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Bilateral Teleoperation under Time-Varying Delay using Wave Variables

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Abstract— **Any teleoperation system involving two distant devices is affected by communication delay due to the physical gap between the devices. Several approaches based on wave variables have already been proposed to deal with time-varying delay. However, these approaches are too conservative resulting in high degradation from the constant time delay case. In this paper, we propose a new control scheme for bilateral teleoperation under time-varying communication delay entirely developed in the wave variables domain. The proposed method minimizes the performance degradation from the constant time delay case. Experimental results show the validity of the proposed scheme.**

I. INTRODUCTION

Telerobotics is the field of robotics that deals with distant, yet coupled robots. Teleoperation systems have been originally used in hazardous environment (Goertz [9]). Control laws for such systems are either unilateral (i.e. without force feedback) or bilateral. For an overview on the control challenges and a survey on current approaches see [18], [11] and [4], [1] for a quantitative comparison of different control architectures.

A Bilateral teleoperation system consists in a double information flow that allows the user to interact with the remote environment and, at the same time, provides him with a force feedback. It has been proved that adding force feedback to a teleoperation system emphasizes the sense of telepresence improving the user's ability to perform complex tasks [27]. Position-Position (PP) and Position-Force (PF) schemes are examples of conventional bilateral control law which are well used in practice. Although bilateral teleoperation can provide better performances than unilateral one, in combination with even a small communication delay stability problems may arise.

Several results using H_∞ optimal control appeared in the mid 1990s [15], [12], [29]. Leung [16], introduced a compensator for delayed teleoperators that achieved stability for a prescribed time delay margin while optimizing performance specifications. Sano et al. [26], [25], suggested the use of gain scheduled H_∞ controller using measured time delay. Sliding-mode approach has also been used: one degree of freedom teleoperated system without delay [5], and time-varying delayed communication by Park et al. [24], [23] and Cho et al. [6]. Anyway these kinds of approaches assume that the slave environments and the human users are known linear time-invariant systems.

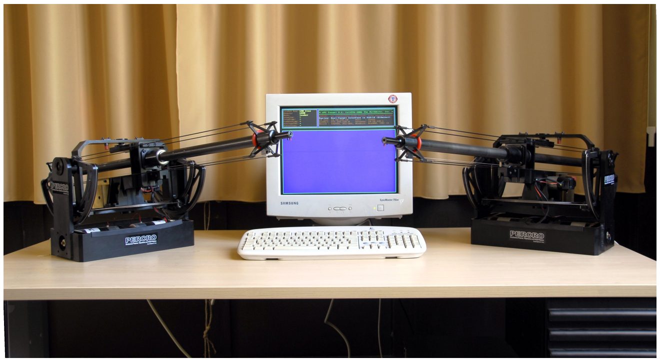
Fig. 1. CREATE system installation

In the late 1980s and early 1990s, network theory came into play through impedance representation, hybrid representation and passivity-based control. The passivity-based approach paved the way for stable time-delayed teleoperation. Anderson and Spong [2], [3], introduced the notion of scattering variables which were well-known in transmission line theory. A conceptually similar formulation to the scattering variables appeared subsequently in Niemeyer and Slotine [21], the so called wave variables. These approaches provided the basis for the modifications of classical two-channel teleoperation architecture such as PP and PF scheme, in order to deal with communication delays. In essence, wave variables method introduces a new telemanipulator controller design approach in which the stability of the overall system will be dependent on both the local controllers and the interacting environment. Dependence on the communication channel latencies is no longer present.

Recently, computer networks, as e.g. the Internet, are becoming very attractive since they allow widespread and economic installation of teleoperation systems [13], [20] and [28]. Kosuge pointed out the problem of time-varying delay over a computer network, especially on the Internet, and proposed a virtual time delay method. All data are temporarily stored into a buffer and later re-extracted with a fixed sample time. The method seems too conservative since the system behaves like under a constant time delay that is estimated at the worst case. Niemeyer and Slotine also proposed a model which guarantees both no drifting and passivity. Their approach keeps the system passivity rigorously and thus the performance, especially in blackout stage, seems to degrade too much. Brady and Tarn used a forward time observer developed for supervisory control over the Internet.

