Experimental Comparison Study of Control Architectures for Bilateral Teleoperators

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***Abstract*—A detailed experimental comparison study of several published algorithms for motion and force control of bilateral teleoperators, with emphasis on Internet-based teleoperation, is presented. The study investigates the effects of data losses, communication delays, and environmental constraints on a teleoperation system for different control techniques, which are based on wave variables, Smith predictors, and recent algorithms on synchronization. The controllers are compared on stability, transparency, and complexity using two identical nonlinear robots coupled via a stochastic network model that allowed transmission round-trip delays and data-loss rates to range from 8 to 1088 ms and 0% to 50%, respectively. A total of 18 subjects, which were distributed among 26 experiments with the aims of regulating the effects of the operators learning process and dynamic properties, participated in this study. Overall, the comparison study reports a deteriorating effect in the performance (i.e., larger position errors and lower fidelity of contact information) from delays and data losses. Yet, the effect of data losses is less critical when compared with time delays. In addition, the preference for a particular control framework is shown to strongly depend on the operational conditions of the system, such as the characteristics of the coupling channel, the specifics of the remote task, and the computational capabilities of the manipulators.**

***Index Terms*—Internet-based teleoperation, performance evaluation, physical human–robot interaction, telerobotics.**

I. Introduction

The USE of bilateral teleoperators, which are defined as electromechanical machines that enable humans to move, sense, and physically manipulate objects at a distance by the exchange of position, velocity, and/or force information [1], has become increasingly popular, as new technology continues to emerge. Bilateral teleoperators are currently employed in a wide range of applications that includes outer space exploration [2], handling of toxic materials [3], and minimally invasive surgery [4], raising a very diverse set of control and communication challenges according to the task, equipment, and environment [5], [6]. For instance, in applications where the separation distance between the local and remote environments is substantial (e.g., outer space assembly, underwater surveillance, and transcontinental manipulation), time delays incurred in the communication process can degrade the performance and even destabilize an otherwise stable system.

The destabilizing effects of time delays and delayed force feedback in teleoperation systems were first reported by Ferrell [7], [8]. Thereafter, most research efforts were directed toward the design of control schemes that aimed for a stable and reliable performance of time-delayed teleoperators. One breakthrough in this topic was introduced in 1988 when Anderson and Spong [9] combined the concepts of scattering transformation and passivity to guarantee the stability of a bilateral force-feedback teleoperator independently of any arbitrary constant time delay. Then, Niemeyer and Slotine [10] extended and generalized the scattering and passivity theory with the notion of wave variables. These work efforts were parallel to other research trends on H_∞-optimization [11], sliding-mode control [12], and compliant control [13], among others (see [6] and references therein).

For more than 30 years (starting with the findings of Ferrell), research on bilateral teleoperation was primarily (if not exclusively) emphasized for constant and continuous delays. It was not until the introduction of the Internet in the mid-1990s that a new dimension to the study of teleoperation was added: When the Internet is used as the coupling channel, inherent time-varying delays, packet losses, and disconnections may degrade the performance and even induce the instability of a teleoperator [14], [15]. Therefore, several of the former research trends have been adapted to the new challenges. Passive wave-scattering (WS) transformation, which was first introduced by Anderson and Spong [9], has been complemented to compensate for time-varying delays, data losses, and discrete communication mediums [16]–[20]. Likewise, other techniques based on H_∞-optimal control [11], share-compliant control [13], predictive control [21], proportional–derivative (PD) control [22], passive set-position modulation [23], [24], and event-based control [25] have been proposed.

The wide spectrum of control architectures, which are developed for teleoperation, has continuously led researchers to design guidelines and conduct comparison studies among control frameworks. The first studies date from the early 1970s, when evaluation criteria were based on task-completion time and accurate execution of outer space assembly and exploration. For

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instance, Kugath [26] studied the effects of complaint and force-feedback manipulation reporting an increase of task-completion time over nonforce-feedback configurations in simulated space tasks. Similarly, in the same year, Mullen [27] published the results of a comparison study between position and rate controllers without force feedback. Mullen found that position control was up to four times faster in performing various manipulative tasks than resolved motion rate control. Wilt *et al.* [28] extended Mullen's results by showing that task-completion time for large-sized bilateral teleoperators with position and force-feedback control was up to two times faster than with resolved motion rate control. These early experiments were followed by several comparatives studies, which were led initially by Bejczy at the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory [29]–[31], then by Akin in the mid-1980s [5] and, finally, by different researchers with NASA between 1989 and 1993 [32], [33]. In general, these studies evidenced a faster completion time for position controllers over velocity frameworks [33]. Kim *et al.* [34] arrived at a similar conclusion in 1987 substantiating the advantages of position controllers for small workspace teleoperation tasks.

