave impedance controller (K_s, B_s) and a slave device in contact with the environment. The interchanged variables are either power variables (forces f_i and velocities \dot{x}_i , with $i \in \{h, m, s, e\}$ and the additional subindex d for delayed variables); or wave variables (u_m, u_s, w_m, w_s) which result from the scattering transformation of the former.

The communication channel contains the time delays, which will be considered constant and known throughout the paper. This is a frequent assumption when deriving theoretical results for the first time; these may be extended for time-varying delays later¹. It is well known that a time delay provokes a loss of passivity, which can be arranged using the scattering theory [3] or the equivalent wave-variables [24] formulation given by the equations:

$$\begin{pmatrix} u_m \\ \dot{x}_{md} \end{pmatrix} = \begin{pmatrix} \sqrt{2}B^{-1/2} & -I \\ B^{-1} & -\sqrt{2}B^{-1/2} \end{pmatrix} \begin{pmatrix} f_m \\ w_m \end{pmatrix} \quad (1)$$

and

$$\begin{pmatrix} w_s \\ \dot{x}_{sd} \end{pmatrix} = \begin{pmatrix} \sqrt{2}B^{-1/2} & -I \\ -B^{-1} & \sqrt{2}B^{-1/2} \end{pmatrix} \begin{pmatrix} f_s \\ u_s \end{pmatrix} \quad (2)$$

where the matrix $B > 0$ is the line impedance. The actually transmitted variables are the wave variables:

$$u_s(t) = u_m(t - \Delta T), \quad w_m(t) = w_s(t - \Delta T), \quad (3)$$

¹Here we limit ourselves to constant time delays; only in the last example in subsection V-B, and as a preliminary experimental validation, we apply the method to unknown, time-varying delays.

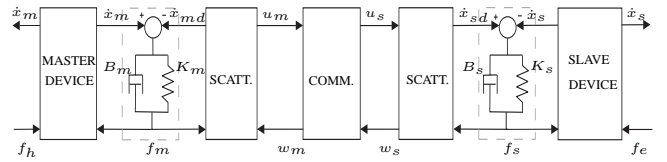


Fig. 1. Teleoperation scheme

where $\Delta T \geq 0$ is the communication delay, unknown but considered constant. This configuration behaves as a lossless system with respect to the storage (hamiltonian) function

$$H_c(t) = \frac{1}{2} \int_{t-\Delta T}^t (\|u_m(\tau)\|^2 + \|w_s(\tau)\|^2) d\tau, \quad (4)$$

that is, the integral of the power of the waves for the duration of the transmission. It easily follows that

$$-f_s^\top(t)\dot{x}_{sd}(t) + f_m^\top(t)\dot{x}_{md}(t) = \dot{H}_c(t) \quad (5)$$

This fact is true for all ΔT , so, from the point of view of passivity, we do not have to worry about its actual value. The interconnection of passive subsystems leads to an overall system that is itself passive [28], and hence a stable behaviour is guaranteed.

As wave reflections can occur at both sides of a teleoperation scheme, there is a need for impedance matching [24], which can be achieved if both sites are placed under velocity control. This is one of the motivations for using the two symmetric ‘‘impedance controllers’’ mentioned before, which are placed at each end of the transmission channel. Thus, each side is receiving force information and providing velocity signals.

The master side of the setup consists of a master device, its impedance controller, and the corresponding scattering transformation. The master device interacts with the human operator, allowing him to specify the desired movement of the plant (velocity command), while receiving some force feedback representing information about the operating conditions. Similarly, the slave side consists of the slave device, its impedance controller, and the scattering transformation.

The master and slave devices will be considered as mechanical systems whose equations can be written in the port-hamiltonian notation as:

$$\begin{aligned} \dot{z} &= [J(z) - R(z)] \frac{\partial H(z)}{\partial z} + g(z)u \\ \dot{x} &= g^T(z) \frac{\partial H(z)}{\partial z} \end{aligned} \quad (6)$$

where z are the states, \dot{x} the outputs (velocities), u the inputs (forces), H the hamiltonian function, and J, R the interconnection and dissipation structures respectively.

The equations of the impedance controllers can be written as

$$\begin{aligned} f_m &= K_m \int (\dot{x}_m - \dot{x}_{md}) dt + B_m (\dot{x}_m - \dot{x}_{md}) \\ f_s &= K_s \int (\dot{x}_{sd} - \dot{x}_s) dt + B_s (\dot{x}_{sd} - \dot{x}_s) \end{aligned} \quad (7)$$

which are two Proportional-Integral (PI) controllers with transfer functions

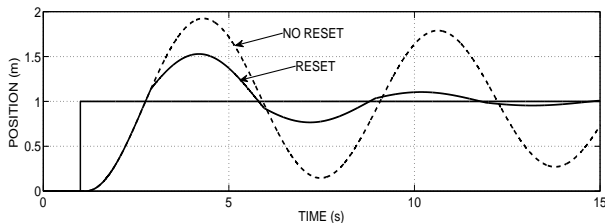


Fig. 2. Step responses with and without reset

$$\begin{aligned} f_m &= \left(\frac{K_m}{s} + B_m \right) e_m, & e_m &= \dot{x}_m - \dot{x}_{md} \\ f_s &= \left(\frac{K_s}{s} + B_s \right) e_s, & e_s &= \dot{x}_{sd} - \dot{x}_s \end{aligned} \quad (8)$$