Recently, interesting results were obtained by Lozano [17],

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where a modification to the scattering transformation of [3] was proposed. A time varying gain is introduced into the communication block in order to guarantee passivity for arbitrary time-varying delays having the rate of change bounded. In [7] an improvement is achieved using an outside position channel. Leeraphan et al. [14] proposed a method that could be used for time-varying delay and that doesn't require any time delay knowledge. However, thier approach is not sufficient for passive control and even if it was, passive control does not necessarily mean that the system performance will be acceptable [17]. Another recent approach on wave variables, was proposed by Yokokohji et al. in [30], [31] and [32]. They developed a compensator located at both sites to compensate the distorted waveform. Zhang and Li [33] also used the wave integral setup in a similar way to that proposed by Yokokohji.

In this paper a novel control algorithm to cope with the teleoperation over the Internet is introduced and developed. The proposed method introduces new solutions to the base structure of the Yokokohji compensator in order to overcome the limits of such approach. Our algorithm is able to handle the reordering of information flow through the time stamp, to compensate the position drift due to time-varying delays as well as to rigorously guarantee the passivity of the channel without excessive energy dissipation. Further it provides flexible energy limits, both in blackout and restoring phase, in order to use and restore the exactly amount of energy that has been restored and used during the previously resuming and blackout phase, respectively. Finally it is also capable to cope with communication blackouts as well as with packet loss. In essence the propose control scheme can assure a stable teleoperation under an Internet-like communication channel. Experimental results show the validity of the proposed methods.

The remainder of this paper is organized as follows. Section II introduces and briefly explains the wave variables approach. Section III presents the new wave variable based scheme, which is the main contribution of this paper. Section IV presents a discussion of the experimental results. Finally, in Section V, conclusions are drawn and future work is outlined.

II. BACKGROUND

In this section, a briefly explanation about the wave variables is given. For detailed discussion, refer to [22]. The wave variables were introduced by Niemeyer and Slotine on the basis of the scattering variables. Wave variables are based on the concepts of power and energy and present a modification or extension to the theory of passivity, which provides robustness to unknown, and thus arbitrary, constant time-delays. The method is applicable to nonlinear systems with contact to unknown environments [22]. Wave variables (u, v) definition is based on a pair of power conjugate variables $(\dot{x}, F)$ as follow:

$$u = \frac{b\dot{x} + F}{\sqrt{2b}} \qquad v = \frac{b\dot{x} - F}{\sqrt{2b}} \tag{1}$$

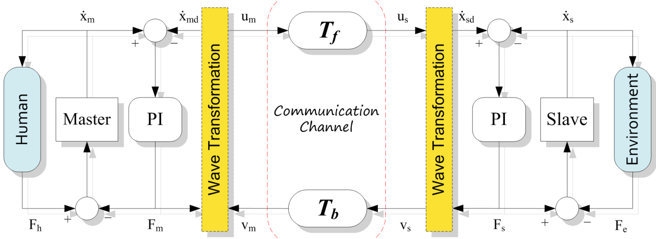

Fig. 2. A generic wave-based PP teleoperation control scheme

where b, called wave impedance, is an arbitrary positive constant that determines the behavior of the transformation and thus the properties of the communication line. As usual in teleoperation systems, the flow and effort variables $(\dot{x}, F)$ coincide with power variables, velocity and force respectively. u is called the right moving wave which travels from master to the slave and v is the left moving wave which is sent from slave to the master. This transformation is bijective, so that it's always unique and invertible. Figure 2 shows typical Position-Position bilateral control scheme where wave variables are used in place of the more conventional power variables (position and force). Note that both master and slave devices are controlled locally in power domain. In particular the wave transformation implemented for the master side and the slave side, are respectively:

