Internet-based Bilateral Teleoperation Using a Revised Time-Domain Passivity Controller

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Abstract: This study presents a teleoperation system for remote control of mobile manipulators over the Internet. A bilateral control algorithm is proposed that can assure both stability and proper force reflection in the presence of non-constant delay in the communication channels between the master and the slave. The control approach in this paper is based on the time domain passivity concept and proposes a modified passivity controller to assure enhanced transparency with bounded control actions in the presence of time-varying communication delay. Transatlantic and inter-European bilateral teleoperation experiments are also reported (Montreal, Canada - Tirgu Mures, Romania; Budapest, Hungary - Tirgu Mures, Romania). The experimental measurements show the applicability of the control approach and its benefits on the teleoperation performances.

Keywords: Telerobotics; Internet; Networked control systems; Delay systems; Passivity

1 Introduction

The Internet represents the common communication medium for the implementation of such teleoperation applications that have a significant physical distance between the human operator and the teleoperated robot. For such cases when the teleoperated robot is mobile, wireless links should also be included in the communication channel. These wireless hops in most cases represent the critical link regarding the communication performances. The communication channel's performance can severely be compromised, e.g. by other data transfer channels sharing the same wireless communication medium, or by wireless signal strength change, which appears in the case of mobile teleoperation.

The communication performance degradation manifests in increased delay (communication lag) and delay variation [24].

In teleoperation systems, the desired position and velocity of the remote robot is generated by the human operator using a haptic device (master). During bilateral teleoperation, the controlled robot (slave) sends back to the master haptic information about forces or torques that influence the robot's motion, allowing the human operator to feel the effect of the environment-robot contact during the teleoperation.

A major challenge during the control system design for bilateral teleoperation systems is to guarantee stability under any operating circumstances and, simultaneously, to assure a reliable position tracking and accurate force reflection (transparency) under various communication conditions [4], [7].

Several approaches were proposed to implement telerobotic systems over the Internet, such as the Plugfest experiment [10] (unilateral teleoperation) or teleoperation over the PlanetLab overlay network [1]. In the work [9], a control and communication co-design approach was proposed for the distant teleoperation of drive by wireless vehicles.

Such extended PD (Proportional - Derivative)-like control algorithms that can also assure the passivity of delayed bilateral teleoperation systems were introduced, e.g. in [16]. The dissipation parameters of such controllers are designed in function of the upper bound of the communication lag [15]. A similar concept was applied in the paper [8] considering discrete-time controllers. Generally, for greater delay values greater dissipation gain is required in the control algorithm. The Passive-Set-Position-Modulation approach [11] also applies a PD-like algorithm for the distantly teleoperated robot. This method modulates the position set-point such to assure as good position tracking performance as possible without violating the passivity of the teleoperation system.

The wave variable based bilateral control [3] is also applicable for such teleoperation systems in which communication delay is non-constant. With this approach, the stability can be assured if the variation of the delay is upper bounded.

In the case of the time domain passivity control the controller term that assures stability is activated only when an observer indicates that the passivity of the system is compromised [19]. The time domain passivity approach does not necessitate information about the communication lag, but it can be seen that the greater the delay the more energy is dissipated by the passivity controller both on the master and the slave side, as it was discussed in [14]. The paper [2] extends the concept of r-passivity to time domain passivity control schemes to assure precise position tracking and meanwhile to preserve the stability of the teleoperation in the presence of time-varying communication lag. The paper [13] combines the time domain passivity control approach with the identification of the remote environment's parameters to achieve stable force tracking. The time domain passivity control approach is also applicable for teleoperated mobile robots [18].

Along with the clear advantage of the time domain passivity control that it modifies the force and velocity signals only when the passivity condition is violated, it also has two shortages. The first is related to the magnitude of the control signal: as was already mentioned in the early paper [6], for near-zero force and velocity values the control signals can take such large values that compromise the implementability of the passivity controller. Second, the control signal can show oscillatory behavior. This phenomenon was already reported in previous works (see, e.g. the experimental measurements presented in [18] or [19].) The switching is accentuated, when the communication delay is time-varying [14], as in the case of Internet-based teleoperation. To deal with these shortcomings, this paper proposes a modified time domain passivity control which assures enhanced force reflection in the presence of non-constant communication lag with bounded control actions. Our first attempt to formulate a time domain passivity controller with bounded control signals can be found in the conference paper [14]. Another approach to solve the unbounded control signal problem was proposed in the paper [25]. However, in this paper the authors assumed that the upper bound of the communication delay variation is known.

In this current work, we give a more general form of the revised time domain passivity controller and we also perform the analysis of it. New realistic bilateral teleoperation experimental results are also presented to support the theoretical results. Teleoperation experiments over the Internet using commercial mobile manipulator and haptic devices between robotics laboratories situated in different countries (Hungary-Romania and Canada-Romania respectively) are presented.

The rest of the paper is organized as follows: before introducing the proposed improved control algorithm, the time domain passivity controller is invoked in Section 2. Section 3 presents the new theoretical results, i.e. the proposed control algorithm and its analysis. Experimental measurements are presented in Section 4. Finally, Section 5 concludes this paper.