In this way, we are not only transmitting energy through the strings K_m, K_s , but also dissipating some of it in the dampers B_m, B_s . Consequently, artificial damping is injected, which is a requisite to ensure a passive behavior when it is possible that the plant interacts with the environment. The parameters of this controller are the stiffness constants of the springs, K_m and K_s , and the viscous frictions, B_m and B_s . If the latter are chosen to be equal to the scattering parameter of the transmission line, B , no wave reflections will take place [24].

III. ADVANTAGES OF RESET CONTROL

A. Introduction to Reset Control

A general reset controller with linear base dynamics can be described by the following continuous-impulsive equations:

$$\mathcal{R}: \begin{cases} \dot{x}_r &= A_r x_r + B_r e, & e \neq 0 \\ x_r^+ &= A_\rho x_r, & e = 0 \\ u &= C_r x_r + D_r e \end{cases} \quad (9)$$

where (e, x_r, u) are input, state and output vectors, respectively, and the second equation represents the impulsive or reset actions, applied when the input $e(t)$ crosses zero. Typically, A_ρ takes the form $A_\rho = \text{diag}(1, \dots, 1, 0, \dots, 0)$ so that some of the controller states are affected by reset while others remain unaltered. The *Base Linear Compensator* (BLC) is the linear system obtained from (9) after removing reset, $R_{bl}(s) = C_r (sI - A_r)^{-1} B_r + D_r$.

The purpose of reset control can be easily understood by means of the following example, taken from [7]. Consider a plant with a transfer function $P(s) = e^{-\Delta T s} \frac{s+1}{s(s+0.2)}$, in feedback interconnection with a reset controller with a BLC given by $\frac{1}{s+1}$. The continuous and impulsive modes of the reset controller are given by (9) with $(A_r, B_r, C_r, D_r) = (-1, 1, 1, 0)$ and with $A_\rho = 0$. With a delay $\Delta T = 0.15$, the time responses to a step input are those shown on Fig. 2. It can be seen that the use of reset enables to maintain the fast transient response while reducing the overshoot.

B. Fundamental Limitations of Linear Control Systems

If a plant has poles or zeros in the right half plane, or time-delays, it is called a *non-minimum phase system* and it is subject to some fundamental limitations [2]. Let us factor the loop transfer function of one such system as $L(s) = L_m(s)L_a(s)$,

where $L_m(s)$ is the minimum phase part and $L_a(s)$ the non-minimum phase part. We normalize this factorization so that $|L_a(i\omega)| = 1$ (all-pass). In teleoperation applications this part can be identified with the transmission delay ΔT , so let us assume $L_a(s) = e^{-s\Delta T}$.

Following [2], we characterize the bandwidth by the gain crossover frequency ω_c given by $|L(i\omega_c)| = |L_m(i\omega_c)| = 1$ (L_a is all-pass). Let us denote the slope of $|L_m(i\omega)| = |L(i\omega)|$ in dB/dec as $n(\omega)$, and let $n_c = n(\omega_c)$ be the ‘‘crossover slope’’. Two measures of robust stability are given by the guaranteed phase margin, ϕ_m , and by the crossover slope n_c . The loop formed around $L(s)$ is more robustly stable as ϕ_m is larger (60° better than 45°) and n_c is more negative (-20dB/dec better than -10dB/dec). Two relations hold:

$$\arg L(i\omega_c) \geq -\pi + \phi_m \arg L_m(i\omega) \approx \frac{n(\omega)}{20} \frac{\pi}{2} \quad (10)$$

The first inequality ensures the guaranteed phase margin ϕ_m and the second one is the *Bode’s relation*, which says that, for minimum phase systems, angle and modulus slope are not independent (-90° corresponds to -20dB/dec). If we use $\arg L = \arg L_m + \arg L_a$, with $\arg L_a = -\omega\Delta T$, and Bode’s relation (with $=$ instead of \approx), we reach

$$\omega_c \Delta T \leq \pi - \phi_m + \arg L_m(i\omega_c) = \pi - \phi_m + \frac{n_c \pi}{20 \cdot 2} =: c(\phi_m, n_c) \quad (11)$$

where the restriction on the bandwidth ω_c imposed by the coefficient $c(\cdot, \cdot)$ gets larger as the robustness requirements (ϕ_m, n_c) are stronger. For example, if $(\phi_m, n_c) = (45^\circ, -10\text{dB/dec})$ then $c = \pi/2 \approx 1.57$, but if $(\phi_m, n_c) = (60^\circ, -20\text{dB/dec})$ then $c = \pi/6 \approx 0.52$. Therefore, the previous inequality establishes an unavoidable limitation for linear systems, a tradeoff between bandwidth and robust stability.

