TELEROBOTICS THROUGH INTERNET: PROBLEMS, APPROACHES AND APPLICATIONS

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Abstract: This paper presents the problems arising in the realization of an Internet-based telerobotic system. Variable delays, data losses, unknown available throughput and unknown enviroment dynamics are the common problems faced in designing a reliable control strategy. The design of a stabilizing controller can be approached with several techniques, each of them with merits and limitations. The paper introduces some of the newest techniques, and presents some applications.

Keywords: telerobotics, communication networks, time delay, delay compensation

1. INTRODUCTION

According to recent statistics, Internet has reached the amazing count of 489,774,269 hosts around the world on July 2007 (ISC, 2007). Moreover, the throughput offered is also constantly increasing, to support multimedia sessions involving sharing of multimedia content, phone calls, audio, etc. Internet is the preferred form of interactive communication, with new applications in entertainment, teleconferencing and tele-medicine being developed and tested every day. One very interesting area of application of Internet is the control of remote devices. We can find now on the market Internet-controlled house appliances, like refrigerators, air conditioning systems etc. The term "control" however, has to be intended for such devices as the possibility for the remote user to send to the apparatus a sequence of commands that will be executed later. As an example, there is a certain number of robotic equipment accessible through Internet, as can be found in (Yahoo, 2007). Most of those devices, however, do not fall into the category of bilaterally controlled teleoperators, since the user does not receive any real time feedback from the remote environment.

Instead, the user interacts with the remote robot by sending it a program, which is executed later and the result of the action is reported to the user through an e-mail, with an updated picture of the working area or other off-line communications. Another solution, proposed in (Brady, and Tarn, 1998), makes use of a sensor-based action reference, in which operations, commanded by the master robot, are executed under the supervision of the slave robot controller, which makes decisions on the task to be executed on the basis of sensors readings (e.g. the trajectory requested by the master can be modified in order to avoid obstacles detected by the slave sensors). This lack of real-time interaction with the remote equipment is due to the Internet limitations, considered as an unavoidable constraint by all designers.

In developing an Internet-based telerobotic system that is bilaterally controlled in real time, thus giving to the user a sense of *immersion* in the remote environment, it is then necessary to find a way to

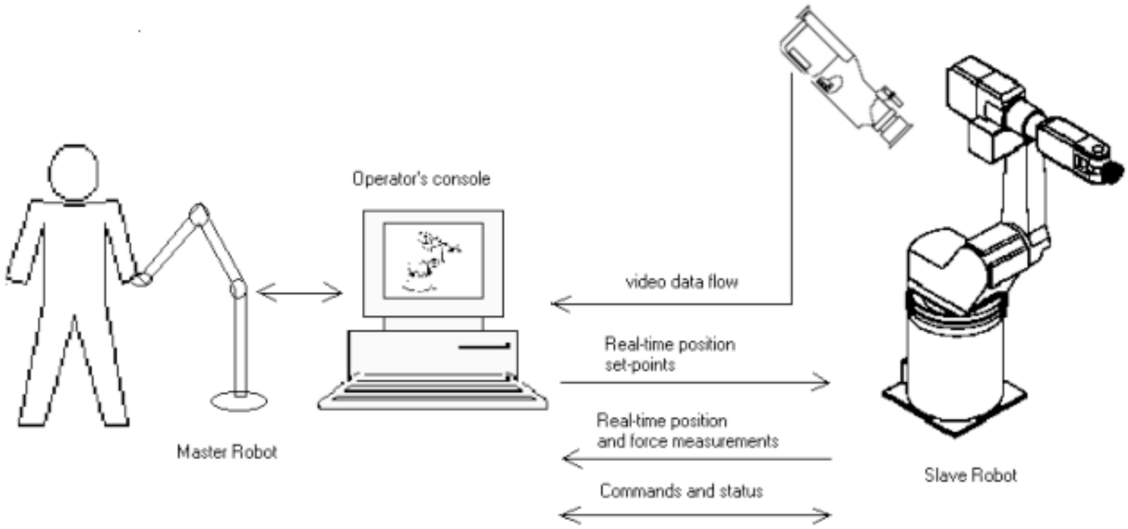

Fig. 1 – Schematics of a telerobotic equipment

overcome all limitations posed by this communication system. To this aim, we must analyze the communication flow between master and slave stations, in order to find its control-relevant characteristics and to design the proper control algorithms.