2 Reminder on Time-Domain Passivity Control Approach for Delayed Bilateral Teleoperation Systems

This section recalls the original time domain passivity control approach (see, e.g. also [5]) which will be developed further in the next section.

A typical bilateral teleoperation system is shown in Fig. 1. The user (H) generates position/velocity commands using the haptic master device (M). The notation v_m stands for the master-side velocity. This command is sent through the communication medium to the slave robot's control system. On the slave-side the delayed v_m value is applied as the reference for the robot controller (SC). The robot controller has to ensure that the slave robot (S) tracks the received master-side velocity value. When there is direct contact between slave robot and the environment (E), the slave-side force f_s shows the effect of the environment on the slave robot. In Fig. 1, v_s and f_m represent the slave-side velocity and master-side force. In the communication channels d_{ms} and d_{sm} denote the time-varying communication lags.

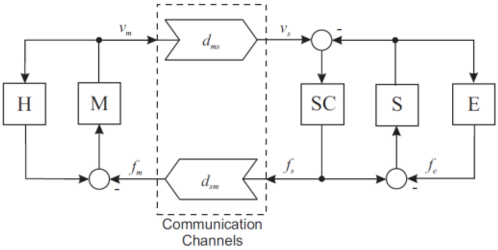

Figure 1
Block scheme of teleoperation system

The time domain passivity controller is designed such to compensate the effect of the communication delay on the stability of the closed loop teleoperation system. During the controller design, it is assumed that both the master side (master robot controlled by the human operator) and the slave side (slave robot that can be in contact with the environment) are passive. As the power-continuous interconnections of passive systems is also a passive system, if the passivity of the ``Communication Channels'' can be guaranteed, the bilateral teleoperation system is passive. The *energetic passivity* condition for the communication medium has the form:

$$E(t)=\int_0^t \left(f_m(\tau)v_m(\tau)+f_s(\tau)v_s(\tau)\right)d\tau \geq 0, \forall t>0, \tag{1}$$

where *E(t)* is the energy measured at the ports of the ``Communication Channels'' block. It is considered that *E(0)=0*.

According to the time domain passivity concept the passivity controller, which is responsible for the energy dissipation is active only when passivity condition (1) is not satisfied. The energy at the ports of the ``Communication Channels" (see Fig. 1) is computed by using the numerical approximation [20]:

$$E[k] = E_m[k] + E_s[k] = T\sum_{i=1}^{k}\left(f_m[i]v_m[i] + f_s[i]v_s[i]\right). \tag{2}$$

Here $T>0$ represents the sampling period used for the approximation. E_m stands for energy computed the master-side port, and E_s is the energy computed at the slave-side port.

When there is a communication lag between the master- and slave-side, the energy function (2) cannot be computed: at the master-side port there is no information about the slave-side velocity and force at the *k*th sample because of the delay, and vice versa.

This problem can be solved by decomposing of the computed energy into input (*IN*) and output (*OUT*) energies at both ports [19]:

$$E_s^{IN}[k] = \begin{cases} E_s^{IN}[k-1] + Tf_s[k]v_s[k], \text{if } f_s[k]v_s[k] > 0, \\ E_s^{IN}[k-1], \text{otherwise}, \end{cases} \tag{3}$$

$$E_s^{OUT}[k] = \begin{cases} E_s^{OUT}[k-1] - Tf_s[k]v_s[k], \text{if } f_s[k]v_s[k] < 0, \\ E_s^{OUT}[k-1], \text{otherwise}, \end{cases} \tag{4}$$

$$E_m^{IN}[k] = \begin{cases} E_m^{IN}[k-1] + Tf_m[k]v_m[k], \text{if } f_m[k]v_m[k] > 0, \\ E_m^{IN}[k-1], \text{otherwise}, \end{cases} \tag{5}$$

$$E_m^{OUT}[k] = \begin{cases} E_m^{OUT}[k-1] - Tf_m[k]v_m[k], \text{if } f_m[k]v_m[k] < 0, \\ E_m^{OUT}[k-1], \text{otherwise}, \end{cases} \tag{6}$$

As it was presented in [19], the ``Communication Channels" module is passive if

$$\Delta E_m[k] \le 0 \text{ and } \Delta E_s[k] \le 0 \tag{7}$$

$$\Delta E_m[k] = E_m^{OUT}[k] - E_m^{IN}[k - d_M[k]] \tag{8}$$

$$\Delta E_s[k] = E_s^{OUT}[k] - E_s^{IN}[k - d_s[k]] \tag{9}$$

where d_M and d_S are the discrete-time delays that are calculated as: $d_M = d_{sm}/T$, $d_S = d_{ms}/T$. The term (8) is computable at the master side and the expression (9) computable at the slave side.

When the passivity conditions (7) are not satisfied, the passivity controller adds to the signals received through the communication channels an extra energydependent term. The role of this energy extra dissipation term is to assure the passivity of the “Communication Channels" module. On the master side, the Passivity Controller has the form [19]:

$$f_m[k] = f_s[k - d_M[k]] + \Delta f_m[k] \tag{10}$$

$$\Delta f_m[k] = \begin{cases} \dfrac{\Delta E_m[k]}{T v_m[k]}, \text{ if } v_m[k] \neq 0 \text{ and } \Delta E_m[k] > 0 \\ 0, \text{otherwise.} \end{cases} \tag{11}$$

$\Delta f_m[k]$ is an energy dissipation term which is active only when the condition (8) is not satisfied.