The development of high-fidelity, force-reflecting teleoperators, and the introduction of passivity-based algorithms in the late 1980s inspired researchers to further investigate the utilization of force-feedback and passivity-based algorithms. For instance, Hannaford *et al.* [35] conducted a series of experiments with and without force feedback in teleoperation systems. They reported a positive effect in task-completion time when force feedback was exploited in the control loop. Then, in a later effort, Lawn and Hannaford [36] compared the performance of passivity-based control with nonpassive traditional methods. The results indicated a negative 50% increment in task-completion time for passivity-based control.

Up to 1993, comparison studies were explicitly based either on task-completion time, stability, or position tracking, ignoring other transparency-based objectives, such as force reflection and remote haptic (e.g., impedance) perception. Many applications, such as telesurgery, require the operator to properly discern material properties (e.g., stiffness and impedance) and effect adequate forces in order to avoid damages to the physically separated working environment [37]. In these situations, it is crucial for the teleoperation system to provide the operator with accurate sensory information (e.g., force, compliance, impedance, and vision) regarding the remote location.

Lawrence [38] was the first to explicitly compare different control frameworks on the basis of force and impedance perception, and to demonstrate a conflict between stability and transparency in 1993. He found that in comparison with traditional position and force controllers, passivity-based approaches were able to improve stability but not transparency. His work was succeeded by Daniel and McAree [39] who investigated the limitations in performance imposed by stability constrains. Later, in a comparison analysis with position-force controllers published in 2001, Hashtrudi-Zaad and Salcudean [40] concluded that perfect transparency cannot be achieved due to unknown parameters and instability concerns induced by time delays. Nevertheless, they reported an improvement on transparency when both force and position information are communicated between master and slave. Other experiments include the work of Sherman *et al.* [37], who evaluated the performance of a position-error-based force-feedback control, a kinesthetic force-error control, and a position-force-feedback control when interacting with a simulated soft tissue [37]. They reported a higher detection of compliance changes in soft tissues when employing position-force-feedback configurations. Overall, all these research efforts suggested the use of delayed force feedback to improve transparency in a teleoperation system.

More recently, Arcara and Melchiorri [41] compared the performance of modern control techniques based on passivity, compliance, predictive, adaptive, and sliding-mode control. They simulated each control scheme under constant time delays and evaluated their performance on stability, tracking error, stiffness, and perceived inertia. They did not arrive to a set of specific conclusions, but rather provided some recommendations when selecting a particular algorithm or task. Their work was followed in separate studies by Botturi *et al.* [42], Moschini and Fiorini [43], Marcassus *et al.* [44], Aziminejad *et al.* [45], and Aliaga *et al.* [46]. In particular, Aliaga *et al.* found that position with force-feedback control has a more faithful force and position-tracking response than position and force controllers separately. These studies confirmed the advantages of combining position and force control into the teleoperation system.

The formerly discussed studies are based on a twofold assumption: a constant time delay and an uninterrupted data rate, which are conditions not suitable for modern applications, such as Internet-based teleoperation. Until recently, it has not been that comparison studies have addressed teleoperation over time-varying-delayed and discrete communication mediums. For instance, Kim *et al.* [47] proposed a methodology to quantitatively evaluate the performance of bilateral teleopeators modeling discretized signals and time-varying delays as perturbations of the continuous, time-constant-delayed system. Sankaranarayanan and Hannaford [48], [49] also conducted a series of comparative experiments on peer-to-peer teleoperation over time constant and time-varying-delayed transmission channels. They concluded that PD controllers provide better position convergence, while WS-based approaches improve force reflection. These studies, however, did not address nor identify the effects of data losses on the system performance.

To the knowledge of the authors, this paper, which is the extension of [50], represents one of the first comparison studies that evaluates the performance of several published algorithms for motion and force control of bilateral teleoperators over time-varying-delayed and lossy communication channels. Six control techniques [10], [16], [17], [19], [51], [52], which are based on wave variables, Smith predictors, and recent algorithms on synchronization, are compared under variable and constant time delays, packet losses, and environmental disturbances. The evaluation criteria are based on the following parameters:

1) motion tracking;
2) force tracking;
3) perceived stiffness;
4) qualitative stability assessment;
5) complexity of the control framework.

Since performance criteria are sensitive to the manipulation capabilities and dynamics of the operator, 18 different subjects participated in the study. By comparing different control architectures with different operators and scenarios, this paper aims to provide design guidelines for teleoperator control designers.