In an advanced telerobotic system, the master station controls a remote robot by sending position commands and receiving force and visual feedback, in addition to information on slave robot position and status. As shown in Fig.1, the communication system must support three types of data flows. The first one is for the real-time control data, i.e. the set points from master to the slave robot and the interaction force data, generated at the slave side and sent to the master station, along with slave position. The data flow in this case is bi-directional and constituted by small packets issued at a constant rate. The issuing rate corresponds to the sampling frequency of the control loop, and the quality of the force feedback perceived at the master station depends on it. Moreover, since closed loop operation is influenced by the loop delay, the traveling time of each packet limits the overall performance in terms of closed loop control bandwidth. Finally, the performance of the closed loop control can be heavily influenced by the loss of some data packet, which may occur in Internet connections, as shown in the next Section.

The second data flow is from the slave to the master, and it is relative to the video stream. The characteristics of this flow depend on the programming of the video encoder, in terms of both bit rate and size of the data packets, usually user-defined and variable during encoder operations. Nowadays, there are several solutions available for video streaming over a digital communication media, each tailored for a specific target application (e.g. videoconferencing, video on-demand, digital satellite broadcasting etc.). For all the available standards, video quality may be traded with bit rate, and most of them have been conceived for non-reliable communication media, so they are robust against limited data losses.

Finally, the third flow is from the client to the server and it is relative to high level commands, such as those for changing the sampling frequency of the control loop, resetting the system, etc.. It is worth noticing that this flow can be neglected in terms of use of network resources, since it is made up of small packets, issued few times during the robot operation. This data flow, however, requires a reliable data connection.

At this point, it is clear that the design of an Internet-based bilaterally controlled telerobotic system can be split into two main issues. The first is to design a control loop, in which human operator, slave robot and remote environment are involved, and where the stability must be ensured in spite of the variable performance of the communication network. The second issue is to implement a strict resource allocation policy, since the most common scenario is to have all the data flows sharing the same physical connection. To this aim, we need first a control-relevant model of an Internet connection and this will be presented in Section 2, where it is shown how it exhibits an unpredictable behavior, in terms of communication delay, data losses and throughput.

Clearly, by overcoming Internet limitations, it would be possible to design a telerobotic system in which the control loop is closed across an Internet connection and the user at the master station receives visual and haptic information. This would also allow to have widespread applications of bilateral telerobotic systems, with applications ranging from remote medical care to entertainment, from collaborative work to safe interaction with inaccessible or dangerous sites. Then, Section 3 reports some of the solutions used to addresses the problem of stabilizing the teleoperator in presence of variable delays and data losses.

The first reported application of bilateral control over Internet, with visual and force feedback the JBIT (Java Based Interface for Telerobotics), realized at the Department of Electronics and Informatics of University of Padova (Oboe, 2003). Since the appearance of such system, many other applications of Internet-based telerobotics in Internet have appeared. Each of them tries to solve the problems of telepresence (i.e. ensuring to the user the correct perception of the features of the remote system) and system stability. In Section 4, we describe a possible application of telerobotic systems to remote diagnosis. Section 5 concludes the paper, giving some suggestions for future researches.

2. INTERNET MODELLING

As a first approximation, Internet can be considered as a strongly connected network of computers, communicating with each other using packet switched protocols (Comer, 1991). The delay affecting the data packets exchanged between two computers depends on several factors. First, packet's routes are assigned dynamically, depending on the network load. Then, packets are subject to different handling policies at each node they traverse, since nodes may have different throughput, routing policy, and buffering and queues management. Furthermore, when the number of data packets exceeds the bandwidth available, congestion occurs. Congestive behavior can be modeled as a Markov chain whose states depend on the communication protocol (Bolot et al., 1990). Thus, it is almost impossible to determine a detailed analytical model of an Internet communication.

An accepted approximate model of Internet consists of a network of queues, one for each node along the dynamic path connecting two computers (Hammond, and O'Really, 1986). Queuing and dynamic routing introduce a variable transmission delay or jitter. A congested path results in an unpredictable deferral of the packets and their possible elimination in case of long deferral, since packets have limited lifetime.

Thus, a possible first approximation of an Internet connection can be characterized by the statistics of the packet delay and of the packet losses. These parameters are usually measured in terms of the communication Round Trip Time (RTT), i.e. the time taken by a packet to reach a remote computer and return to the issuing computer. Several experiments were carried out to measure the parameters of the connections between a local computer and two computers located at distances of 30 km (Host1) and 10000 km (Host2), respectively. Here, the RTT is measured using a modified ping procedure, consisting of packets 32 bytes long, sent with a period δ = 100 ms, using the Internet Control Message Protocol (ICMP). Since this protocol has a negligible overhead, it allows measuring the true delay of the connection. UDP connections used by more sophisticated network applications are subject to the same delay, because of a comparable overhead. Note that the TCP protocol is not suitable for these experiments, since its overhead includes the acknowledgment of each received packet, i.e. a packet is transmitted only after the previous packet has been acknowledged.