The passivity controller has a similar form at the slave side as well.

3 Enhanced Time-Domain Passivity Controller

3.1 The Proposed Control Law

The control signal given in (10) can take hardly implementable values when v_m takes near-zero values.

On the other hand, the force signal displayed to the human operator can oscillate in the presence of time-varying communication lag. This phenomenon appears because the second, damping term in (10) switches off for small delay values, but for large delay, it can take high values.

To handle these problems a novel passivity controller is introduced in this section. The master-side controller will be presented.

To avoid the excessive control values, replace the $1/v_m$ term in the control law (10) with a bounding function $\delta(v_m)$ which has the following properties:

- $\delta(v_m) \to 1/v_m$ if $|v_m|$ is large, and
- $\delta(v_m) \to 1/\delta_v \,\mathrm{sgn}(v_m)$ if $v_m \to 0$. Here $\delta_v > 0$.

An example for such a function is (see Fig. 2)

$$\delta(v_m) = \frac{1}{v_m + \delta_v \,\mathrm{sgn}(v_m)} \tag{12}$$

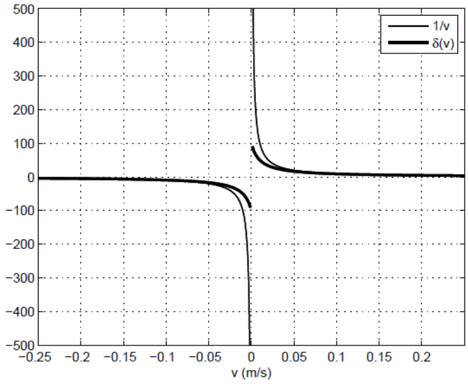

Figure 2

The *δ(·)* function

The function δ(·) assures the avoidance of the excessive control values, but in the low velocity regime the control law could dissipate less energy as the original control law. To tackle this problem, a modified energy term ($\Delta\hat{E}_m[k]$) is used in the control algorithm:

$$f_m[k] = f_s[k - d_M[k]] + \Delta f_m[k] \tag{13}$$

$$\Delta f_m[k] = \begin{cases} \delta(v_m[k])\dfrac{\Delta\hat{E}_m[k]}{T}, \text{if } \Delta E_m[k] > 0 \\ 0, \text{otherwise.} \end{cases} \tag{14}$$

The value of $\Delta\hat{E}_m[k]$ is formulated such that $\delta(v_m[k])\dfrac{\Delta\hat{E}_m[k]}{T} \to \dfrac{\Delta E_m[k]}{Tv_m[k]}$.

Accordingly, $\Delta E_m[k]$ can be generated by the following dynamic law:

$$\Delta\hat{E}_m[k+1] = \begin{cases} \Delta\hat{E}_m[k+1] + \dfrac{1}{T_I}\left(\Delta E_m[k] - v_m[k]\delta(v_m[k])\Delta\hat{E}_m[k]\right) \\ \text{if } \Delta E_m[k] > v_m[k]\delta(v_m[k])\Delta\hat{E}_m[k] \\ \Delta E_m[k+1], \text{otherwise.} \end{cases} \tag{15}$$

Here $T_I > 0.5$ determines the convergence speed of dynamic equation above.

3.2 The Analysis of the Control Law

3.2.1 Steady-State Analysis

Proposition 1: If $v_m \neq 0$, the control law given by (13), (15) and (12) in steady-state is equivalent to the original control (10).

If $|v_m|>0$ is constant, then the equation (15) is a first order discrete time filter with a pole $z = 1 - v_m\,\delta(v_m)/T_I$. As $0 \leq v_m\,\delta(v_m) < 1$ this filter is stable for $T_I > 0.5$.

If $\Delta\hat{E}_m[k+1]=\Delta\hat{E}_m[k]$, then $\Delta\hat{E}_m[k]=\dfrac{\Delta E_m[k]}{\delta(v_m[k])v_m[k]}$. With this value, the control (13) is equivalent to the control (10).

It can also be seen that the dynamics (15) has a low pass filter character, the filtered value of ΔE_m appears in the dissipation term of the control law; hence the high-frequency switching of the control signal is attenuated.

On the other hand, if $v_m = 0$, the dissipation term Δf_m in the original time domain passivity controller is unbounded. In the modified control (13), it increases with finite increments in each sampling period if $\Delta E_m = v_m \delta(v_m)\Delta\hat{E}_m$.

3.2.2 Passivity Analysis

To perform the analysis of time domain passivity control with bounded control signals the notion of *controller passivity* [12] is used. According to this condition, the maximum amount of energy generated by the network "Communication Channels" (see Fig. 1) that has the passivity controllers on its ports must be bounded. The controller passivity implies the energetic passivity of the bilateral teleoperation system if the master and slave side teleoperators are passive [12].

In the case of bilateral teleoperation systems that apply time domain passivity control the controller passivity condition is satisfied if:

- $\Delta E_m[k]$ is bounded for all k, and
- $\Delta E_m[k] > 0$ only for a finite number of sampling periods.