C. Overcoming Fundamental Limitations with Reset

How can reset control contribute to solve this problem? Checking the previous steps of the inequality $\omega_c \Delta T \leq c$, it follows that the limitation could be alleviated if we could replace $\arg L_m(i\omega_c)$ by a quantity less negative (larger) than $\frac{n_c \pi}{20 \cdot 2}$. Unfortunately, no linear system is able to solve this, because the non-minimum phase factor is the cause of the problem ($L_a(s) = e^{-s\Delta T}$ in our case) and the minimum phase factor $L_m(s)$ is restricted to the approximate Bode relation.

Thus, the only way to achieve a significant reduction of the limitation is by using some new type of nonlinear system L_r (the reset controller). It will be useful to define an approximate frequency response $L_r(\omega)$ of L_r by describing function analysis. The reset system L_r can be used instead of L_m , or combined in series with it, $L_r(\omega)L_m(i\omega)$. As the angles and decibel slopes n_r, n of the factors in $L_r(\omega)L_m(i\omega)$ behave additively, then it follows that the Bode’s relation is drastically beaten (and the limitation outperformed) if

$$\arg L_r(\omega) \gg \frac{n_r(\omega) \pi}{20 \cdot 2} \quad (12)$$

Fortunately, it is well documented that a variety of reset controllers (FORE, Clegg, etc.) satisfy the previous relation.

For example, the Clegg integrator L_{CI} (an integrator with reset) has an approximate describing function $L_{CI}(\omega) = \frac{1.62}{\omega} e^{-i 38^\circ}$, i.e., $\arg L_{CI}(i\omega) = -38^\circ$ and $n_{CI}(\omega) = -20\text{dB/dec}$, which means a valuable improvement of about 52° in phase lag [13].

Consider a very simple example: let us compare two feedback loops with delay ΔT , the first one with a standard integrator $L_m(s) = 1/s$ and the second one with the Clegg or reset integrator $L_r = L_{CI}$. In both cases the modulus slope has to be $n_c = -20\text{dB/dec}$. Let us impose a phase margin $\phi_m = \pi/3 = 60^\circ$. As we have seen, the linear control system is subject to the limitation $\omega_c \Delta T \leq \pi/6 \approx 0.52$. On the other hand, the reset control system is restricted to $\omega_c \Delta T \leq \pi - \phi_m + \arg L_r = \pi - \pi/3 - \pi 38/180 \approx 1.43$. Thus, for the same phase margin and delay, the reset system outperforms the linear one. The bandwidth limitation $\omega_c \Delta T \leq 0.52$ is improved to $\omega_c \Delta T \leq 1.43$ by a factor $1.43/0.52 = 2.75$ (almost three times larger) provided by reset control.

D. Clegg Integrator with Advanced Reset

This subsection presents a new reset integrator, called advanced Clegg integrator, that improves the Clegg integrator, providing also -20dB/dec but with a phase lag even less negative than -38° , that can be made close to -25° . The simple idea is replacing the reset condition $e(t) = 0$ by a new condition $u(t) = 0$ where $u(t)$ is obtained by passing $e(t)$ through some block $C(s)$ providing phase advance. This idea of advance reset is applied in the subsequent sections to the teleoperation control systems. So, consider now the Clegg Integrator with *advanced* reset:

$$\begin{aligned} \dot{x}(t) &= e, & u(t) &\neq 0, \\ x^+ &= 0, & u(t) &= 0, & u(t) &= \mathcal{L}^{-1}[C(s) E(s)] \end{aligned} \quad (13)$$

where $\mathcal{L}, \mathcal{L}^{-1}$ are the direct and inverse Laplace transforms and $C(s)$ is an anticipative block, for example $C(s) = K_p + K_d s$, which introduces a phase lead or phase advance on $e(t)$ (if $C(s) \equiv 1$ then $u = e$, and we recover the standard Clegg Integrator). The describing function of an Advanced Clegg Integrator with a *phase advance* of $\phi = \phi(\omega) = \arg C(i\omega)$ is

$$L_{ACI}(\omega) = \frac{1}{\omega} \left[\frac{4 \cos^2 \phi}{\pi} - i \left(1 - \frac{4 \cos \phi \sin \phi}{\pi} \right) \right] \quad (14)$$

In Fig. 3 its modulus-times-frequency ($|L_{ACI}| \cdot \omega$) and phase ($\arg L_{ACI}$) are plotted as functions of the phase advance ϕ introduced by $C(s)$. Notice that for $\phi = 0$ (point 'C') we get the Clegg Integrator, $\frac{1.62}{\omega} e^{-i38^\circ}$. Since the modulus always takes the form $\frac{k}{\omega}$ (-20dB/dec), the key feature is the phase. The largest achievable phase ('A') is about -25° , corresponding to an advanced reset of $\phi \approx +30^\circ$. Thus, if we are able to design the phase lead block $C(s)$ so that it provides $\phi \approx +30^\circ$, we will obtain $L_{ACI} \approx \frac{1}{\omega} e^{-i25^\circ}$, which is *the same attenuation as an integrator but with $90^\circ - 25^\circ = 65^\circ$ of phase improvement*, a very valuable issue regarding fundamental limitations.

