Bilateral Haptic Guided Robot Teleoperation Via Packet Switched Networks Using Wave Variables with Impedance Adaptation

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***Abstract*—This paper presents the use of haptic devices in teleoperation systems with motion restrictions during robot teleoperation in order to provide the operator with increased awareness and better feeling of immersion, hence, improving his ability to perform complex tasks. The use of wave variables in the proposed system renders passive the communication channel, and moreover the new packet switched protocols like Internet Protocol version 6 (IPv6) with high Quality of Service (QoS), provides differentiated services for control signals.**

***Index Terms*— Haptic-Teleoperation, Wave-Variables, Passivity, Motion-Restrictions, IPv6-Quality-of-Service.**

I. INTRODUCTION

Teleoperation systems have been studied since the late 40s. The first ‘remote-manipulators’ were developed for handling radioactive materials. Outstanding pioneers in this field were Raymond Goertz and his colleagues at the Argonne National Laboratory outside of Chicago, and Jean Vertut at a counterpart nuclear engineering laboratory near Paris. Starting there, the application of teleoperation systems is found in a wide number of different fields. The most illustrative are space, underwater, medicine and hazardous environments, amongst others.

In our days, with an ever-growing number of Internet connected devices that are now accessible to a multitude of users, the Internet can enable any user to reach and command any device connected to the network. The use of robots through Internet dates from The Mercury Project in 1995 at the University of Southern California [1], [2], that allowed users to interact with a robotic arm by means of a standard web browser.

Several of the above mentioned applications involve large distances or impose limited data transfer between the local and the remote sites. Such situations can result in substancial delays between the time a command is introduced by the operator and the time the command is executed by the remote robot. This time-delay affects the overall stability of the system. In order to preserve passivity for making the system stable, in this work a communication channel passivation using wave variables with an impedance adaptation has been implemented.

The use of haptic guided robot teleoperation allows the operator to define motion restrictions which depend on the task to be performed. On the master side, the deviation from the restriction generates an attractive force to the restriction subspace, providing the operator with an intuitive interface to ensure movements inside this subspace. This teleoperation framework in which motion restrictions can be easily defined and modified by the operator can highly improve the task performance and the sensation of immersion.

The paper is organized as follows: section II presents a brief state of the art in teleoperation via packet switched networks, in section III some theory about passivity and scattering is outlined; section IV deals with the proposed teleoperation scheme; some simulations are presented in section V, and in section VI the experimental testbed with a experiment of motion along a line restriction over a rail. Finally in section VII some conclusions and future work are proposed.

II. TELEOPERATION VIA PACKET SWITCHED NETWORKS

Packet switching refers to the transmission protocols in which messages are divided into packets before they are sent. Each packet is transmitted individually and can follow different routes to its destination. Once all packets forming a message arrive at the destination, are recompiled into the original message. This is the case of Internet transport protocols TCP (Transmission Control Protocol) and UDP (User Datagram Protocol). These protocols are the most suitable to be used in teleoperation systems. Liu et al. [3], propose the use of a rate-based (trinomial) protocol for Internet teleoperated robots. In this protocol, the source adjusts the sending rate depending on the packet RTT (Round Trip Time). The underlying idea of the trinomial protocol is to have the reliability of TCP with the reduced time-delay of UDP.

The drawback of the today Internet best-effort service, is mainly the congestion over the network. With the use of recent protocols like the Internet Protocol version 6 (IPv6), the performance of the whole teleoperation system can be improved. In order to achieve this improvement, *Quality of Service* (QoS) based schemes have been used to provide priorities on the communication channel, the use of the QoS resulting in a more efficient network operation. In [4] it can be found a description of the QoS approach of the IPv6 domain that aims to service the real-time applications with a minimum delay and packet loss. Reference [5] shows a comparison of QoS performance between IPv6 QoS model and other schemes that have been used in the last decade (IntServ and DiffServ). Their conclusions show that IPv6 QoS management has achieved the best results compared with the others.

A. Haptic guided teleoperation

In recent years haptic devices have been employed in teleoperation systems in order to give force feedback to the human operator. Shon and McMains [6] describe some experiments for evaluating speed and accuracy when drawing 3D objects with a haptic device and conclude that, if the operator is provided with a guidance method, the drawings are clearly better.