First, it is considered that, in concordance with the practical applications, the absolute values of the force, velocity and control signals in the bilateral teleoperation system are upper-bounded:

Assumption 1 $|v_m|\leq v_{MAX}$, $|v_s|\leq v_{MAX}$, $|f_m|\leq f_{MAX}$, $|f_s|\leq f_{MAX}$, $|\Delta f_m|\leq f_{MAX}$, $|\Delta f_s|\leq f_{MAX}$.

Second, the communication delays are assumed finite:

Assumption 2 $0 \leq d_{ms} < \infty$ and $0 \leq d_{sm} < \infty$.

Third, it is presumed that the controller passivity can be assured with bounded control signal.

Assumption 3 The bounded dissipation term ($|\Delta f_m| \le f_{MAX}$) assures that the $\Delta E_m > 0$ only for a finite number of sampling periods.

Proposition 2 If the Assumptions 1, 2 and 3 hold, the Communication Network with the proposed controller (13) on its ports satisfies the controller passivity condition.

If $\Delta E_m[k] > v_m[k]\delta(v_m[k])\Delta\hat{E}_m[k]$, the energy term $\Delta\hat{E}_m[k]$ for all k is increasing, see the equation (15).

As $\Delta\hat{E}_m[k]$ is increasing and $\delta(v_m[k])$ is lower bounded for $|v_m| \le v_{MAX}$, $|\Delta f_m|$ also increases, and it reaches $\min\{\Delta E_m/T|v_m|, f_{MAX}\}$ within a finite number of sampling periods. Hence, by Assumption 3, ΔE_m exceeds zero only for a finite number of sampling periods.

On the other hand, by Assumptions 1 and 2, ΔE_m is upper bounded in each sampling period.

3.3 Extension to Multi-DOF Teleoperators

The proposed algorithm can be extended to multi-DOF (Degree Of Freedom) master- and slave-side robots by applying the method presented in [17].

Consider that the master-side and the slave-side robots have the same DOF i.e., dim ($\mathbf{f}_m$)= dim ($\mathbf{v}_m$)= dim ($\mathbf{f}_s$)=dim ($\mathbf{v}_s$) =DOF. Then the energy at the ports of the Communication Network is computable as:

$$E[k] = E_m[k] + E_s[k] = T\sum_{i=1}^{k}\left(\mathbf{f}_m[i]^T\mathbf{v}_m[i] + \mathbf{f}_s[i]^T\mathbf{v}_s[i]\right) \tag{16}$$

Based on this relation, the master- and slave-side observers and the passivity condition can be formulated in the same way as in the equations (3)-(9).

The passivity controller (13) can be reformulated as:

$$\mathbf{f}_m[k] = \mathbf{f}_s[k - d_M[k]] + \begin{cases} \dfrac{\Delta\hat{E}_m[k]}{T(\delta_v + \mathbf{v}_m^T[k]\mathbf{v}_m[k])} P_{\mathbf{f}_s}(\mathbf{v}_m[k]), \text{if } \Delta E_m[k] > 0 \\ 0, \text{otherwise.} \end{cases} \tag{17}$$

where $P_{\mathbf{f}_s}(\mathbf{v}_m[k])$ denotes the orthogonal projection of $\mathbf{v}_m$ onto $\mathbf{f}_s$ and $\delta_v > 0$. Here, the bounding function has the form

$$\delta(\mathbf{v}_m) = \frac{P_{\mathbf{f}_S}(\mathbf{v}_m[k])}{T(\delta_v + \mathbf{v}_m^T[k]\mathbf{v}_m[k]))} \tag{18}$$

and the modified energy term $\Delta\hat{E}_m[k]$ can be formulated as:

$$\Delta\hat{E}_m[k+1] = \begin{cases} \Delta\hat{E}_m[k+1] + \frac{1}{T_I}\left(\Delta E_m[k] - P_{\mathbf{f}_S}(\mathbf{v}_m[k])^T \delta(\mathbf{v}_m[k])\Delta\hat{E}_m[k]\right) \\ \quad \text{if } \Delta E_m[k] > P_{\mathbf{f}_S}(\mathbf{v}_m[k])^T \delta(\mathbf{v}_m[k])\Delta\hat{E}_m[k], \\ \Delta E_m[k+1], \text{otherwise.} \end{cases} \tag{19}$$

4 Experimental Results

4.1 Description of the Experiments

To analyze the performances of the proposed bilateral control approach, two sets of experimental measurements were performed.

In the first experiment (*E1*) the teleoperation system was implemented using the facilities of two robotic laboratories situated in different European countries: Antal Bejczy Center for Intelligent Robotics, Óbuda University, Budapest, Hungary (slave side) and Robotics and Control Laboratory, Sapientia Hungarian University of Transylvania, Tirgu Mures, Romania (master side). The physical distance between these laboratories is about 500 km.