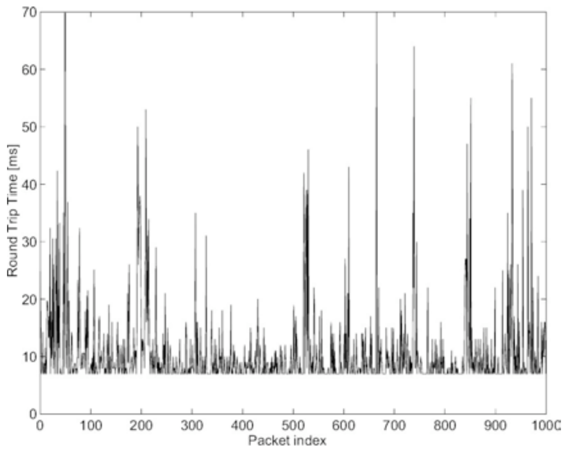

Fig. 2. RTT for Host1

The time series of Fig. 2 shows that RTT has a random component added to a constant term, which represents the minimum service time along the network. This term however, is constant only for short periods, since it is affected by daily variations, as shown in Fig. 3 for a weekly record of the connection to Host2.

In addition to time plots, it is possible to show the distribution of the delays, which largely depends on the number of nodes traversed. Roughly, the number of traversed node, i.e. routing computers, increases with distance. In the experiments performed, the number of nodes are 5 for the connection to Host1 and 18 for the connection to Host2. As a result, the RTT for the first connection shows the exponential distribution of Fig. 4, whereas the measurements with the other lead to the Gaussian distribution shown in Fig. 5.

It is worth noticing that, until few years ago, one way delay measurements could not be performed in an accurate way, since the measurement was relying on NTP (Network Time Protocol), and it didn't provide a sufficient resolution. This also limited the number of approaches that could be used in designing a control law for the telerobotic equipment. With the introduction of GPS on the market and after the reduction of the clock jamming by US, it has been possible to synchronize precisely the clocks of two computers (within 1 microsecond), even if they are thousands miles apart, then to compute the one-way delay by marking outgoing data packets with a timestamp at the transmitter side, and subtracting the local clock of the receiver to the timestamp of the incoming packets, to get the traveling time, which can be rather different in the two directions (mainly due to largely different bit rate between uplink and downlink).

Another aspect of Internet connection, perceived by all Internet users, is the large variability of the performance of the connection, in terms of throughput. This fact is due mainly to network overload that eventually may lead to congestion, i.e. data packets are dropped at some router along the path from the local host to the remote one. Of course, it is possible to set up a connection with prescribed Quality of Service (QoS), in terms of available bandwidth and latency, but usually such services are not for the large audience, but only for a limited group of selected users, paying a relevant cost for this.

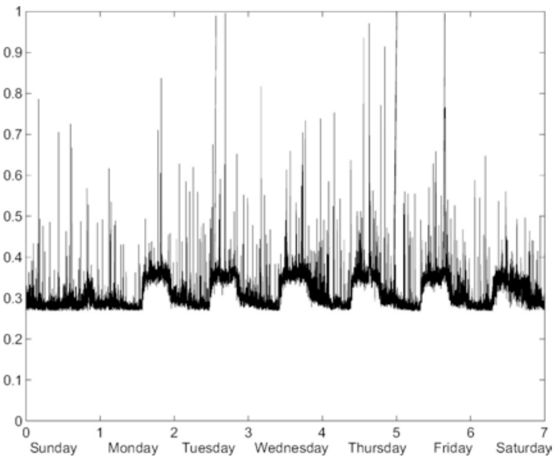

Fig. 3. Weekly variation of RTT for Host2

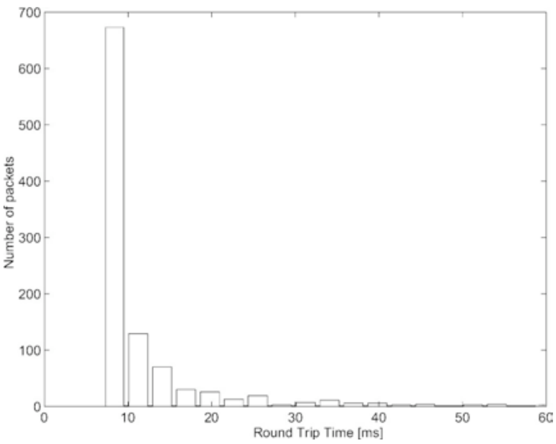

Fig. 4. RTT distribution for Host1.