However, there are some restrictions to this: the phase lead can not be held constant $\phi \approx +30^\circ$ for all frequencies, and

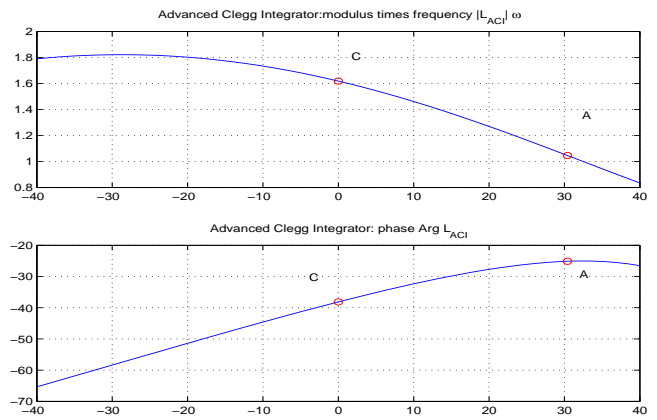


Fig. 3. Frequency plots of the advanced Clegg integrator. X axis units: degrees ($^\circ$). Y axis units: rad/second (top), degrees ($^\circ$), (bottom)

the describing function is only an approximation. Despite these minor aspects, the main advantage of a reset integrator remains, and can be summarized as the ability to provide -20dB/dec with a much smaller phase lag than the standard integrator.

IV. RESET PROCEDURE

A. Master PI+CI controller

In this section a reset strategy for improving performance of the impedance controllers is presented. Recall that their transfer functions are given by equation (8), thus defining them as Proportional-Integral (PI) controllers with respect to the velocity error. The proposed reset procedure entails, to begin with, *partially resetting* the integral value of the *master* PI, and leaving the slave PI unchanged (i.e., linear). In this way, the master PI=P+I is, using the terminology in [6], [29], transformed into a PI+CI controller. PI+CI means a proportional-integral controller plus a ‘‘Clegg’’ [13] or reset integrator. The overall master controller can be then written in the form (9) with

$$\begin{cases} \dot{x}_I = \dot{x}_{CI} = e_m, & c \neq 0 \\ \begin{bmatrix} x_I^+ \\ x_{CI}^+ \end{bmatrix} = \begin{bmatrix} x_I^- \\ 0 \end{bmatrix}, & c = 0 \\ f_m = K_m[(1-p) p] \begin{bmatrix} x_I \\ x_{CI} \end{bmatrix} + B_m e_m \end{cases} \quad (15)$$

with c the condition determining the reset instants, (x_I, x_{CI}) the states of the linear and Clegg integrators, respectively; and $(1-p, p)$ the parameters that multiply the integrators' states.

The PI+CI controller proposed here is an evolution of the P+CI originally used in [15]. The PI+CI adds a new integrator (and hence a new state) to the controller, and resets only one of the integrators after a reset instant. This can be implemented as two parallel integrators (see Fig. 4), one of them being a Clegg integrator and the other a normal one. The outputs of these two integrators are multiplied by p and $1-p$ respectively, being $0 < p < 1$. Thus, the modification of parameter p provides a simple way of tuning the controller.

The reason for performing only “partial” reset is that a totally reset integrator loses the fundamental property of eliminating the steady-state error. Since feedback control is performed on the velocity signal, full reset leads to a loss of information about the slave position that cannot be recovered. When this happens, position drift appears, a well-known problem in bilateral teleoperation. However, when partial reset is used, position information is being kept in the linear integrator (the non-reset integrator placed in parallel to the reset one).

This can be more formally explained as follows. A steady state is achieved if all the forces and velocities in Fig. 1 are zero. According to [12] and references therein, the steady-state tracking-position error, referred to as “position drift”, is zero if:

$$\Delta x_m = \int_0^t (\dot{x}_m - \dot{x}_{md}) dt = 0, \quad (16)$$

where t is some time at steady-state. Let us assume that the error is initially zero, i.e. $\Delta x_m(0) = 0$. Now consider the master impedance controller in Fig. 4, where gain k and integral time T are related to (B_m, K_m) in Fig. 1 by $k = B_m$ and $T = \frac{B_m}{K_m}$. The general equation for $(0 < p < 1)$ is

$$y = f_m = B_m(\dot{x}_m - \dot{x}_{md}) + K_m(x_I(1-p) + x_{CI}p) \quad (17)$$

where $x_I = \int_0^t (\dot{x}_m - \dot{x}_{md}) dt$ and $x_{CI} = \int_{t_k}^t (\dot{x}_m - \dot{x}_{md}) dt$, where t_k is the last reset time. Now, when in steady state, the controller depicted in Fig. 4 has zero input (velocities) and zero output (force). The problem is whether there may exist nonzero steady-state values x_I, x_{CI} compatible with zero input and output. We will discuss three possible cases: PI, CI and PI+CI.