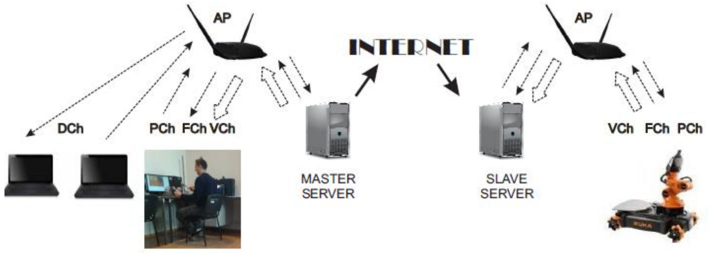

Figure 3
Experimental setup for measurements

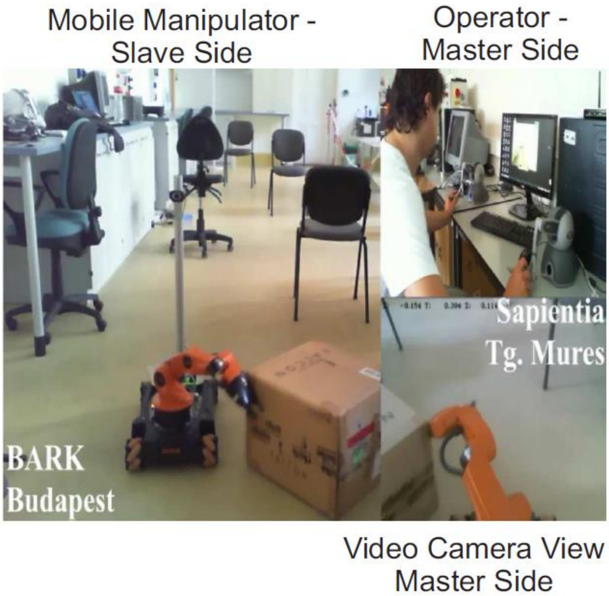

Figure 4

Teleoperation experiment

During the second experiment (*E2*) the master side was implemented at the Centre for Intelligent Machines, McGill University, Montreal, Quebec, Canada and the slave side was put in operation at the Robotics and Control Laboratory, Sapientia Hungarian University of Transylvania, Tirgu Mures, Romania. The physical distance between the master and the slave side during this transatlantic teleoperation experiment was about 7500 km.

In both experiments, a KUKA youBot mobile manipulator (KUKA Roboter GmbH, Germany) served as the slave robot. It has an omnidirectional mobile platform equipped with four Mecanum wheels; hence the longitudinal, lateral and angular velocities can separately be prescribed for the platform. A 5 DOF serial robot arm is placed on the manipulator and a gripper serves as the end effector for the slave robot. The control equipment of the arm provides position, velocity and force information about each joint separately. The robot used for teleoperation was also equipped with a USB video camera having 640X480 resolution; it renders video feedback about the motion of the slave robot.

During the experiment *E1* two PHANTOM Omni haptic devices (SensAble Technologies, Inc., USA) served at the master side to separately control the arm and the platform of the mobile manipulator. These haptic devices have 6 DOF and can provide force feedback on the first three joints. The first haptic device was applied to control the mobile platform. The first and third joints were used to prescribe the longitudinal and lateral velocity components, while the angular velocity of the platform was set with the fifth joint. The platform was controlled by the human operator based on the video information provided by the camera mounted on the slave robot. The second haptic device was used to control the arm of the robot. The first 5 DOF of the second haptic device were used to control each joint of the arm. In the first three joints, the force feedback was implemented. Accordingly, the teleoperation system provides both haptic and visual information for the remote robot arm control. Using the buttons on the haptic devices the motions of the arm and the platform can separately be enabled and the gripper can be opened or closed by the operator.

In the experiment *E2* a Novint Falcon haptic device (Novint Technologies, Inc, USA) served to control both the arm and the platform of the mobile manipulator. The motion of the platform and the arm can be separately enabled with the buttons of the haptic device`s grip. For the distant control of the mobile platform the three DOFs of the haptic device were used to prescribe the longitudinal, traversal and angular velocities of the platform. In robot arm control mode, the same DOF's of the haptic device were applied to control the first three joints of the KUKA youBot's arm. During the bilateral teleoperation measurements, the force feedback was implemented for the first joint of the arm.

In Figure 3 the communication channels of the teleoperation system are presented. PCh (Position Channel) is used to transmit position and velocity information from the master side to the mobile slave. FCh (Force Channel) is applied to send the force data from the mobile slave to the master side. Through VCh (Video Channel) the video information is sent from the slave to the master. Other data channels can also be present in the communication medium applied to teleoperation (DCh – Disturbance Channel).

The software that was used for experimental measurements and implements the proposed bilateral teleoperation method is available on the Github.com web-based repository hosting service: https://github.com/TARC-Sapientia/TO.

A detailed description of the software can be found in [21].

4.2 Measurement Results - *E1*

The developed teleoperation system and bilateral control methods were tested through Internet-based teleoperation experiments. During the test scenario, the task of the human operator in Tirgu Mures was to navigate the KUKA youBot mobile manipulator in Budapest among obstacles to a target place. The mobile platform part was remotely controlled based on video information. During the motion, the mobile manipulator also had to push aside non-fixed obstacles by using its arm. These types of tasks are common in search and rescue applications. Fig. 4 presents the mobile manipulator, the operator and a frame of the video which was displayed during the teleoperation experiment.