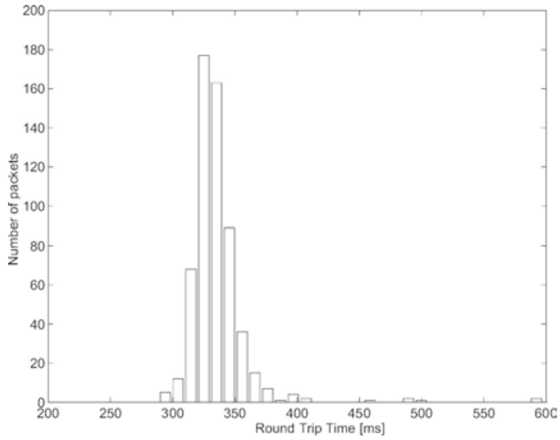

Fig. 5. RTT distribution for Host2

To give an idea of what may cause congestion, we report in the following the results obtained by increasing the data injection rate on the two connections under test, reducing the transmission period δ from 100 ms to 10 ms. As a result, loss rate increases dramatically, making the connection useless.

Table 1. Packet loss statistics

Host name	δ	Average RTT [msec]	Std. Dev. [msec]	Packet Loss rate
Host1	10	8.44	6.25	5.97
Host2	10	319.0	16.70	51.13
Host1	100	8.10	5.35	0.08
Host2	100	326.3	27.20	41.36

So, if the target is to have remotely controlled robots at home, in order to introduce innovative services like remote rehabilitation or diagnosis, it is necessary to address the problem of adapting the telerobotic equipment to the operating conditions. As rule of thumb, one should keep the data rate of his/her application one order of magnitude below the maximum allowed, in order to avoid congestion. This, however, is a very simplistic solution and it does not take into account that the connection between two hosts goes through link with different capacity and which are shared by other applications that may flood the network with data (e.g. during file transfer). So, it is necessary to have a reliable way to estimate the characteristics of the communication link in real time. In addition to this, It must be noticed in fig.1 that at least two data flows are sharing the same physical connection in a telerobotic system, namely the video stream and the real-time data exchange of the control loop. Note that current Internet implementations (referred in literature as “IP version 4”) do not provide any resource allocation feature, i.e. an application running on a computer and sharing the same Internet connection with other applications on the same computer, may seize all the available bandwidth if no appropriate provisions are taken. This is a problem when both video and real-time data are sharing the same connection, since video encoders can easily saturate the network, causing a dangerous interruption in the control loop. For instance, an H.263 encoder can be programmed in order to generate a certain average output data rate, but its instantaneous data rate may be much higher, especially in occurrence of wide changes of the scene. Furthermore, the operating conditions (i.e. available network bandwidth and delays) may vary during the session. As a consequence, there are two important issues that must be addressed in the design of Internet based telerobotics equipment with live video feedback. The first one is a constant monitoring of the characteristics of the connection in use, in order to adapt the data flow injected into the network to the operating conditions. The second one is the implementation of a strict data flow management policy, in order to avoid network saturation, to guarantee that the control loop is always active. To this aim, a bandwidth estimator and a data flow handler must be implemented and a possible solution is described in (Oboe, 2003).

3. CONTROL OF INTERNET-BASED TELEROBOTICS EQUIPMENT

From the previous discussion, it is clear that an Internet-based control system must face the variable time delay and the packet losses introduced by the computer network. We are interested in evaluating the feasibility of Internet-based, force-feedback telerobotics equipment, in which the control loop between master and slave robots is closed across Internet. This is equivalent to deal with the stability of telerobotic equipment with a variable communication delay and data losses.