$$\dot{x}_{md} = \frac{\sqrt{2b}\, v_m + F_m}{b} \qquad \dot{x}_{sd} = \frac{\sqrt{2b}\, u_s - F_s}{b} \tag{2}$$

$$u_m = v_m + \sqrt{\frac{2}{b}}\, F_m \qquad v_s = u_s - \sqrt{\frac{2}{b}}\, F_s \tag{3}$$

where $\dot{x}_{md}$ and $\dot{x}_{sd}$ are the desired master and slave motion velocity respectively and F_m and F_s are the local commanded force control. If the wave variables are transmitted under a transmission line which is subjected to a constant delay, the right moving wave at the slave side is the delayed one of the master side (the same is valid for the left moving wave), i.e.:

$$u_s(t) = u_m(t - T_f) \qquad v_m(t) = v_s(t - T_b) \tag{4}$$

where T_f represents the constant time communication delay from the master to the slave and T_b represents the other constant time delay in the backward direction.

A. *Passivity Condition*

Passivity theorem, which is based on the input-output point of view, deals with stability problem for linear as well as nonlinear systems. Passivity is closely associated with power dissipation. Dynamic systems that absorb more energy than produce, are said to be passive. Define the power input P_{in} in a system as the scalar product between the input (x) and output (y) vector, a nonnegative power dissipation function $(P_{diss} \geq 0)$ and a lower bounded energy storage function (E_{store}). The system is passive if and only if it fulfills the following equality:

$$P_{in} = \frac{d}{dt} E_{store} + P_{diss} \tag{5}$$

in other words, if the power input is stored or dissipated. In term of energy (5) can be re-expressed as:

$$\int_0^t P_{in} d\tau = E_{store}(t) - E_{store}(0) + \int_0^t P_{diss} d\tau \qquad \forall t \geq 0 \tag{6}$$

Consider again the system depicted in Fig.2. The power flowing in the communication channel is:

$$P_{in}(t) = \dot{x}_{md}(t) F_m(t) - \dot{x}_{sd}(t) F_s(t) \tag{7}$$

Reformulating (7) from the power domain to the wave variable domain and integrating, we obtain:

$$\int_0^t P_{in} d\tau = \int_0^t \frac{1}{2} \left[u_m^2(\tau) - v_m^2(\tau) - u_s^2(\tau) + v_s^2(\tau) \right] d\tau \tag{8}$$

If no time delay exists in the communication channel, then $u_m(t) = u_s(t)$ and $v_m(t) = v_s(t)$, and thus, (8) is identically zero. In this case, the wave transforms in completely transparent and transfer information without any loss. Suppose now that constant time delay exists, as shown in Fig.2, thus (4) held. Combining (4) and (8), with few mathematical manipulations, we obtain:

$$\int_0^t P_{in} d\tau = \frac{1}{2} \int_{t-T_f}^t u_m^2(\tau) d\tau + \frac{1}{2} \int_{t-T_b}^t v_s^2(\tau) d\tau \geq 0 \tag{9}$$

Equation (9) means that the passivity condition will be always met because the integral terms are always greater than or equal to zero regardless of the wave signs. Notice further that all the input power is stored and that the power dissipation, P_{diss}, is zero. In essence the communication channel becomes temporary an energy storage elements. The key feature is its temporariness. The power is only integrated over the duration of the delay. If the wave signals become zero for longer time than the channel latencies, all the energy that was stored in it is delivered to the output. This means that the communication in wave domain is not only passive, but also lossless. Hence, the delayed communication can be achieved passively, when using wave variables, whereas those on the power variables are active.