In order to assist humans while performing different task some approaches have already been developed. These approaches can be divided into two groups, depending on how the motion restrictions are created: by software or by hardware. To the first group belongs the work by Turro et al. [7] that have implemented three types of constraints for the operator movements: constraint movement along a line, virtual obstacle avoidance using a potential field force and geometric cube constraint in order to limit the robot workspace. However, this approach needs to be reprogrammed when a new restriction must be introduced and moreover this teleoperation scheme does not guarantee stability with time-delay. In [8] constrained teleoperation has been develop using predictive control techniques. The constraints act in the nominal path of the robot end effector, but on the master side motion guidance is not implemented, and the operator does not have the resulting feed forward force. An often used method is to provide the obstacles with a repulsive force potential field. Thus, the operator will not make the robot collide with the obstacles. This method has been used in [9] with a mobile robot, where the force generated by the obstacles is fed back to the operator. Several authors propose the use of hardware to guide motion, for example guide-rails [10] and sliders with circled rails [11]. Mechanical guides such that only translation is allowed, would make it easy to move into a restricted space [12].

III. Background

This section is intended to give a brief description of the theoretical tools that have been used in this work. These tools allow us to study the effects of passivity on the proposed teleoperation scheme.

A. Passivity

The passivity formalism represents a mathematical description of the intuitive physical concepts of power and energy. It provides a simple and robust tool to analyze the stability of a system based only on its input-output properties. If $\mathbf{x}$ is the input vector and $\mathbf{y}$ the output vector of the system, then the 'power input' P_{in} is defined as the scalar product of these two vectors

$$P_{in} = \mathbf{x}^T \mathbf{y} \tag{1}$$

This power input should be either stored or dissipated in the system. Let be E_{store} the lower bounded energy storage function, $E_{store} \geq E_{min}$ (generally $E_{min} = 0$) and P_{diss}, the nonnegative power dissipation. A system is passive if

$$P_{in} = \frac{d}{dt} E_{store} + P_{diss} \tag{2}$$

meaning that the system does not generate energy and can provide only as much energy as was stored initially. This passivity condition is also often expressed in the integral form

$$\int_{t_0}^{t} P_{in} d\tau = E_{store}(t) - E_{store}(t_0) + \int_{t_0}^{t} P_{diss} d\tau \geq -E_{store}(t_0) \tag{3}$$

If the power dissipation is zero for all time, the system is called lossless. Otherwise, if the power dissipation is positive, the system is called dissipative. The use of passivity in the analysis of stability properties is mainly based on two properties: 1) a combination of passive subsystems is passive and 2) the overall combination of passive subsystems is asymptotically stable if at least one subsystem is dissipative.

B. Scattering operator

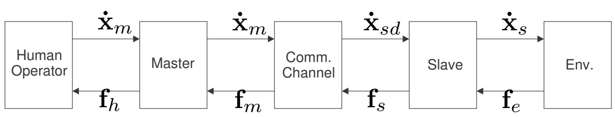


Fig. 1. Traditional force reflection scheme

In a traditional force reflection scheme, as shown in figure 1, the master, the communication channel and the slave are represented by two-ports elements, the human operator and the environment are typified by one-port elements. For a Linear Time Invariant (LTI) two-port system, the relationship between effort (force, $\mathbf{f}$) and flow (velocity, $\dot{\mathbf{x}}$) is defined by its hybrid matrix $\mathbf{H}(s)$ according to

$$\begin{bmatrix} \mathbf{F}_m(s) \\ -s\mathbf{X}_s(s) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} s\mathbf{X}_m(s) \\ \mathbf{F}_s(s) \end{bmatrix}$$

$$\begin{bmatrix} \mathbf{F}_m(s) \\ -s\mathbf{X}_s(s) \end{bmatrix} = \mathbf{H}(s) \begin{bmatrix} s\mathbf{X}_m(s) \\ \mathbf{F}_s(s) \end{bmatrix}$$

In this system $\mathbf{F}_m(s)$ and $s\mathbf{X}_m(s)$ are the force and velocity of the master in the Laplace domain. The force and velocity associated to the slave are given by $\mathbf{F}_s(s)$ and $s\mathbf{X}_s(s)$. The elements h_{11}, h_{22} are the input and output teleoperation impedances and the elements h_{12}, h_{21} are the force and velocity gains. In case of ideal telepresence the elements of the hybrid matrix become $h_{11} = h_{22} = 0, h_{12} = -h_{21} = 1$, which means that $\mathbf{F}_m(s) = \mathbf{F}_s(s)$ and $s\mathbf{X}_s(s) = s\mathbf{X}_m(s)$. The human operator feels the interaction of the slave with the environment instantaneously and the master and slave motions are the same.