3.1 Time-varying time delay

Initial work on teleoperation with time delay has focused on constant delay systems (Anderson, and Spong, 1989; Nìemayer, and Slotine, 1991; Kim et al., 1992). In (Eusebi and Melchiorri, 1996), it is shown that some of these methods achieve IOD (independent of delay) stability, i.e. the stability is guaranteed, provided that the delay is constant (Brierly et al, 1982). It could be expected that such methods are applicable even in case of random time delay, by designing the control for the maximum value of the delay (worst-case controller). However, it is shown in (Hirai and Satoh, 1980) that a control algorithm designed for a fixed (possibly unknown), maximum delay T, may not stabilize the system when the delay varies between 0 and T. Some new control algorithms have been recently developed in the field of Internet-based telerobotics, in which a certain degree of stability (or overall passivity) is guaranteed even in case of variable communication delay (Niemeyer, and Slotine 1998; Park, and Cho, 1999). Performance gradually deteriorates, as the average delay increases, but no analysis has been carried out on the effects of packet losses. Moreover, almost all approaches proposed in literature are developed in a continuous time framework, with a common assumption that the time derivative of the delay is strictly less than 1. Internet, however, is inherently a discrete time environment, and the telerobotic system should be analyzed as a sampled data system with variable delay. It can be easily shown that a zero-order holder can be represented as a variable time delay, with its time derivative equal to 1 for almost all the time, thus making all the proofs for continuous time system inapplicable to internet-based telerobots. Recently, new approaches to prove the stability in a discrete-time framework, based on passivity, have been proposed in (Secchi et al. 2003b). Another promising approach is the Bilateral Generalized Predictive Control (BGPC) proposed in (Slama et al., 2007), which is base don an extension of Model Predictive Control.

Model Predictive Control (MPC) is an advanced method for process control that has been used in several process industries such as chemical plants, oil refineries and in robotics area. The major advantages of MPC are the possibility to handle constraints and the intrinsic ability to compensate large or poorly known time-delays. The main idea of MPC is to rely on dynamic models of the process in order to predict the future process behavior on a receding horizon and, accordingly, to select command input w.r.t the future reference behavior. Motivated by all the advantages of this method, the MPC was applied to teleoperation systems (Bemporad, 1998, Sheng, and Spong, 2004). The originality of the approach proposed in (Slama et al., 2007) lies in an extension of the general MPC, so-called Bilateral MPC (BMPC), allowing to take into account the case where the reference trajectory is not a priori known in advance due to the slave force feedback. The bilateral term is employed to specify the use of the signal feedback, which alters the reference system dynamic in the controller.

Generalized Predictive Control. Generalized Predictive Control (GPC), suggested in (Clarke et al., 1987), is one of the most popular predictive control strategies. GPC is based on the minimization of a quadratic cost function of the form (1) including a future control sequence on a receding horizon.

$$J = \frac{1}{2}\left(\sum_{j=H_w}^{H_p} \left\| \hat{y}(k+j|k,W) - r(k+j) \right\|_{Q(j)}^2 + \right. \\ \left. + \sum_{j=1}^{H_u} \left\| \Delta w(k+j-1) \right\|_{R(j)}^2 \right) \tag{1}$$

where $\hat{y}(k+j|k)$ is an optimum j-step ahead prediction of the system output on updated with time k and $r(k+j)$ is the future reference trajectory known in advance. H_{ω}, H_p are the initial and prediction horizons respectively. H_u is the control horizon with $H_u < H_p$ and, $\Delta\omega(k+j) = 0$, $\forall j \geq H_u$. $Q_j \geq 0$ and $R_j \geq 0$ are diagonal elements of the weighting matrices **Q** and **R**. **W** is a sequence of future controls with W = $[\Delta w(k) \ldots \ \Delta w(k+H_u-1)]^T$. The objective of predictive control is to compute the future control sequence **W** in such a way that the future plant output $y(k+j)$ is driven close to $r(k+j)$. This is accomplished by minimizing J.

Predictive control, commonly grouped as model predictive control (MPC), uses a model of the plant to predict the output in the future $\hat{y}(k+j|k)$. The GPC uses the Controlled Auto-Regressive and Integrated Moving Average (CARIMA) structure which is an input-output formalism taking into account the noise influence on the system through the C polynomial:

$$A(z^{-1})\Delta y(k) = z^{-\tau}B(z^{-1})\Delta w(k-1) + C(z^{-1})\xi(k) \tag{2}$$

where $y(k)$ and $w(k)$ are respectively the output and the control of the system. $\Delta(z^{-1}) = 1 - z^{-1}$ is the differencing operator. The τ parameter, a multiple of the sampling period, is the pure system delay and $\xi(k)$ is an uncorrelated random sequence. A, B, C are polynomials of the backward-shift operator z^{-1} with respectively the following degrees n_A, n_B and n_C. A and C have unit-leading coefficients. The C polynomial may be used as a tuning parameter, since its identification is usually avoided. It has been shown by that the C polynomial plays a crucial role in the robustness and disturbance rejection of the control law. More generally, this polynomial influences the robustness and disturbance rejection.