The remaining of the paper is organized as follows. Section II introduces the six control schemes under comparison. Section III details the testbed employed for the study, the set of experiments, and the comparison criteria. This is followed by the experimental results in Section IV, a discussion of the results in Section V, and a measure of complexity of the control frameworks in Section VI. Finally, Section VII presents conclusions and future research directions.

II. Control Architectures

Most published bilateral teleoperation control schemes are rooted from common control engineering theories that include passivity-based algorithms, predictive control, adaptive control (AC), PD-based techniques, and impedance control, among others. The following is a brief chronological list of some representative passivity-based bilateral teleoperation architectures that are currently available in the literature.

A. Wave-Scattering Transformation

Prior to 1988, stability of arbitrarily delayed bilateral teleoperators seemed unachievable. The solution came in 1988 when Anderson and Spong [9] combined concepts on network theory, scattering transformation, and passivity to guarantee the stability of a teleoperation system independently of any constant time delay. Then, Niemeyer and Slotine [10] added the notion of wave variables, thus simplifying the scattering-transformation approach. In this wave-based framework, wave variables are communicated via the delayed transmission lines instead of the typical power-conjugated variables (i.e., force and velocity), which are employed in many traditional bilateral systems. The use of the WS approach solved the destabilizing effects incurred in the transmission lines by passifying the communication channels independently of the size of the delay [10].

The WS framework offers the advantage that no knowledge of the system, such as the size of the delay and the model parameters, is required to guarantee stable performance. It, however, does not guarantee stability for time-varying-delayed communication channels (e.g., Internet). In fact, under time-varying delays, wave variables are distorted compromising the passivity of the system and leading to significant position errors [17]. Likewise, the WS approach does not provide compensation for data losses, and thus, stability and position convergence are not enforced. Despite this, in [15], it is shown that for discrete communication channels, which is the case of this study, if a zero-valued wave is assumed when a data packet is missing, passivity is preserved. Moreover, if duplicated packets are ruled out, it can be proved that the system remains passive even for time-varying delays [53].

B. Wave Prediction (WP) With Energy Regulation

Intuitively, an operator should expect the performance of the telemanipulator to deteriorate as the transmission delay increases. Based on this idea, Munir and Book [19] introduced a wave-based control scheme for Internet teleoperation that predicts the incoming wave variable from the slave, thereby minimizing the negative effects of transmission delays. Their scheme combines the use of the Smith predictor and the Kalman filter to estimate the behavior of the slave and to compensate, at the master side, for delays and losses in the communication channel. It also employs a position-correcting input and an energy regulator that mitigates position errors and limits the energy generated by the Smith predictor, respectively.

In general, the WP control framework enforces passivity for bilateral teleoperators independent of constant delays. Stability for time-varying delays is claimed under the assumption that the slave robot dissipates enough energy, which, in practice, is frequently unknown. Yet, if the nonduplicate and zero-valued lost packet convention is assumed, it can be shown that passivity is preserved independent of time-varying delays and data losses (following similar arguments as in [53]).

Finally, when implementing the WP framework, position errors may still arise even with the position-correcting input. This unwanted errors occur when the system dynamic model is inaccurate or when the round-trip delay is uncertain [54].

C. Digital Data (DD) Reconstruction Filter

To avoid the adverse effects of wave distortion due to time-varying delays and data losses, Berestesky *et al.* [17] proposed a novel solution based on the digital reconstruction of the wave variables. Their approach introduces the use of a buffering and interpolation scheme that conserves the passivity of the system and reduces the tracking error under time-varying delays and packet losses. The strategy is to transmit the summation over time of the wave variable in sync with the current time, which enables the receiving side to determine if the wave variable has been distorted and, accordingly, reconstruct the wave variable such that passivity is enforced and position tracking is enhanced. The DD schemes does not require knowledge of the dynamics of the system or delay.

D. Wave Integral and Reconstruction Filter

The original-wave variable scattering transformation does not provide the teleoperation system with explicit position information. Therefore, position tracking is, in general, not guaranteed. Niemeyer and Slotine [16], [55] proposed an original approach to solve this problem: transmitting the wave integrals (WIs). The WIs encode position and momentum information, thus explicitly providing the teleoperator with position feedback and enforcing position convergence between master and slave.

Yet, under time-varying delays, the transmission of WIs may violate passivity. Therefore, Niemeyer and Slotine included a reconstruction filter in the design that guarantees a stable performance by preserving the passivity of the communication channel under time-varying delays and data losses. As with the WS scheme, the WI approach does not require knowledge of the parameters of the system.