The scattering matrix (or scattering operator) **S**(s) for a one port system, in the Laplace domain, is defined as the mathematical operator that relates force and velocity:

$$[\mathbf{F}(s) - s\mathbf{X}(s)] = \mathbf{S}(s)\,[\mathbf{F}(s) + s\mathbf{X}(s)]$$

This scattering matrix is useful in the analysis of teleoperation systems because it links the passivity theory with the small gain theorem, and it is part of the main inspirations for the introduction of the wave variables. In the case of a two-port system, the scattering matrix is related to the hybrid matrix $\mathbf{H}(s)$ as follows

$$\mathbf{S}(s) = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} [\mathbf{H}(s) - I]\,[\mathbf{H}(s) + I]^{-1} \quad (4)$$

Anderson and Spong [13] state that an LTI *n*-port system is passive if and only if the norm of its scattering operator is less than or equal to one.

$$\|\mathbf{S}(s)\| \leq 1 \quad (5)$$

C. Wave transformation

In the wave variables approach, velocity $\dot{\mathbf{x}}$ and force $\mathbf{f}$ are encoded with an appropriate transformation and only the resulting wave variables are transmitted. The first teleoperation system based on passivity concepts appeared in [13]. Following these results, Niemeyer and Slotine [14] propose the first wave variable scheme. The equations governing a constant time-delay communication channel are then

$$\begin{aligned} \mathbf{u}_s(t) &= \mathbf{u}_m(t-T) \\ \mathbf{v}_m(t) &= \mathbf{v}_s(t-T) \end{aligned} \quad (6)$$

and the wave transformation is given by

$$\begin{aligned} \mathbf{u}_m(t) &= \tfrac{1}{\sqrt{2b}}(\mathbf{f}_m + b\dot{\mathbf{x}}_m) & \mathbf{v}_m(t) &= \tfrac{1}{\sqrt{2b}}(\mathbf{f}_m - b\dot{\mathbf{x}}_m) \\ \mathbf{u}_s(t) &= \tfrac{1}{\sqrt{2b}}(\mathbf{f}_s + b\dot{\mathbf{x}}_{sd}) & \mathbf{v}_s(t) &= \tfrac{1}{\sqrt{2b}}(\mathbf{f}_s - b\dot{\mathbf{x}}_{sd}) \end{aligned} \quad (7)$$

Doing some algebra it can be seen that all power input is stored, according to the eq. (3), as

$$E_{store}(t) = \int_{t-T}^{t} \left(\frac{1}{2}\mathbf{u}_m^T(t)\,\mathbf{u}_m(t) + \frac{1}{2}\mathbf{v}_s^T(t)\,\mathbf{v}_s(t)\right) d\tau \geq 0 \quad (8)$$

Therefore, the system is passive independent of the magnitude of the delay T if zero initial conditions are assumed. The wave energy is thus temporarily stored whilst in transit, making the communication channel passive. Although the strictly positive parameter *b* can be chosen arbitrarily, it defines a characteristic impedance associated with the wave variables and directly affects the system behavior [14].

IV. Haptic Guidance Teleoperation Scheme

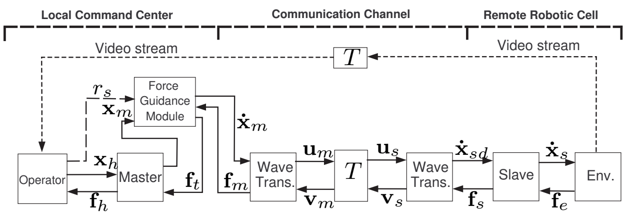


Fig. 2. Teleoperation scheme

A scheme depicting the approach proposed in this paper is shown in figure 2. Three main subsystems are pointed out in the figure: the Local Command Center, where information concerning to the restrictions and guidance are computed; the Communication Channel, which manages the information flow; and the Remote Robotic Cell, where the actual task is performed.

- The *Local Command Center* hosts the Force Guidance Module, which handles the forces that have to be fed to the operator as well as the integration of position/velocity with the motion restriction data. In addition to the main control loop, a video stream provides video feedback from cameras located at the Remote Robotic Cell, whose zoom and orientation can be remotely actuated.
- The *Communication Channel* is responsible for the management of the data flow between the Local Command Center and the Remote Robotic Cell. It is served by a high-speed Local Area Network (LAN) with a client-server application structure. These structures are implemented using a socket based configuration with TCP/UDP and IPv6 protocols.
- The *Remote Robotic Cell* is composed by a robot, its controller, a force-torque sensor and a video server with two 3 DOF cameras. The subsystem sends information about the interaction of the robot with the environment to the Local Command Center.