B. Problem Statement

In teleoperation over packet switched communication networks, the originally delay issue, essentially confined into constant time case, is moved towards time-varying delay. Actually the delay varies with such factors as congestion, bandwidth, or distance and it can reach very high values. As a result the performance of the wave-based teleoperation system, which supposes a constant time delay, may deteriorate drastically and may potentially become unstable.

As pointed out by Munir and Book [19], for networked robotics the internet User Datagram Protocol (UDP) is preferred since a consistent sample rate with lower fluctuations can be maintained. This choice brings the requirement to deal with discrete-time exchange of data and loss of information. Actually, in discrete domain, the time-varying delay will result in some samples time when no data is received and other instants when at one time more than one signal will arrive. It is important to remember that the wave signal has an energetic meaning. Holding the Last Sample (HLS) or setting the zero value (Zeroing) for the empty instants are the main strategies adopted in literature. Hirche et al. [10] showed that the HLS strategy doesn't guarantee the channel passivity, meanwhile Zeroing does it. On the other hand Zeroing dissipates a lot of energy and it introduces too much degradation (position drift appears).

III. PROPOSED METHOD

Our method is drawn on the base structure of the Yokokohji compensator. Anyway new solutions are introduced in order to obtain a suitable algorithm able to handle a real teleoperation. The major drawbacks of the Yokokohji approach are:

- the method uses numerical integration to obtain the position. Without direct position information, position drift may happen due to both data loss (typical in packet switched communication networks) and numerical errors. Notice that numerical integration is very prone to large errors using sparsely sampled data (the sampling frequency for data transmission over the computer network is generally slower than the local control frequency);
- the algorithm is switched off abruptly when the compensator seems to generate energy. This is traduced in discontinuities of the output and if implemented on a real communication medium, as Internet, produces a continuous on/off switching. This should be avoided because it generates highly varying motor torques and also bang-bang like control commands which reduce the robot life cycle;
- the method is able to handle the communication blackout and even its next resuming, but it doesn't address the packet loss issue;
- such approach considers only fixed energy thresholds both for the normal and for the resuming phase. This is inadequate for a real application because it may happen that the energy limits will never be achieved, or again, that the resuming procedure will not be completed. In the last scenario the compensator may generate energy for next blackouts.

For the sake of simplicity we explicitly refer to the forward communication path and so to the compensator on the slave side. The basic idea is to adjust the received wave variable to reduce position drift. This is done using position feedback from the wave integral signal. Our approach is mainly divided in the following points

- handling the packet validation and the packet reordering
- handling the position drift compensation with the energy input/output balance monitoring constraint both in normal communication and in blackout cases
- handling the restoring procedure of the energy margin when necessary.

A. Packet treatment

Recent communication systems have largely solved bandwidth issue, while latency is still high. Consequently increasing size of packets are not affecting round trip performances. Action performed is the preliminary treatment of the received data. In order to handle corrupted signals the transmission of single wave variable is replaced with a more complete packet. The packet structure consists in six values: the wave variable (u_m) and wave integral (U_m) signals, the energy injected by the master into the channel (E_m), the time stamp (t_m), the packet number and the communication flag. Such structure allows the packets reordering, the position drift compensation and to observe and control the energy behavior of the communication channel. Working principle uses the latest valid packet. Hence when an older packet than the last recorded one, arrives it is discarded and the algorithm utilizes the last valid packet stored in the memory.

B. Normal phase

Utilizing the last packet available, the wave variable is compensated by the position error feedback:

$$u_s^{comp}(t) = u_m(t_m^{last}) + K\left[U_m(t_m^{last}) - \int_0^t u_s(\tau)d\tau\right] \tag{10}$$

where K denotes the positive proportional gain (considerations on K given in [31] are still valid). Note that $u_m(t_m^{last})$ represents both the newly arrived value and the latest stored value and $U_m(t_m^{last})$ is updated coherently. The position drift due to data loss or numerical errors is avoided because direct position feedback is given. To ensure the passivity of the communication channel (8) has to be fullfilled. Since (4) are not longer true under time-varying delay, (9) cannot be obatained. An on-line energy observer is used to monitor the energy balance and to take corrective actions according to the level of the activity. For the slave side the on-line energy monitoring is given by:

$$E_{mon}^S(t) = E_m(t_m^{last}) - E_s(t) \tag{11}$$

where $E_m(t_m^{last})$ is the energy flows from the transmission line and $E_s(t)$ the outgoing energy flows from the compensator block. Actually the channel passivity has to be tested comparing the whole input/output balance monitoring at the same time instant, that means $E_{mon}^S(t) = E_m(t) - E_s(t)$. However such relation cannot be measured in real-time because the compensator has no information about the packet entered into the communication at the same instant. Hence for online passivity tests, (11) has to be used. As showed in (12), using (11) for passivity observation is more conservative. It gives the system some passivity margins against the activity.

$$E_{fw}(t) = E_m(t) - E_s(t) \geq E_{mon}^S(t) \tag{12}$$

The compensator works satisfying the following energy constrain

$$E_{mon}^S(t) \geq -E_s^{limit} \tag{13}$$

where E_s^{limit} is an appropriate positive constant value which defines the activity allowed. Unlike what has been done by Yokokohji, the transmitted wave variable (u_s) is not abruptly stopped when (13) is violated. Actually the compensator checks whether (13) is met and then executes the following routine:

- if relation (13) is fulfilled the wave signal obtained by (10) is transmitted
- if relation (13) is not fulfilled some other checks have to be performed. The algorithm tests whether the activity can get compensated reducing the magnitude of the obtained wave variable:
  - Yes: the compensator modifies the wave value in order to achieve the limit condition: $E_{mon}^S(t) = -E_s^{limit}$
  - No: the compensator does Zeroing which correspond to the maximal energy absorption.

In essence (10) is kept except in instants where channel activity may happen. In those cases, based on the energy balance value, the system dissipates energy either by Zeroing strategy or by reducing the energy of the conveyed wave. The transmitted wave variable will be

$$u_s(t) = \begin{cases} u_s^{comp}(t) & if\ E_{mon}^S(t) > -E_s^{limit} \\ u_{s,reduced}^{comp}(t) & if\ E_{mon}^S(t) = -E_s^{limit} \\ 0 & otherwise \end{cases} \tag{14}$$

Such choice improves the compensator performance and at the same time provides smooth transition between u_s^{comp} and zero output.

Blackout is treated as an extreme case of the time delay fluctuation. However, it should be noted that blackout is characterized by no energy provided. To compensate the position error, the compensator uses the available energy until the energy tank is empty. If the communication line is recovered soon this approach is effective, because enforces a sort of prediction of where will be the master after the recovery. On the other hand, if the communication line is suspended for long time, the compensator forces the slave to follow the predicted trajectory until the end of the energy margin. After that the slave stops and waits for new commands.

C. Restoring phase

When the line comes back resuming procedure is required to recharge as soon as possible the energy tank. Restoring phase basic objectives are:

- to recharge the energy margins used during the blackout
- to correct the position drift error which has grown during the blackout phase.

As before, packet check is done. Actually, when a new valid packet is received the compensation procedure can start, otherwise an energetic check, using HLS strategy, has to be previously performed. This time no activity is tolerated because the main target is to recharge the energy margin previously consumed ($E_s^{limit} = 0$). The wave variable used for the compensation is chosen according to:

$$\widetilde{u}_s(t) = \begin{cases} u_m(t_m(t)) & if\ new\ packet\ is\ arrived \\ u_m^{HLS} & if\ E_{mon}^S(t) > 0 \\ u_{m,reduced}^{HLS} & if\ E_{mon}^S(t) = 0 \\ 0 & otherwise \end{cases} \tag{15}$$