When a PI is used as matching controller, the fact that the output is zero under zero input yields (16) directly because Δx_m corresponds to the state of the PI controller. On the other hand, if a CI controller (this is, a PI+CI with $p = 1$) is used, Δx_m can be non-null under zero output and zero input due to the fact that every reset action is deleting the controller’s memory; null reset state entails $\int_{t_k}^t (\dot{x}_m - \dot{x}_{md}) dt = 0$, where t_k is the instant of the last reset action. The advantage of using a PI+CI with $p < 1$ is that (16) is guaranteed. This is based on the fact that the reset state (x_{CI}) cannot keep a non-null value under zero input. In principle, there may exist a combination (x_{CI}, x_I) of non-null states in (15) that yield zero output (f_m) with zero input. However, a sustained zero input entails that the reset law holds and that the reset state is made zero. Therefore, at steady-state, the linear state (x_I) has to be zero, and since $\Delta x_m = x_I$, (16) holds and the steady-state tracking-position error is zero, as in the linear (PI) case.

Hence, the PI+CI manages to improve the transient response while retaining the zero steady-state error property. This entails a trade-off between transient and steady state performance, and the parameter p offers an intuitive way of adjusting it. This can be done by a simple trial-and-error procedure, decreasing its value from $p = 1$ until the steady state performance is good enough, this is, with an overshoot and settling time which are both small enough to be acceptable.

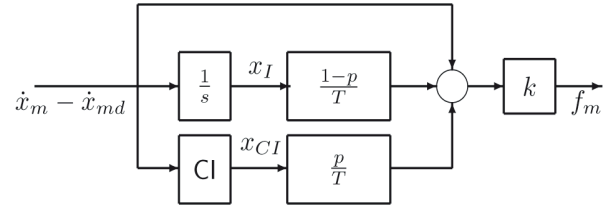


Fig. 4. Structure of a PI+CI

The option of resetting the master side controller and not the slave one is backed by several sets of simulations and experiments. In them, the effect of resetting the master has been found to be much more important, while reset of the slave has little influence. The explanation is related to the fact that the signal round trip (from the velocity specified by the operator \dot{x}_m to force feedback f_m in Fig.1) is closed by the master controller forming an external loop around the plant (slave) that contains the time-delays. On the other hand, the slave PI forms an inner loop not affected by delay. As the expected performance improvement due to reset is more effective under fundamental limitations (time-delays), the master controller, and not the slave, is the one that should be reset. The value of p should be chosen so that it is close enough to 1 to reduce overshoot, but not so high as to affect the capability of eliminating the steady state position error.

Remark 1. Passivity of the PI+CI

We make use of the result that states that the parallel connection of two passive systems is itself passive [28]. Since a PI+CI is the parallel connection of a PI compensator and a CI compensator (see Fig. 4), its passivity results from the passivity of both subsystems as follows. Without loss of generality, gains have been restructured in order to show a simpler and easier to understand proof. First, passivity of a PI can be proven with the classical result for linear systems [19]: a system with a transfer function $H(j\omega)$ is passive if $\text{Re}[H(j\omega)] \geq 0$ for all $\omega \in \mathcal{R}$. The PI transfer function is given by:

$$H_{PI}(j\omega) = k \left(1 + \frac{1}{T'j\omega} \right) \quad (18)$$

where $T' = \frac{T}{1-p}$ and T is the integration time constant. Its real part is given by

$$\text{Re}[H_{PI}(j\omega)] = k \geq 0, \quad (19)$$

Therefore, the PI compensator is passive. On the other hand, using the Prop. 1 in [10], passivity of a full reset compensator results from the passivity of its base linear compensator. The CI base linear compensator is a linear integrator and its transfer function is $H_{CI}^{blc}(j\omega) = \frac{1}{j\omega}$. Since $\text{Re}[H_{CI}^{blc}(j\omega)] = 0 \geq 0$ for all $\omega \in \mathcal{R}$, the linear integrator is passive and therefore, using the above mentioned result, the full reset compensator CI is also passive.

Hence, it is immediate to see that the PI+CI compensator defined by (15) is passive.

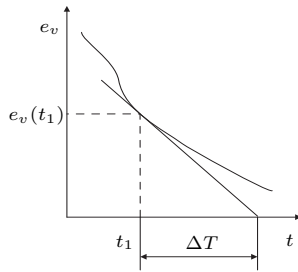


Fig. 5. Choosing the reset instants

B. Reset instants

The aforementioned passivity property is independent of the reset instants, provided that there are a finite number of resets in any finite interval. This enables the designer to choose the reset instants in the most convenient way for each application. In the case of teleoperation with a known, constant delay, it is possible to profit from this freedom by anticipating to this delay: the reset instants can be chosen so that they correspond to the times when the velocity error is *approaching* zero. The resulting strategy can be visualized in figure 5, where the evolution of the velocity error, $e_v(t) = \dot{x}_m(t) - \dot{x}_s(t - \Delta T)$, is plotted. By monitoring the velocity error and its variation, the reset instants can be chosen as those satisfying the following condition:

$$\dot{e}_v(t_1) = -\frac{e_v(t_1)}{\Delta T} \Leftrightarrow e_v(t_1) + \dot{e}_v(t_1)\Delta T = 0 \quad (20)$$

Hence, (20) defines the reset condition $c = 0$ in (15), which amounts to applying a PD control on the error signal $e_v(t)$, implementing the $C(s)$ anticipation block introduced in section III-D. Thus, instead of waiting for the error to be zero, this situation is predicted and reset is carried out in advance. This mechanism also holds if the slave interacts with the environment: in case of a contact, the slave's velocity is modified and the reset instants are changed accordingly.