A. Local command center

One of the main components of the local command center is the Force Guidance Module, which holds different functions:

- Definition by the operator of a motion restriction r_s.
- Computation of the restriction force $\mathbf{f}_r$ that must be exerted to maintain the position of the end-effector inside the currently selected motion restriction r_s, as well as of the viscous force $\mathbf{f}_v$ that prevents the velocity of the end-effector from becoming too large for the robot to follow. The restriction force $\mathbf{f}_r$ and viscous force $\mathbf{f}_v$ are combined with the force measurement $\mathbf{f}_m$ coming from the Remote Robotic Cell to generate the total force $\mathbf{f}_t$, which is fed to the operator via a haptic device.

The total force (at an instant k) that is fed back to the operator is $\mathbf{f}_t = \mathbf{f}_m + \mathbf{f}_r + \mathbf{f}_v$, where $\mathbf{f}_m$ is the master force generated by the interaction of the robot with the environment, $\mathbf{f}_r$ is the restriction force due to the motion restriction and $\mathbf{f}_v$ is the viscous force.

·*Master force.* The raw force measurement that comes from the sensor's data is filtered in the Local Command Center at a cutoff frequency of 500 Hz given $\mathbf{f}_e$. The resulting force $\mathbf{f}_m$ is then calculated as $\mathbf{f}_m = \mathbf{T}_m \mathbf{f}_e$, where $\mathbf{T}_m$ is a transformation between the force frame and the master frame.

·*Restriction force.* This is the attractive force $\mathbf{f}_r$ that tends to fix the haptic position to the restriction subspace. It is modeled as a spring-damping system. This force at instant k is given by $\mathbf{f}_{r_k} = K_P \mathbf{e}_k + \mathbf{D}_k$, where $\mathbf{D}_k$ is the corresponding damping part of the controller

$$\mathbf{D}_k = K_D \left(\mathbf{e}_k - \mathbf{e}_{k-1}\right)$$

$\mathbf{e}_k$ is the position error $\mathbf{e}_k = \mathbf{x}_r - \mathbf{x}_{hd}$, $\mathbf{x}_r$ is the reference point that lies on the restriction subspace and $\mathbf{x}_{hd}$ is the human operator position at instant k. The value of $\mathbf{f}_r$ will be zero if no restriction is set. K_P and K_D are chosen to set the stiffness and the damping of the restriction.

·*Viscous force.* If the velocity of the master is too high, the slave may not be able to follow the velocity commands. In order to deal with this problem an additional restriction has been implemented: above a certain velocity value, which depends on the maximum velocity achievable by the slave, the motion restricting force is a function of the master velocity $\dot{\mathbf{x}}_m$, and it is zero below that value. The resulting force of this effect $\mathbf{f}_v$ is given by $\mathbf{f}_{v_k} = K_v \hat{\mathbf{v}}_k$, where K_v is a gain that fits the needs of restrict velocity, and

$$\mathbf{v}_k = \frac{1}{T}\left(\mathbf{x}_{m_k} - \mathbf{x}_{m_{k-1}}\right)$$
$$\mathbf{v}'_k = \mathbf{v}_k - \mathbf{v}_{k-1}$$
$$\hat{\mathbf{v}}_k = b_0 \mathbf{v}'_k + b_1 \mathbf{v}'_{k-1} + a_0 \mathbf{v}_{k-1}$$

$\hat{\mathbf{v}}_k$ corresponds to a velocity estimation using a 1st order Butterworth filter with coefficients b_0, b_1, a_0 calculated at a frequency ratio (sample freq / cutoff freq) of 10, and T is the sample period (see [15] for more details).

It is important to stress the difference between the three components of the total force. While the sensed force represents a feedback signal –the reaction arising from the interaction of the robot with its environment– the restriction and viscous forces represent feed forward signals in the sense that they respond to known inputs –the deviations from the restriction subspace and from the permitted velocities, respectively– without the need of any information from the workcell. The motion restriction r_s is updated at a much lower frequency than the other signals.

B. Communication channel

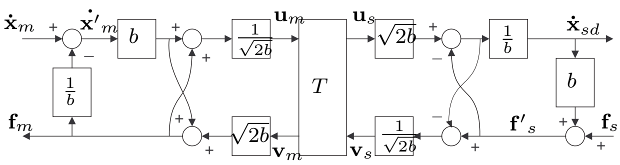


Fig. 3. Passivity based teleoperation with impedance adaptation scheme

The overall structure of the client-server application uses the IPv6 protocol due to its Quality of Service (QoS) benefits [5]. Amongst the new implementations of IPv6 applications over next generation networks all over the world (as an example see [16]), telerobotics have a great potential to develop. Comparative studies between using TCP or UDP as the transport layer protocol [17], [18] state that TCP provides a point to point channel for applications that require reliable communication while UDP provides communication that is not guaranteed. This is because TCP is a confirmation based protocol and UDP is not. However, TCP has the drawback that it has an unpredictable data arrival time because it retransmites lost packets after a timeout of any acknowledge message of the transmitted packet. Since UDP does not require any acknowledgment message, the network delay can be substantially lower. In this work, sockets are compatible with both transport layer protocols.