This time the compensation law is given by:

$$u_s(t) = \begin{cases} \widetilde{u}_s(t) + Ke(t) & if\ |\widetilde{u}_s(t) + Ke(t)| \leq |\widetilde{u}_s(t)| \\ \widetilde{u}_s(t) & otherwise \end{cases} \tag{16}$$

where $e(t) = U_m(t) - \int_0^t u_s(\tau)d\tau$. Appling (16) saves power when the master moves towards the slave (first case in (16)). The restoring procedure stops when the energy used during the blackout was completely recovered. For example, consider that the communication line from the master to the slave was in blackout at $t = t_b$ and recovered at $t = t_r$ with $t_r > t_b$. The first packet received brings in itself the master energy level and the actual master position. If the slave has used more energy than what has been provided through the master, restoring procedure starts. Mathematically this can be expressed as $E_m(t_r) - E_m(t_b) < E_s^{blkout}$. $E_m(t_r)$ and $E_m(t_b)$ represent the received energy at the recovery and blackout instants, respectively. Their difference represents the energy injected into the communication channel during the blackout. E_s^{blkout} indicates the effective energy margin used (of course $E_s^{blkout} \leq E_s^{limit}$) and allows to restore the exact amount of energy spent during the blackout. The restoring phase stops as soon as the following inequality is verified or another blackout happens.

$$E_m(t_r) - E_m(t_b) + \frac{1}{2}\int_{t_r}^{t} P_s^+(\tau)d\tau \geq E_s^{blkout} \tag{17}$$

$P_s^+(t)$ is called the surplus power and represents the saved energy using (16). As seen the position error is compensated with the energy restriction so that the compensator never generates extra energy. Note that correction of the position error will not happen if the operator does not move the master arm at all. An effective way to recharge the energy margin, while correcting the position error, would be waving the master arm back and forth.

Generally restoring phase terminates when all the energy has been restored. However, may arise that another blackout happens. In this case the algorithm immediately interrupts the resuming procedure in order to handle the blackout condition. Wave variables obtained by (10), (11) and (14) are used but the amount of energy margin available will be reduced according to the energy which previously was not restored. In essence E_s^{limit} represents the biggest thresholds allowed. It is used when blackout/restoring/blackout sequence occurs occasionally or at least in long times during which the restoring phase terminates.

IV. EXPERIMENT

The experimental setup uses the system known as CREATE [8]. The tests confirmed the conclusions from math and simulation studies.

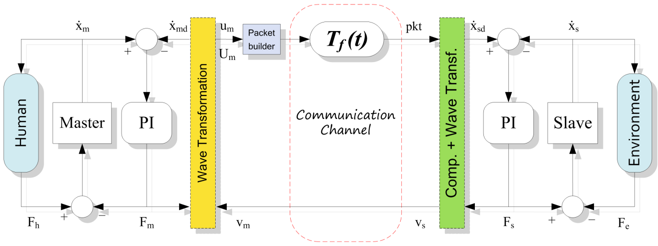

Fig. 3. Conceptual scheme of the system implemented

A. Experimental Setup

Two identical Haptic Interfaces (HIs) are used as master and slave devices, Fig. 1. Such a system has been designed and optimized for reflecting forces on the user hand. In the design phase all the expedients to ensure the transparency of the HI have been taken in account. The result is that the weight, the perceived inertia and the friction of the HI are very low and the force feedback is very accurate. Each HI has serial kinematic with 3 actuated and sensorized DOFs (2 orthogonal rotational joints followed by a prismatic one). High resolution encoders have been used to obtain accurate position information. Brushed PM-DC motors with high torque to inertia ratio are used. The transmission has been realized with tendons and idle pulleys with no gear reduction. Master and Slave are located side by side and the operator can monitor the task directly. Both the devices are under impedance control during the tests but many other setups could be used. They are interfaced by a dedicated computer, called target PC, with real-time operation system having the sampling time equals to 0.5[ms]. The control is designed in MATLAB/Simulink environment using xPC Target toolbox. The conceptual scheme of the system is depicted in Fig. 3. The left wave transformation block implements (2) and (3), while the right block contains the compensator also. The subsystem called Packet builder forms the packet that will be sent to the slave side.