V. EXAMPLES

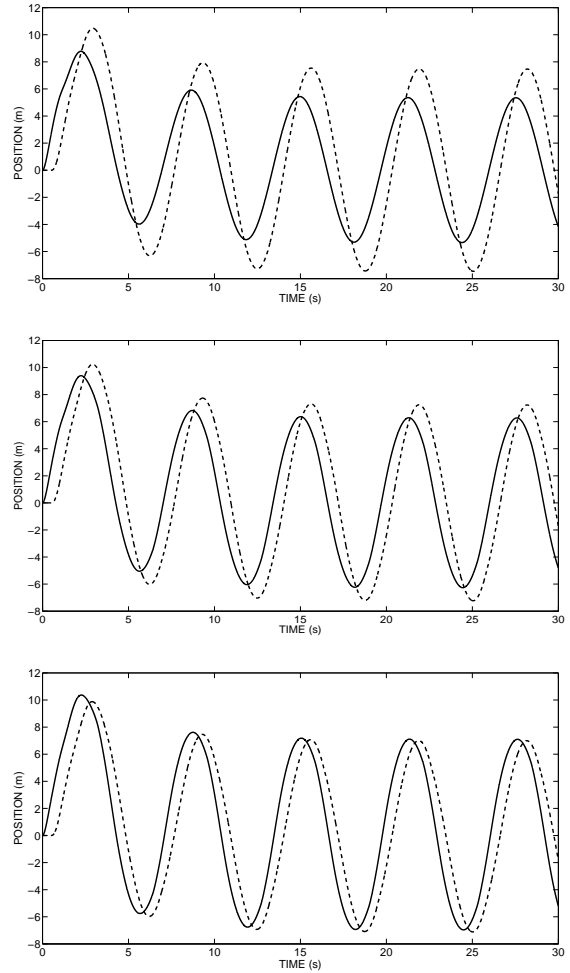
In order to show that the reset control action is useful in different applications, two different teleoperated systems with two different approaches are chosen.

A. Example 1: Simple robot

First we choose a simple model of a one-dimensional robot used in many simulations of bilateral teleoperation, consisting of a mass with friction. The ‘‘Master Device’’ and ‘‘Slave Device’’ blocks depicted in 1 are then given by:

$$\begin{aligned} \dot{x}_m &= \frac{1}{m_r s + b_r} (f_h - f_m) \\ \dot{x}_{cr} &= \frac{1}{m_r s + b_r} (f_s - f_e) \end{aligned} \quad (21)$$

The force exerted by the human operator, f_h , is simulated as a sinusoidal force command applied to the master device. The force f_m produced by the master side impedance controller is fed back to the master device, influencing its movement in


 Fig. 6. Teleoperation in free space. Solid lines: master device, dashed: slave. Top: without reset, medium: with partial reset ($p = 0.5$), bottom: full reset.

the same way as the operator command. Symmetrically, the force acting on the slave device is the output of the impedance controller at the slave side.

Firstly, we will show simulation results that illustrate the potential of reset control for eliminating overshoot. Two identical ‘‘robots’’ with mass $m_r = 1 \text{ kg}$ and friction $b_r = 1 \frac{\text{kg}}{\text{s}}$ are considered at the master and slave sides. A constant time delay of 0.5 seconds is present in both directions of the communications channel (round trip delay: one second). The coefficients of the impedance controllers are $K_m = K_s = 10 \frac{\text{kg}}{\text{s}^2}$, $B_m = B_s = 10 \frac{\text{kg}}{\text{s}}$, and the scattering factor is also set to $b = 10 \frac{\text{kg}}{\text{s}}$. This is an aggressive tuning of the controllers, intended to provide fast transient response; hence the high-gain values K_m and K_s . In Fig. 6 the result of a manoeuvre in free space is plotted, with the master trajectory as a solid line and the slave as a dashed line. It can be noticed that the non-reset controller indeed manages to obtain this fast transient, but at the cost of a large overshoot. A partial reset controller with $p = 0.5$ yields the same fast transient while achieving a 50% reduction in overshoot. Finally, full reset ($p = 1$) eliminates