When dealing with a teleoperated system one must take into account that delay plays a critical role in the system stability. Packet switched networks with an increased QoS can reduce the delay by using communications based on priorities rather than the usual best effort networks. For instance, in the teleoperation scheme of figure 2 the wave transformations of velocity and force have the highest priority and the video signal the lowest. The scheme shown in figure 3 depicts the encoding signals of velocity and force. The communication channel governing equations are

$$\mathbf{u}_m = \frac{1}{\sqrt{2b}}\left(\mathbf{f}_m + b\dot{\mathbf{x}}'_m\right) \quad \mathbf{u}_s = \frac{1}{\sqrt{2b}}\left(\mathbf{f}'_s + b\dot{\mathbf{x}}_s\right)$$
$$\mathbf{v}_m = \frac{1}{\sqrt{2b}}\left(\mathbf{f}_m - b\dot{\mathbf{x}}'_m\right) \quad \mathbf{v}_s = \frac{1}{\sqrt{2b}}\left(\mathbf{f}'_s - b\dot{\mathbf{x}}_s\right)$$
$$\dot{\mathbf{x}}'_m = \dot{\mathbf{x}}_m - \tfrac{1}{b}\mathbf{f}_m \qquad \mathbf{f}'_s = \mathbf{f}_s + b\dot{\mathbf{x}}_{sd}$$

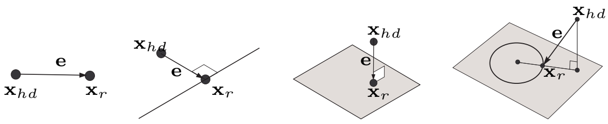
The corresponding hybrid matrix $\mathbf{H}(s)$, in the Laplace domain, associated to this scheme is:

$$\mathbf{H}(s) = \frac{1}{2}\begin{bmatrix} G_f b & G_f e^{-sT} \\ -e^{-sT} & \frac{1}{b} \end{bmatrix}$$

The norm of the scattering matrix for this scheme fulfills the condition to preserve passivity $\|\mathbf{S}(s)\| \leq 1$, and it is preserved even though any constant time-delay occurs, a variation of the force-reflection gain G_f does not lead to passivity loss.

C. Remote robotic cell

The robot controller inputs are either position or velocity commands, sent from the master site. Depending on the task, the robot can move strictly in the restriction subspace ($\mathbf{x}_r$) or with a deviation from it ($\mathbf{x}_{hd}$), allowed by the stiffness and damping implemented in the Force Guidance Module. In figure 4, vector $\mathbf{e}$ represents the deviation of the position command produced by the operator. The position control scheme of the Remote Robotic Cell is stable. Then, if the input references (position/velocity) of the controller are bounded, the overall system will also be stable.



(a) Point (b) Line (c) Plane (d) Circle

Fig. 4. Geometrical restrictions

V. SIMULATIONS

In this section a simulation of the aforementioned scheme is presented. The simulations have been carried out on a simulink model of the teleoperation system. The master and the slave are modeled as a 1 DOF simple mass-damper systems. The dynamics of the simulated models are

$$M_m\ddot{x}_m + B_m\dot{x}_m = F_h - F_m$$
$$M_s\ddot{x}_s + B_{s1}\dot{x}_s = F_s - F_e$$

where F_s is generated by a PD controller, and it is given by

$$F_s = K(x_{sd} - x_s) + B_{s2}(\dot{x}_{sd} - \dot{x}_s)$$

$\dot{x}_m$ and $\dot{x}_s$ are the respective velocities of the master and slave, M_m and M_s the corresponding inertias, F_h and F_e the operator force and the force resulting from the robot interaction with the environment. The Time-delay (T) in both, the forward and return paths is fixed to 3s.