B. Communication Channel Description

The communication channel has been modeled to reflect the setup that will be used during a real teleoperation experiment. The total round-trip delay is assumed to be caused by the forward delay. Backward delay is not present. This is not restrictive because from a stability point of view, having only one delay, with double time, in the forward or backward direction, is the same of having a delay in the forward direction and one in the backward. Hence the forward communication path is affected by time-varying delay and replicates the real condition measured during some tests done between PERCRO Lab. and DLR Lab[1]. The result is a random delay showed in Fig. 4.

C. Experimental results

Both free motion and hard contact tasks have been tested. In contact task the slave arm pushed against a rigid object.

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[1] During the tests, packets of six doubles was sent from PERCRO to DLR server and rebounded to PERCRO.

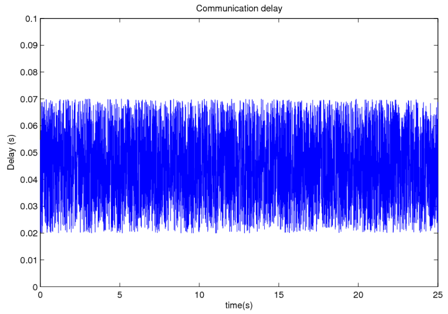

Fig. 4. Communication delay used in the experimentation

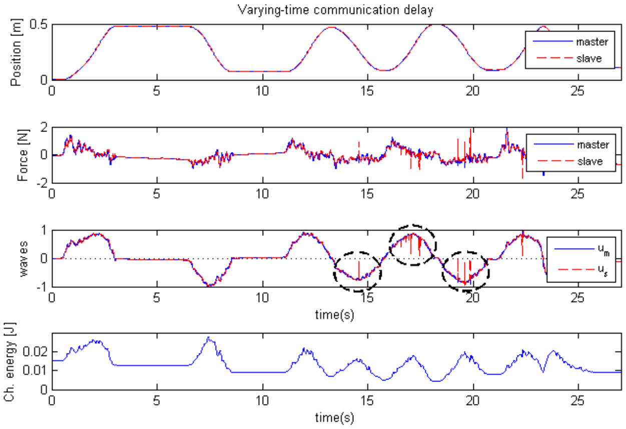

Fig. 5. System behavior in free motion under time-varying delay ($E_s^{limit} = 0[J]$)

Figure 5 shows the position tracking, the force reflection, the forward waves as well as the energy balance of the communication channel when the system was moving in free space and the energy limit set to zero. It is interesting to highlight the perfect position tracking and the passivity of the communication channel. The waves plot shows instants (dashed circles) in which modification of the waves magnitude and zeroing try to dissipate the activity observed by the energy monitoring. Actually the peaks in the force signal are due to zeroing and magnitude reduction actions.

Figure 6 shows the result when a hard contact was performed. The position tracking is very good in free motion instants. During a contact the deflection is necessary to produce the force feedback due to the spring-like behavior of the system. However the deflection is not excessive, confirming a good stiffness value. The force plot points out the different level of force feedback between contact and no-contact. The operator can distinguish clearly the collision without visual aid. The channel activity is greater than the threshold chosen.