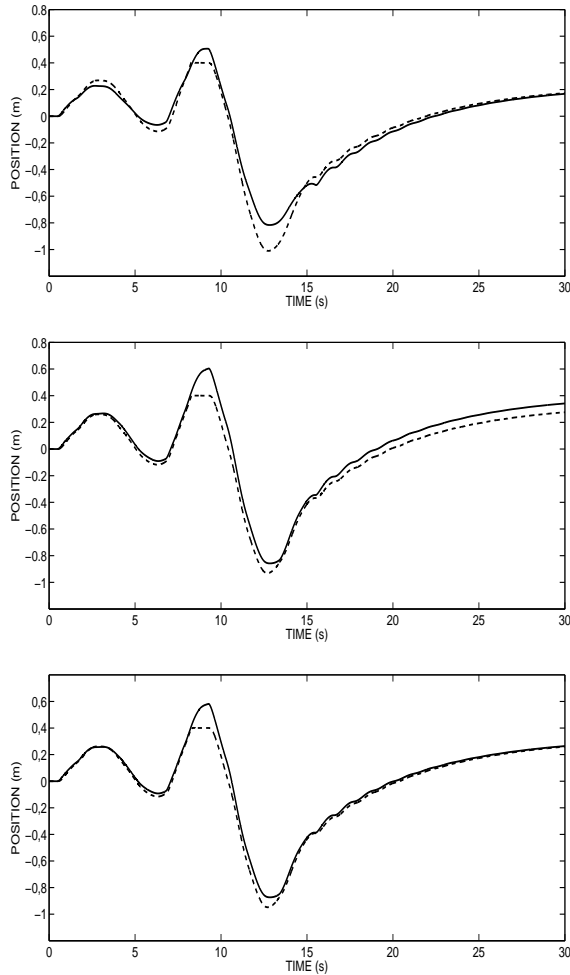


Fig. 7. Manoeuvre with contact. Solid lines: master device, dashed: slave. Top: no reset; medium: full reset; bottom: partial reset ($p = 0.85$).

overshoot almost completely (90 – 100% reduction).

However, the steady state behavior is not shown in these simulations, since the setpoint is always varying. We consider now a different manoeuvre, including contact with the environment, where this steady state behavior can be evaluated. We use the same master and slave devices as before, and place them initially at the same position, $x_m(0) = x_s(0) = 0$ m; but now there is a wall in the slave location at $x_s = 0.5$ m. A sinusoidal force with a frequency of 1 rad/s is applied by the simulated operator at the master side (f_h), with an amplitude of 2 N during the first cycle and of 5 N during the second and third ones. After 15 seconds, this force is made zero, simulating that the operator stops holding the master device. The coefficients of the impedance controllers are now $K_m = K_s = 15 \frac{kg}{s^2}$, $B_m = B_s = 20 \frac{kg}{s}$, and the scattering factor is also set to $b = 20 \frac{kg}{s}$. The evolution of the system is shown in figure 7, for the no-reset, full-reset, and partial-reset cases (from top to bottom). If no reset is performed, the plant exhibits considerable overshoot. A reset strategy can be applied to solve this issue. Since the overall delay is $\Delta T = 1$, the reset instants satisfy $e_v + \dot{e}_v = 0$. In this case, a full

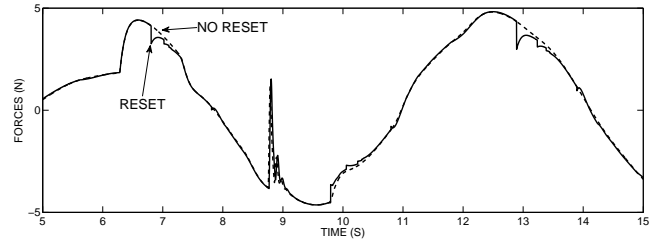


Fig. 8. Feedback forces with partial reset and without reset

reset strategy (Fig. 7, medium) and a partial reset strategy with $p = 0.85$ (Fig. 7, bottom) achieve similar results as far as overshoot reduction is concerned: at time ≈ 3 seconds, the overshoot is eliminated; at time ≈ 6 seconds, it's reduced by more than 50%; and at time ≈ 13 seconds, by more than 60%. In both cases, when moving in free space the overshoot is reduced and, due to the fact that we are anticipating the time delay, the slave position tracks the master position more accurately, so the shapes of the trajectories are more similar. The difference in performance between both strategies is that with full reset there's an error in steady state, which doesn't appear with partial reset: in this latter case, after the master device is released by the operator, this is pushed by the feedback force until it matches the position of the slave device, thus eliminating the steady state position error. Obtaining simultaneously these two features (good tracking with reduced overshoot, and no error in steady state) is possible due to the use of partial reset.

In figure 8 the force feedback to the user (f_m) is plotted for the no-reset (dashed line) and reset cases (solid line). As expected, the use of reset decreases the magnitude of the force at the reset instants, resembling the physical equivalent of a charged spring whose deformation is suddenly reduced.

B. Example 2: Gantry crane

Now we apply the reset control scheme to the teleoperation of a gantry crane. A real plant, Inteco's 3DCrane model, was used as slave device in the experiments. The output to be controlled is the position of the cart moving in the x axis. Its movement is affected by the oscillations of a payload hanging from a cable with constant length. Unlike in the previous case, the master device is not similar to the slave plant; instead, the desired velocity is directly indicated by the operator. Two different experiments will be carried out: in the first one, the operator is simulated in order to obtain a completely repeatable manoeuvre; in the second one, the manoeuvre is actually specified by a human operator.