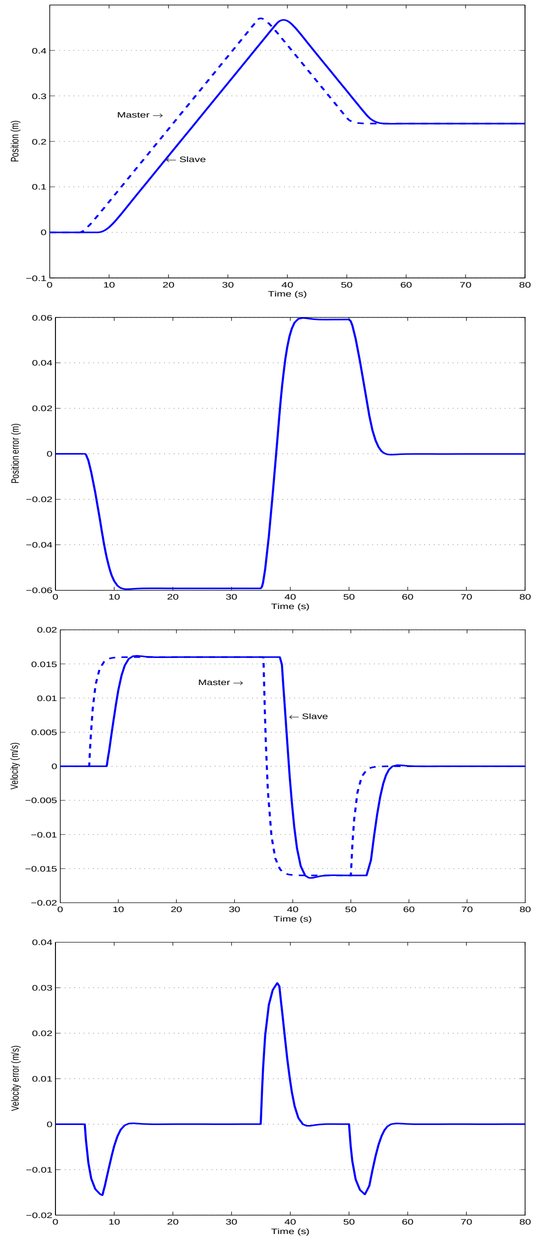


Fig. 5. Simulation of the teleoperation system in free space with $T = 3$s

These simulations do not reflect the guidance scheme, and they are done to verify the stability of the teleoperation scheme. For this purpose two simulations have been performed: 1) the slave moving in free space and 2) the robot interacting with a stiff wall.

Figure 5 shows the results of the first simulation. It can be seen that the slave follows the desired velocity, and although the time-delay is quite substantial the whole system is stable. It is clearly seen in this figure that there is not any position drift, and position and velocity errors converge to zero for a constant steady state input.

Figure 6 depicts the second simulation. In it when the

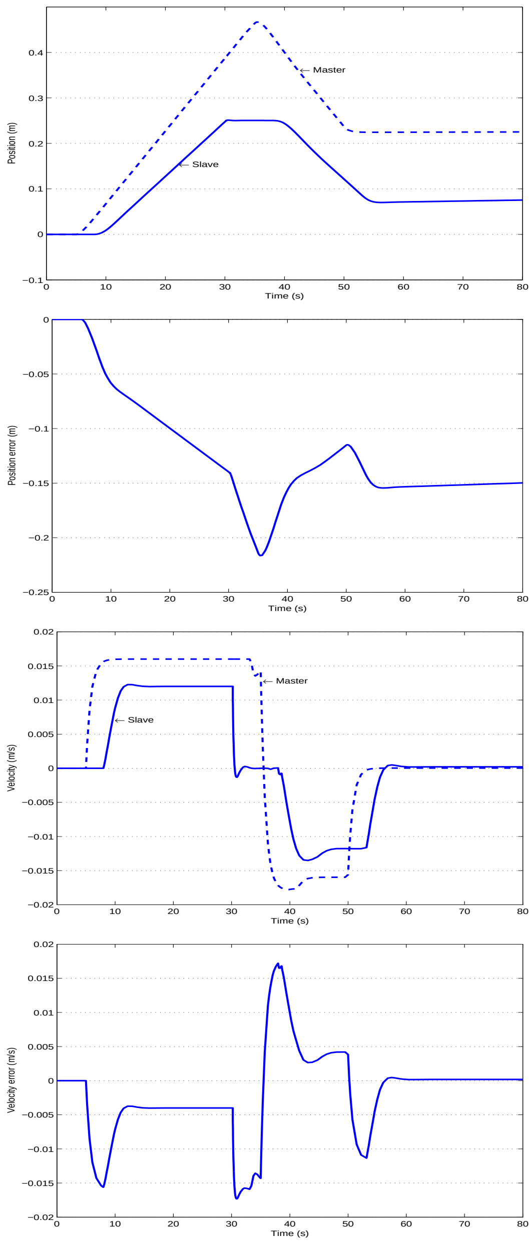


Fig. 6. Simulation of the teleoperation system with an obstacle in 0.25m, with $T = 3$s

slave reaches the virtual wall at 0.25m the stability is preserved but a position drift occurs.