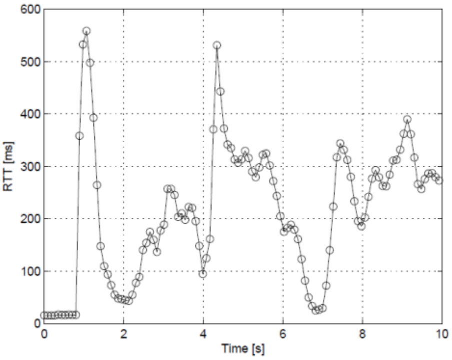

Figure 5
Typical Round Trip Time (RTT) evolution during teleoperation experiments

During the task execution, different bilateral teleoperation scenarios were tested. When the robot pushed the loaded box, the force exerted by the base joint of the arm was sent back to the human operator. The force felt by the human operator through the haptic device gave information to the operator about the magnitude of the friction between the box and the floor. For such cases, the reliable force reflection is important as through the haptic feedback the operator can decide whether the robot is capable of pushing aside the obstacle.

The Internet latency between Romania and Hungary is relatively small (approximately 30 ms). To test the teleoperation system in critical situations, during the experiments another UDP data flow in a bottleneck link of the master-slave communication channel was started (DCh). As bottleneck link the last hop wireless channel on the master side was considered, see Fig. 3. The communication congestion was achieved in this wireless network by activating an extra 5 MB/s UDP data flow. It manifested in increased delay and delay variation in the communication channel. A typical delay evolution during the teleoperation experiments is shown in Fig. 5. As the figure shows, the mean Round Trip Time values ($RTT = d_{ms} + d_{sm}$) were around 200 ms during the measurements, but delay peaks over 500 ms also appeared.

Both time domain passivity controllers presented in sections 2 and 3 were tested during the bilateral teleoperation experiment. In both cases a box, having the same weight, in the same location was pushed. In order to clear the box from its path the robot rotated its first joint approximately in the domain (-2 rad, 2 rad) and it was in direct contact with the box in the second part of the motion. In the case of the method presented in section 3 the following parameters were applied: δ_v = 0.01m/s and T_I = 10 s.

The experimental results in the bilateral control experiments are presented in the Figures 6 and 7. The measurements focused on the force feedback during the robot arm movement. Some similarities can be observed in both cases. First, the bilateral teleoperation is stable, the difference between the master side output and slave side delayed input energy (E_m^{OUT}, E_s^{IN}) remains around zero; hence all three passivity controllers assure the stability of the teleoperation. On the other hand, a lag between the received reference position on the slave side (p_s) and the real joint position (p_r) can be observed. The lag is accentuated when there is contact between the robot arm and the environment.

In both cases the passivity controller activates when the operator starts retreating the robot arm. Fig. 6 shows the behavior of the original time domain passivity controller in the presence of delay variation. As this figure shows, the control signal has high-frequency components which temporarily degrade the quality of the force feedback. This can be avoided by applying the control law (17). The behavior of this control law is presented in the Fig. 7. As this figure shows, in both cases much better-quality force feedback was achieved.

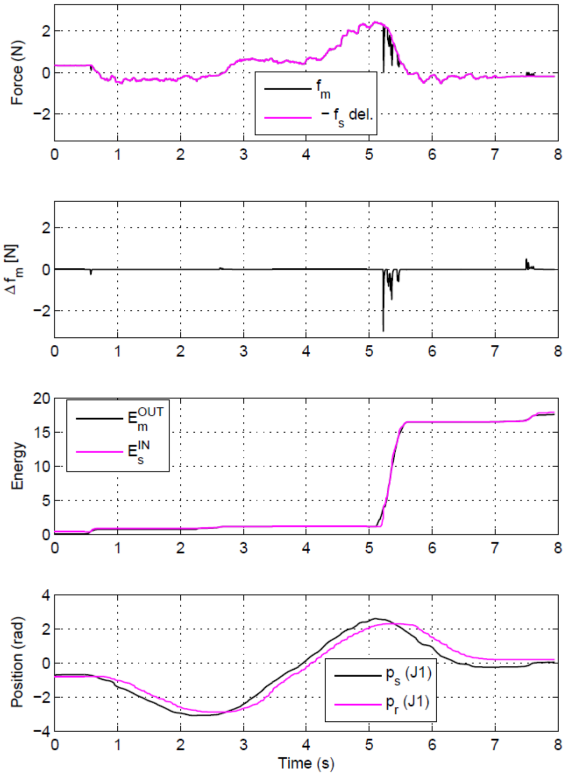

Figure 6

Bilateral control measurement (*E1*) with the original time domain passivity controller