Bilateral Generalized Predictive Control Design. Due to the slave force feedback, the master trajectory is not a priori known in the future. Therefore, we cannot determine a control sequence that minimizes the (1) cost function. To overcome this difficulty, the Bilateral GPC (BGPC) approach proposes to rewrite the master model according to the slave control via the slave force feedback in order to determine the master output optimal prediction (Slama et al., 2007a).

Having determined the master and slave CARIMA models for the BGPC, the minimization problem (3) is solved, where y_m and y_s are respectively the positions of the master system and of the slave robot end-effector.

$$J = \frac{1}{2}\left(\sum_{j=H_w}^{H_p} \left\| \hat{y}_s(k+j|k, W_{ms}) - \hat{y}_m(k+j|k, W_{ms}) \right\|^2_{Q(j)} + \sum_{j=1}^{H_u} \left\| \Delta w_{ms}(k+j-1) \right\|^2_{R(j)} \right) \tag{3}$$

The objective is to determine the control sequence $\boldsymbol{W_{ms}}$ minimizing the quadratic error between the future predictions of the master system output and the future predictions of the slave system output; both of these two outputs depend both on the control sequence. The plant output predictions $\hat{y}_m(k+j)$ and $\hat{y}_s(k+j)$ are obtained by solving two Diophantine equations for each incremental models (see Slama et al., 2007b).

Control law. The receding horizon principle assumes that only the first value of the optimal control sequence resulting from the minimization of (3) is applied. At the next sampling period, the same procedure is repeated. This control strategy leads to a 2-DOF predictive RST controller, implemented through a difference equation:

$$R(z^{-1})\Delta w_{ms}(k) = T(z^{-1})y_m(k) - S(z^{-1})\hat{y}_s(k+\tau_g) \tag{4}$$

By appropriate choices of the horizon lengths H_w, H_p, H_u and of the weighting matrices **Q**, **R** in BGPC, an excellent master reference trajectory tracking may be obtained for the slave system. It is interesting to note that $T(1) = S(1)$ to guarantee offset-free response and that the polynomial $T(z^{-1})$ does not contain a non-causal structure generally inherent in the polynomial predictive control. This major difference, in comparison to the standard GPC, is due to the future reference trajectory, which is not a known priori. The experimental validation of the proposed BGPC approach is presented in the next section.

A robust approach. Stability conditions for constant and time-varying transmission delays of the nominal overall transfer function from the input force of the operator to the environment contact force have been determined on a frequency-domain approach in (Slama et al., 2007a). These conditions are derived by the small-gain theorem. Moreover, the proposed BGPC approach, which has taken into account the slave force feedback, introduces a new prefilter polynomial C_{sem} (Slama et al., 2007b). This C_{sem} polynomial plays a role in robustness and disturbance rejection of the overall system. The advantage about of the proposed approach is to impose the desired behavior at remote system, to ensure a robust stability of teleoperation in the presence of environment and transmission time-delays uncertainties.

Delay jitter compensation. A different solution, proposed in (Luck, and Ray, 1994; Oboe, and Fiorini 1998), is to even out the delay jitter by storing the incoming packets in a memory buffer. Given the standard deviation σ of the delay, a queue capable of absorbing a +/- 3σ variation of the delay is set up on both sides of the communication channel. This is realized with a FIFO queue with a length N=6σ/T, where 1/T is the transmission rate, as shown in fig.6.

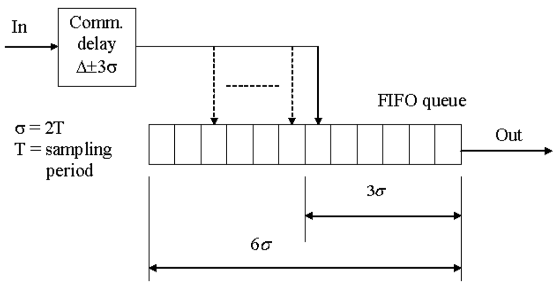

Fig.6 – Delay jitter compensation via buffering

Data extraction begins when the queue is filled up to half of its length. This mechanism introduces an additional delay of 3σ to the transmission delay, but this can be easily handled by simply designing the control algorithm considering an augmented delay or by using an IOD control technique.
With this solution, the connection results to have a constant delay, for which one of the standard control techniques for time-delay teleoperators can be used.