VI. Experimental Test-bed

Figure 7 shows the experimental testbed that mainly consists of a TX-90 Stäubli robot with a CS8–C Stäubli controller and a JR3 force–torque sensor, a PHANToM 1.5^{TM} 6DOF haptic device from Sensable Technologies, and two CANON VC–C5 video cameras with an AXIS 2400 video server which provides a 10–20 fps motion JPEG video stream. On the software side, interaction

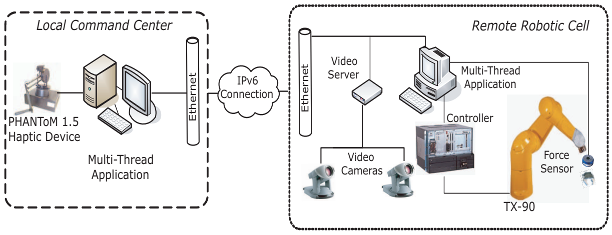


Fig. 7. Physical system architecture

with the haptic device is done with Sensable Technologies' GHoST^{TM} libraries. The haptic's control loop runs at 1kHz, and forces must be calculated within the millisecond time window. All software is written in C++ using sockets and POSIX threads. The Graphic User Interface has been developed with Trolltech's QT library.

A. *Experimental test –motion with a line restriction over a rail–*

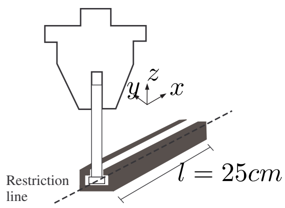
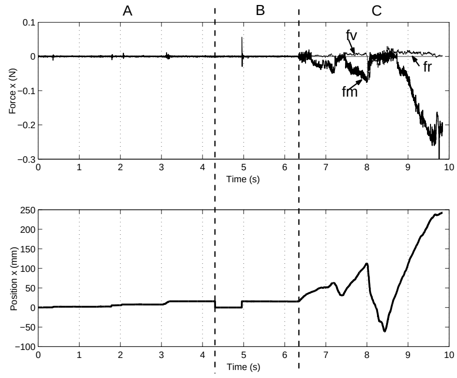


Fig. 8. Line restriction over a rail

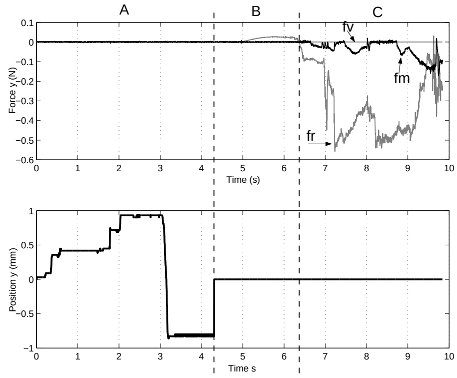
In order to validate the proposed approach an experimental test was remotely performed using the proposed teleoperation architecture. It consists on moving the robot end-effector along a rail with a line restriction. There are two experiments, in the first the robot motion is constrained to the restriction subspace ($\mathbf{x}_r$) and in the second the robot trends to follow the human position, moving with a deviation $|d|$ from the restriction subspace.

The proposed test has the following characteristics:

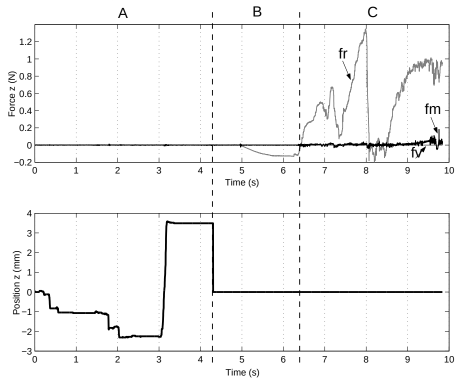
- The motion of the robot end-effector is restricted to a line in the x axis as shown in figure 8.
- The forces coming from the remote robotic cell $\mathbf{f}_m$ provide information about the interaction of the end effector with the environment.
- On the first test the velocity commands $\dot{\mathbf{x}}_m$ correspond to the velocity along the restricted line, namely $\dot{\mathbf{x}}_r$, and on the second test these commands are deviated from the restriction, hence following the human restricted motion.
- Packets have been transmitted using TCP/IPv6 sockets with the scheme of a classical client-server application, providing higher IPv6 QoS to control commands than the video transmission. The Round Trip Time Delay varies from 5ms to 50ms.



a) Position and force in the x axis.