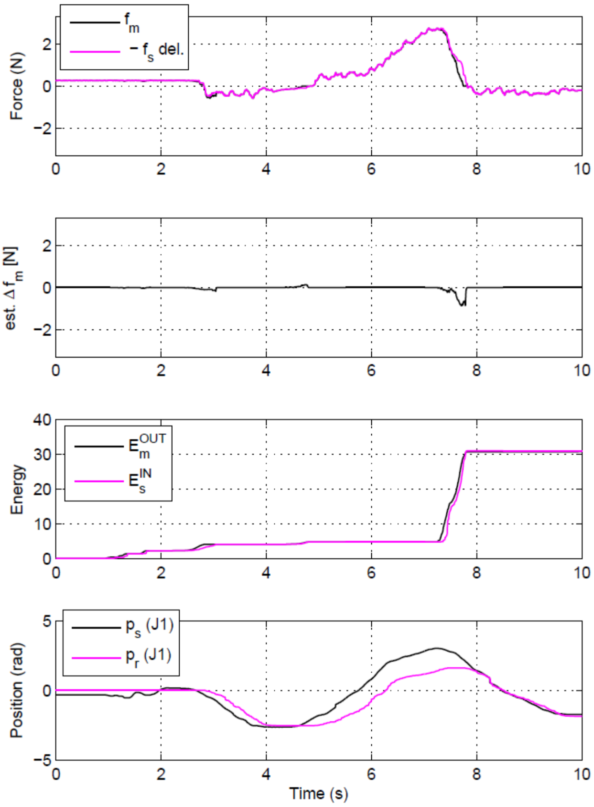

Figure 7

Bilateral control measurement (*E1*) with the proposed controller

4.2 Measurement Results - *E2*

A second set of transatlantic teleoperation measurements were also performed to show the repeatability of the proposed bilateral teleoperation scenario in other communication conditions.

A similar test scenario was elaborated as in the case of *E1*: on the master side (Canada) the human operator teleoperated the mobile manipulator, situated in Romania, among obstacles based on video and haptic information. Using its manipulator, the slave robot pushed aside non-fixed obstacles to advance toward its goal. The bilateral teleoperation was exploited during these events.

The Internet latency between Canada and Romania is approximately 135 ms. The higher delay and jitter values were achieved by starting an extra 5 MB/s UDP data flow in the wireless network that connected the mobile manipulator to the slave-side server. With this strategy, the average *RTT* was increased to 480 ms.

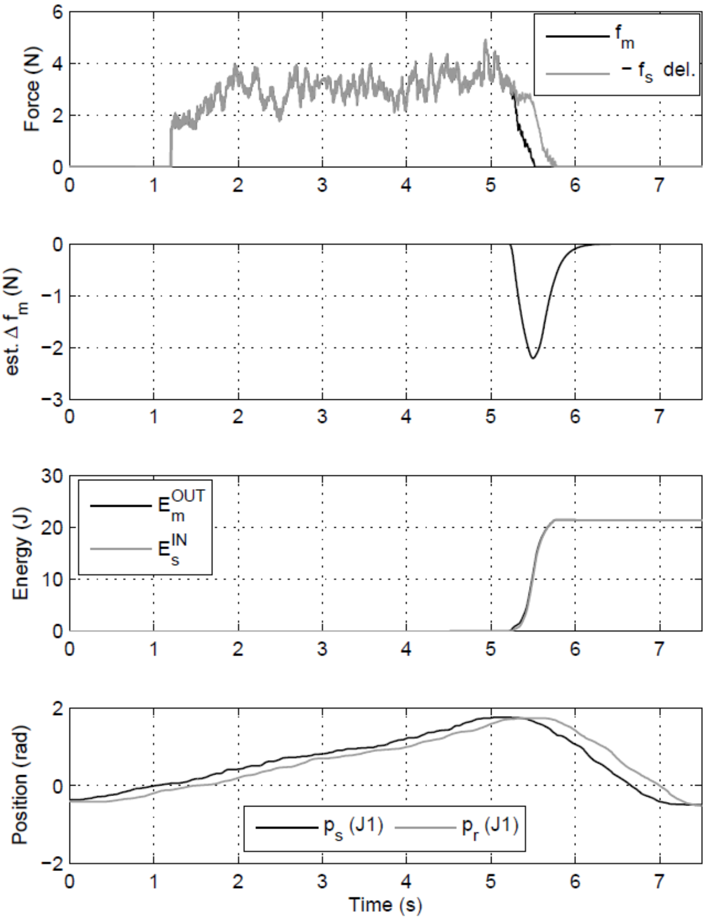

Figure 8

Bilateral control measurement (*E2*) with the proposed controller

During the teleoperation experiment the control method presented in Section 3 was applied with same implementation form and parametrization as in the case of *E1*. The experimental results are presented in Fig. 8. As it can be seen similar control performances are achieved as in the case of the experiment *E1*: with smooth control action, the stability of the teleoperation can be assured in the presence of large, time-varying communication delay. Similarly, as in the case of *E1*, p_s is the slave side position and p_r is the real joint position.

Conclusions

In this paper, a teleoperation system was presented for distant control of mobile manipulators. An enhanced passivity observer - passivity controller approach was introduced to assure stable and transparent bilateral teleoperation in the presence of time-varying communication lag. The proposed algorithm is a modified time domain passivity controller that can ensure the stability of the teleoperation system with adequate force reflection, and with bounded control signal. The control assures smooth control actions even in the critical phases of the teleoperation, providing convenient operation conditions for the human operator.

Experimental measurements were performed using realistic teleoperation scenarios over mixed communication medium (Internet and wireless networks), including vision-based mobile platform navigation and bilateral control of the robot arm. The experimental measurements, performed over communication mediums that include both Internet and wireless network, show that the proposed bilateral control algorithms and software can assure both the stability and reliable force reflection in the bilateral teleoperation systems in different network communication conditions and with different commercial haptic devices.