3.2 Packet losses handling

Packet losses, as pointed out in Section 2, heavily depend on the network congestion. This, in turn, is related to the level of occupation of the available communication channel. This means that the real-time control application has to be designed in order not to require an unbearable throughput, by appropriately choosing both the number of variables to be exchanged with the remote system and the system sampling rate. It is worth noticing that the maximum allowable throughput in not constant, since it depends on the number of applications sharing the same physical connection.
The issue of the packet losses is typically addressed by showing that random losses can be compensated by using a predictor (Luck, and Ray, 1992; Oboe, and Fiorini 1998). In case of a missing packet, the predictor output is used in place of the lost data. The implementation of such recovery procedure has been implemented in (Oboe, 2003). This procedure works in conjunction with the queuing mechanism described previously. When a packet loss is detected, the corresponding queue location is filled with the data provided by an estimator. Two different methods have been used to estimate the missing data. On the slave side, by using a model of the master device and some additional info sent by the master station (i.e. the force the user is exerting on the master device), a Kalman filter generates the prediction for the next master position (Oboe and Fiorini, 1998). On the master side, a simple interpolator generates the value for the missing force data, by using the neighboring data. It is worth noticing that this recovery procedure works only for random losses of a single packet. In case of burst losses (sequences of two or more packets are lost), more sophisticated data recovery schemes are needed.
Another approach is to replace the missing packets with null packets or the last received packet. While the second avoids abrupt motion of the system , the first has the advantage of preserving the passivity of the teleoperator. Sitting halfway between these two approaches, the solution proposed in Secchi et al. (2003a) exploits the passivity to generate a sequence of references for the teleoperator that keeps the overall stability, even in case of multiple missing packets.
Finally, the BGPC shows a very good performance against packet losses, provided that the last packet is used in place of the missing ones.

4. APPLICATIONS

Telerobotics finds its application in many areas, ranging from the handling of hazardous material (its original target application) to telesurgery, from underwater robotics to space robotics and mobile robotics. A good survey on those applications can be found in (Hokayem,,and Spong, 2006). Most of those applications, however, has very little influence in our daily life, since they are confined to very specialized environments and applications.
One major breakthrough in telerobotics will occur when average people can use teleoperators in everyday life, more or less as they use a personal computer. One area that promises to bring such a large development is the remote medical diagnosis, remote care and remote rehabilitation. This kind of application is by far less invasive than telesurgery, since any type of problems occurring on the communication system cannot harm the users. A successful example is given by the tele-operated echography realized within the European project OTELO, described in (Capri et al., 2007). In such system, a manipulator handles an ultrasound probe, following the commands of a physician that receives echographic images in real time. For such system, the BGPC has been used, after being developed in a test application, between the University of Bourges (France) and the University of Padova in Vicenza (Italy).

The experimental setup used is shown in fig. 7, where it can be seen that the master device is a PHANTOM Omni, while the slave robot is a 6