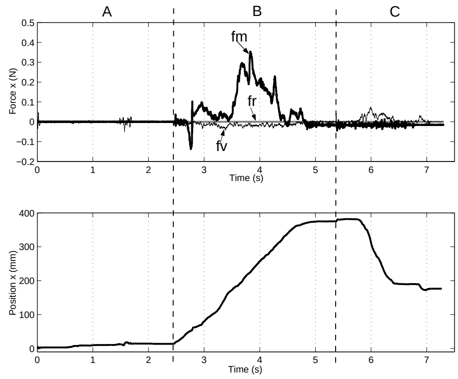


b) Position and force in the y axis.

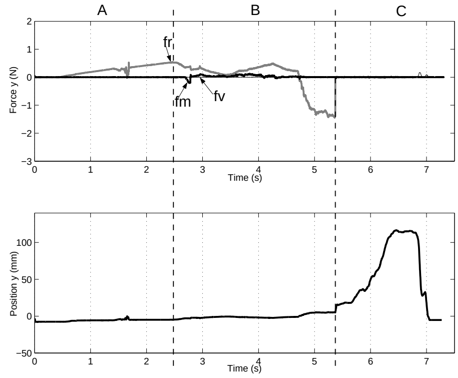


c) Position and force in the z axis.

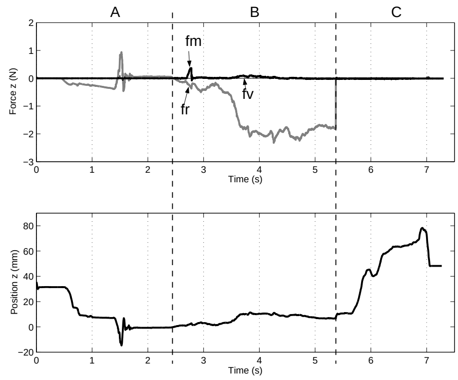
Fig. 9. First experiment. Motion is constrained to the line restriction ($\mathbf{x}_r$). f_r is the restriction force, f_v the viscous force and f_m the force feedback. Zones A: free space, no restriction; B: free space, restriction; C: limited space, restriction



a) Position and force in the x axis.



b) Position and force in the y axis.



c) Position and force in the z axis.

Fig. 10. Second experiment. Motion with a deviation $|d|$ from the restriction subspace r_s. f_r is the restriction force, f_v the viscous force and f_m the force feedback. Zones A: free space, restriction; B: limited space, restriction; C: free space, no restriction

Figures 9 and 10 plot the time evolution of positions and forces along the *x*, *y* and *z* directions. The force figures show the three components of the total force $\mathbf{f}_t$: the restriction force $\mathbf{f}_r$, the viscous force $\mathbf{f}_v$, and the master force $\mathbf{f}_m$. The line restriction is along the *x* axis.

The first three graphics (fig 9a, b and c) represent the resulting data from the first test, which describe the motion of the robot along the restricted subspace ($\mathbf{x}_r$). The graphics have three zones separated by dashed vertical lines: zone A corresponds to free space without motion restriction; B represents free space in which the restriction has been set; and in zone C the end effector moves along the rail.

In these graphics it can be seen that when the restriction is set (at around 4.3s) position in z and y axis goes to the origin, and motion only takes place in the x direction. Near the 7th second where zone C begins the end-effector comes in contact with the rail and the forces produced by this interaction ($\mathbf{f}_m$) are felt to the master.

Since the task has been performed at low speed, the viscous force ($\mathbf{f}_v$) does not have a significant contribution to the total force, and the restriction force is dominated by its spring component. This can be verified comparing the restriction force and position plots.

The second three graphics (fig 10a, b and c) show the results for the second test, which describe the motion of the robot along the human restricted space ($\mathbf{x}_m$). These graphics are also divided in three parts. In zone A the line restriction has been set, in zone B the end-effector gets into the rail and in zone C the restriction is released because the end effector has reached the end of the rail, it can be seen that the robot moves freely in space.

VII. Conclusions and Future Work

The presented teleoperation framework can lower the burden on the operator while remotely executing a task. This is achieved through bilateral haptic guided teleoperation. In addition to the visual and force feedback that are sent from the remote site, the operator is provided with additional force information that guides its motion according to some predefined geometric constraints between the robot tool and its environment. The IPv6 protocol was used to handle communications in an efficient manner, enabling important data such as control signals to be transmitted with higher priority than less relevant and bandwidth-consuming signals like video feeds. The presented approach was validated through a motion with a line restriction over a rail task. A future work will also deal with rotational torques, which will be fed back to the operator. Through the passive scheme used in the communication channel, stability can be guaranteed, as well as nor position drift. A future work will also deal with the implementation of a control scheme based on passivity and position error.

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