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References

[1] Cen, Z., Mutka, M., Liu, Y., Goradia, A., Xi, N.: QoS management of supermedia enhanced teleoperation via overlay networks. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005, pp. 1630-1635

[2] Chawda, V., O'Malley, M.: Position synchronization in bilateral teleoperation under time varying communication delays. IEEE/ASME Transactions on Mechatronics 20(1), 2015, pp. 245-253

[3] Chopra, N., Berestesky, P., Spong, M.: Bilateral teleoperation over unreliable communication networks. IEEE Transactions on Control Systems Technology 16(2), 2008, pp. 304-313

[4] Ferre, M., Buss, M., Aracil, R., Melchiorri, C., Balaguer (Eds.), C.: Advances in Telerobotics, Springer, 2007

[5] Haller, P., Marton, L., Szanto, Z., Vajda, T.: Bilateral Teleoperation in the Presence of Jitter: Communication Performance Evaluation and Control, Springer, 2015, pp. 291-311

[6] Hannaford, B., Ryu, J. H.: Time-domain passivity control of haptic interfaces. IEEE Transactions on Robotics and Automation 18(1), 2002, pp. 1-10

[7] Hokajem, P. F., Spong, M. W.: Bilateral teleoperation: An historical survey. Automatica 42, 2006, pp. 2025-2057

[8] Huang, K., Lee, D.: Hybrid PD-based control framework for passive bilateral teleoperation over the Internet. In: Proc. of 18th IFAC World Congress, 2011, pp. 1064-1069

[9] Khan, Z. H., Genon-Catalot, D., Thiriet, J. M.: A co-design approach for bilateral teleoperation over hybrid network. In: Proc. of 18th Mediterranean Conference on Control & Automation, Marrakech, Morocco, 2010, pp. 286-291

[10] King, H., Hannaford, B., Kwok, K. W., Yang, G. Z., Griths, P., Okamura, A., Farkhatdinov, I., Ryu, J. H., Sankaranarayanan, G., Arikatla, V., Tadano, K., Kawashima, K., Peer, A., Schauss, T., Buss, M., Miller, L., Glozman, D., Rosen, J., Low, T.: Plugfest 2009: Global interoperability in telerobotics and telemedicine. In: IEEE International Conference on Robotics and Automation, 2010, pp. 1733-1738

[11] Lee, D., Huang, K.: Passive-set-position-modulation framework for interactive robotic systems. IEEE Transactions on Robotics 26(2), 2010, pp. 354-369

[12] Lee, D., Li, P. Y.: Passive bilateral control and tool dynamics rendering for nonlinear mechanical teleoperators. IEEE Transactions on Robotics 21(5), 2005, pp. 936-951

[13] Li, H., Kawashima, K.: Bilateral teleoperation with delayed force feedback using time domain passivity controller. Robotics and Computer-Integrated Manufacturing 37, 2016, pp. 188-196

[14] Marton, L., Szanto, Z., Vajda, T., Haller, P., Sandor, H., Szabo, T., Tamas, L.: Communication delay and jitter influence on bilateral teleoperation. In: Proc. of 22nd Mediterranean Conference on Control and Automation, Palermo, Italy, 2014, pp. 1171-1177

[15] Namerikawa, T.: Bilateral control with constant feedback gains for teleoperation with time varying delay. In: Proc. of 48th IEEE Conference on Decision and Control. Shanghai, China, 2009

[16] Nuno, E., Ortega, R., Barabanov, N., Basanez, L.: A globally stable PD controller for bilateral teleoperators. IEEE Transactions on Robotics 24(3), 2008, pp. 753-758

[17] Preusche, C., Hirzinger, G., Ryu, J. H., Hannaford, B.: Time domain passivity control for 6 degrees of freedom haptic displays. In: Proc. of 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2003, pp. 2944-2949

[18] Quang, H. V., Farkhatdinov, I., Ryu, J. H.: Passivity of delayed bilateral teleoperation of mobile robots with ambiguous causalities: Time domain passivity approach. In: Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012, pp. 2635-2640

[19] Ryu, J. H., Artigas, J., Preusche, C.: A passive bilateral control scheme for a teleoperator with time-varying communication delay. Mechatronics 20, 2010, pp. 812-823

[20] Ryu, J. H., Kwon, D.S., Hannaford, B.: Stable teleoperation with time-domain passivity control. IEEE Transactions on Robotics and Automation 20(2), 2004, pp. 365-373

[21] Sandor, H., Szabo, T., Vajda, T., Haller, P., Szanto, Z., Marton, L.: Video supported bilateral teleoperation system: Design and implementation. In: IEEE 14th International Symposium on Computational Intelligence and Informatics, 2013, pp. 105-111

[24] Wirz, R., Marin, R., Claver, J.M., Ferre, M., Aracil, R., Fernandez, J.: End-to-end congestion control protocols for remote programming of robots, using heterogeneous networks: A comparative analysis. Robotics and Autonomous Systems 56(10), 2008, pp. 865-874

[25] U. Ahmad and Y. J. Pan, Switching time domain passivity control for multilateral teleoperation systems under time varying delays, IEEE 55th Conference on Decision and Control (CDC), Las Vegas, NV, 2016, pp. 1429-1434