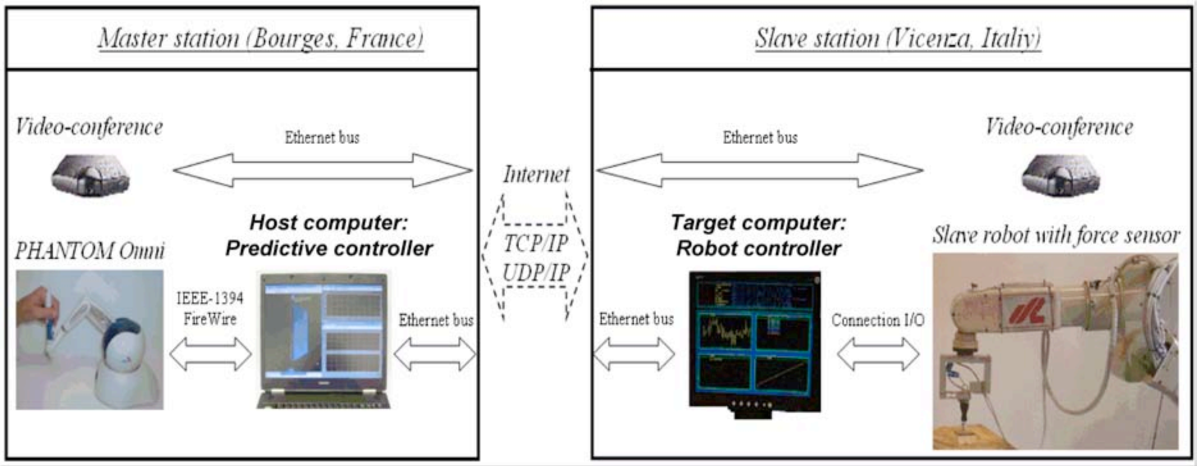

Fig.7 – Experimental setup

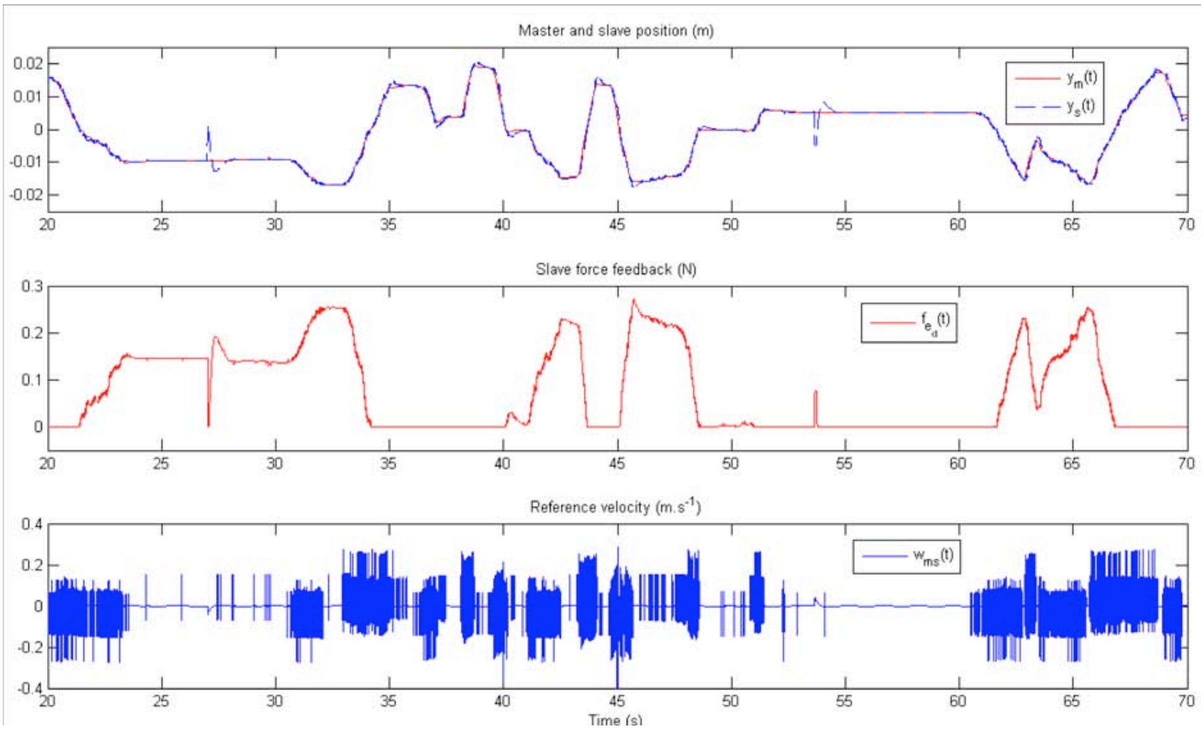

Fig. 8 – BGPC – Experimental results

d.o.f., industrial robot, with a load cell mounted on the end effector.

The typical results obtained are shown in fig. 8, where it can be seen that the slave tracks the reference imposed by the master, when interacting with a soft environment that mimics the human body. The Internet connection used had a 40 ms average delay, with a standard deviation around 6 ms and a loss rate of 31%. As a result, the system behaves in a stable way, even when disturbances are applied at the slave side at 27 s and 54 s.

5. CONCLUSIONS

The realization of a telerobotic equipment that integrates an Internet connection is not a trivial task. Precise knowledge of the connection's characteristics is needed in order to fully exploit the performance of this communication system. Such characteristics have to be constantly monitored, in order to follow the unavoidable variations in network performance. Moreover, reconstruction of lost data should be ensured or explicitly handled, along with some smart strategy to deal with long-term interruptions in the communication channel.
In spite to all limitations, however, it is possible to realize reliable systems that in future will help in improving everyone's quality of life. In fact, remote diagnosis and rehabilitation, access to dangerous and/or remote sites will be more and more accessible and more applications are going to appear, all aimed at easing the interaction between distant worlds.

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