Let us first examine the case where the operator's command is simulated as a velocity pulse with an amplitude of $0.2 \frac{m}{s}$ and 1.5 seconds long. The feedback force has thus no effect on the velocity setpoint. A constant time delay of 0.25 seconds is considered (round trip delay of 0.5 seconds). The controllers are aggressively tuned with coefficients $K_m = K_s = 60 \frac{kg}{s^2}$, $B_m = B_s = b = 6 \frac{kg}{s}$. The desired and achieved positions are pictured on figure 9. It can be noticed that the

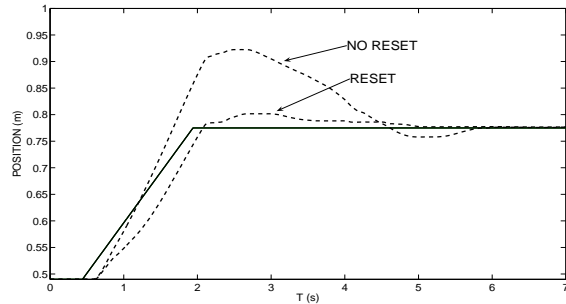


Fig. 9. Gantry crane, with and without partial reset ($p = 0.95$)

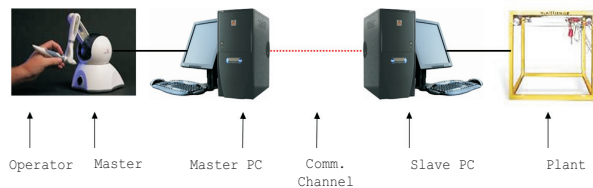


Fig. 10. Setup for crane teleoperation

reset action eliminates the overshoot by 80%, while providing a fast rise time.

Next we perform a human-commanded teleoperation manoeuvre. The operator handles again a SensAble PhanTom Omni haptic device, and the overall teleoperation setup is depicted in Fig. 10. The controllers are tuned as before, but this time the time delay is no longer constant. Instead, the use of a packet-switched network such as internet is simulated, applying the passivity-maintaining solution for signal reconstruction presented in [11] that was applied to crane teleoperation in [14]. The delay follows a normal distribution, with an average value of 0.15 seconds for each channel (master to slave and slave to master), a standard deviation of 0.01, and a 5% packet loss. The reset controller is hence tuned to anticipate to an expected round trip delay of 0.3 seconds. In figure 11 it's shown that the overshoot is completely eliminated.

VI. CONCLUSIONS

This paper reports a study on the application of reset control techniques to passivity-based teleoperation. The advantages of reset control for overcoming fundamental limitations, namely time delays, have been presented and exploited. The proposed method resets the state of the master impedance controller and benefits from choosing the reset instants so that the system anticipates to the communications channel's time delay.

Several improvements have been made with respect to the first version of this paper [15], including a theoretical justification of the reset controllers' capability of overcoming linear fundamental limitations. Furthermore, partial reset with a PI+CI architecture is now used instead of the originally

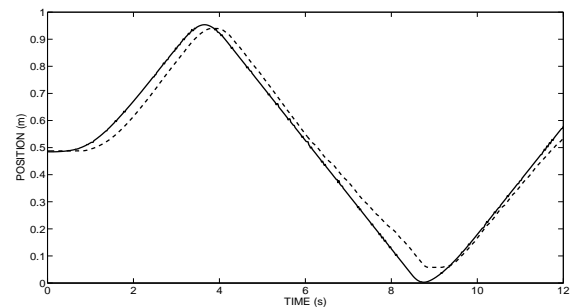
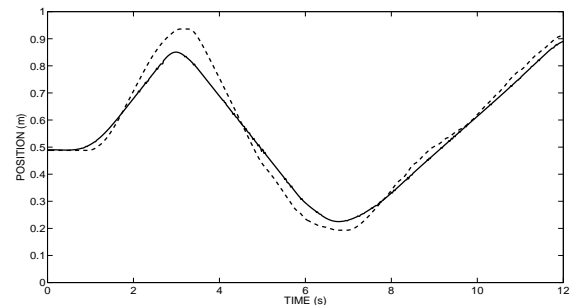


Fig. 11. Teleoperating a crane over the internet. Solid lines: master device, dashed: slave (gantry crane). Top: no reset; bottom: partial reset ($p = 0.95$)

proposed full reset, thus ensuring cancellation of the steady-state error. Passivity of the control system has been proven when the characteristic parameter of the PI+CI controller is constant.

Simulated and experimental results have been shown which demonstrate the good performance of the proposed scheme for different applications. The solution has shown its usefulness even in internet-based teleoperation with time-varying delays.

Future work will be focused on the possibility of using a time-varying parameter p , and its implications for passivity. An extension for unknown, time-varying delays, is another natural line of research.

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