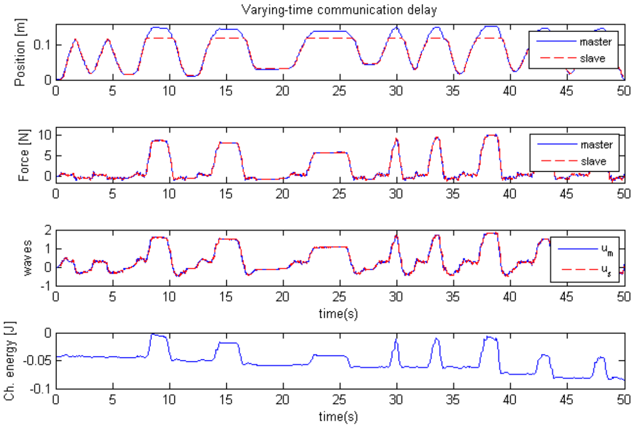

Fig. 6. System behavior in hard contact under time-varying delay ($E_s^{limit} = 0.5[J]$)

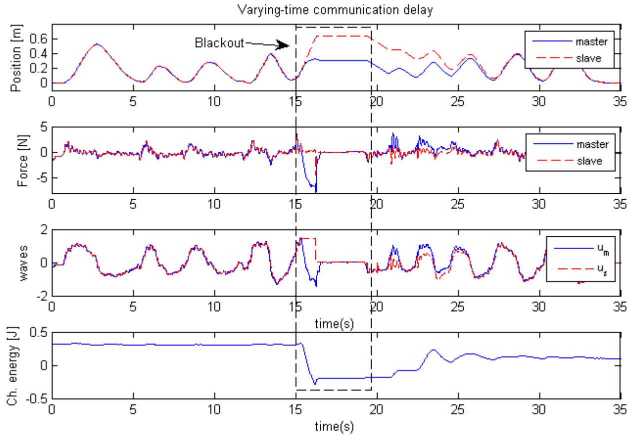

Fig. 7. System behavior in free motion under time-varying delay and blackout ($E_s^{limit} = 0.5[J]$)

The blackout event has also been tested. The system was moving in free space under time-varying delay when, at $t = 15.2[s]$, the communication line, from master to the slave, is suspended. The blackout duration was about $3[s]$. It was long enough to generate a high position drift. Figure 7 reports the system response. The energy margin has been completely used in the first instants of blackout (during $15.2-16.3[s]$). This can be seen by both the position and the waves plots. After the instant $t = 16.3[s]$, the system stopped its motion and waited the resuming. The communication came back at around $t = 18[s]$ and the resuming procedure starts. Position drift has been completely recovered by the compensator which on the other hand has never generated extra energy. Referring to the energy balance note that it never goes under the threshold chosen.

The system response when blackouts happened during a contact with the remote environment is also tested, but for space constraint the plot are not reported. From the experimental test have emerged that the slave device keeps pushing the environment until it consums the entire energy margin, even after the communication line was in blackout. After that, the slave stops to push.

V. CONCLUSIONS

A new method to guarantee the stability of bilateral teleoperation under time-varying communication delay has been proposed. The algorithm is able to cope with Internet-like communication and thus to handle time-varying delays, packet loss and blackouts which actually are regarded as an extreme case of time delay fluctuation. Using direct position information encoded in the wave integral, the control law assures excellent position tracking even after blackouts. When the communication line comes back, the position error is recovered as soon as possible, according to the energetic balance status. The energy input/output balance monitoring with variable threshold limits has been showed to be able to limit the total energy that the system can generate. Thus the system passivity is rigorously ensured even when sudden and repetitive communication breakdowns happen. Several experiments were conducted to show the validity of the propose method. Results show that, according with the energy balance, the algorithm provides smooth modification of the wave magnitude. Discontinuities, typical in the Yokokohji compensator, are not longer present. This improves the felling with the haptic interface since vibrations are drastically reduced. Further motor torques are more regular and so robot life cycle gets better. In our tests we set the energy limits at negative values so that the system could use this energy margin and compensates the response degradation due to the fluctuation of time delay and packet loss. The assumed time delay conditions in the experiments are rather realistic. They are based on the analysis of the communication channel between PERCRO Lab. and DLR Lab. For the next future we aim to test the method in a real teleoperation experiment, where both feedback and feedforward channels have different delays. Internet network with the UDP protocol will be used as communication channel.

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