TABLE I
RELEVANT PROPERTIES OF CONTROL FRAMEWORKS

Property	Control Scheme					
	WS	**WP**	**DD**	**WI**	**AC**	**PD**
Independent of:						
Robot Dynamics	Yes	No	Yes	Yes	No[a]	Yes
Size of Delay	Yes	No[b]	Yes	Yes	Yes	No[c]
Stability under:						
Constant Delay	Yes	Yes	Yes	Yes	Yes	Yes
Time-Varying Delay	Yes[d]	Yes[d]	Yes	Yes	No	No
Position Convergence	No	Yes[e]	No	Yes	Yes	Yes

[a]Robust to parameter uncertainties due to AC.
[b]Knowledge of mean value of round-trip delay is required.
[c]Knowledge of upper bound of round-trip delay is required.
[d]Under the assumptions that duplicated packets are rejected and that missing packets are treated as zero packets.
[e]Given that the system parameters are well known.

E. Passivity-Based Adaptive Control

The last wave-based teleoperation architecture to be discussed is the passivity-based AC by Chopra *et al.* [52], where the wave variables encode position, velocity, and force information. Chopra *et al.* redesigned the WS transformation by incorporating a state-feedback control law that guarantees passivity for any constant time delay, initial offsets, and packet losses. To compensate for uncertain system parameters, Chopra *et al.* proposed the use of the passivity-based AC in conjunction with the gradient projection law, which does not alter the passivity condition of the system for constant delays.

F. Proportional–Derivative Control

Lee and Spong [51] introduced the only teleoperation framework in this comparison study, which is not based on the WS transformation theory. They proposed a PD control scheme with damping compensation that guarantees the passivity of the closed-loop teleoperator in the presence of parametric uncertainties and constant time delay, rather than passivity of the communication channel alone, as in the scattering-transformation theory.

G. Relevant Properties of Control Schemes

The earlier discussion briefly introduced the most relevant properties of each control framework with respect to stability, design, and position tracking. For clarity and comparison purposes, these properties are summarized in Table I.

III. EXPERIMENTAL SETUP AND DESCRIPTION OF EXPERIMENTS

A. Testbed

The experimental setup, which is employed in this comparison study, is shown in Fig. 1. It consists of two direct-drive, two revolute-joints robots coupled via a stochastic network model. Both master and slave robots are equipped with a pair of optical encoders that measure link angular position and velocity (via digital estimation) and a force–torque sensor, which is located at

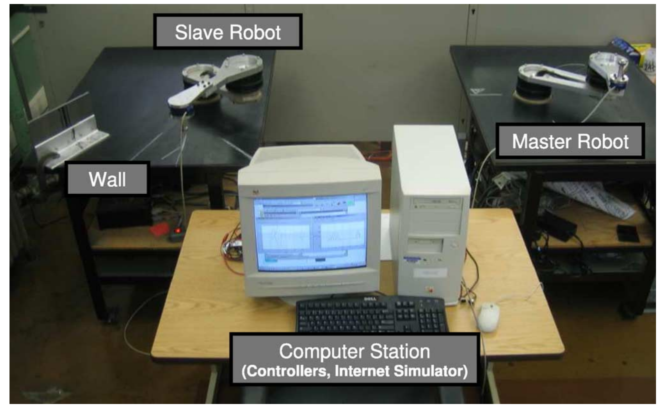

Fig. 1. Experimental testbed.

the end-effector, that measures forces sensed/exerted by the operator/environment. The controllers and the stochastic network model are implemented using Wincon 3.3 (which is a Windows application capable of running Simulink models in real time) with a sampling time of 4 ms. In addition, the experimental testbed contains a detachable, stiff aluminum wall, which is placed in the slave's workspace during restricted-motion experiments.

1) Robot Dynamics: The master and slave robots are two planar revolute-joint manipulators, with identical nonlinear dynamic equations of motion given by [56]

$$\begin{aligned} M_m(\mathbf{q}_m)\ddot{\mathbf{q}}_m + C_m(\mathbf{q}_m, \dot{\mathbf{q}}_m)\dot{\mathbf{q}}_m &= \boldsymbol{\tau}_m + \bar{\boldsymbol{\tau}}_m \\ M_s(\mathbf{q}_s)\ddot{\mathbf{q}}_s + C_s(\mathbf{q}_s, \dot{\mathbf{q}}_s)\dot{\mathbf{q}}_s &= \boldsymbol{\tau}_s + \bar{\boldsymbol{\tau}}_s \end{aligned} \tag{1}$$

where gravitational effects have been neglected due to the system's planar configuration. The 2×1 vectors $\mathbf{q}_i = [q_{1_i}\ q_{2_i}]^T$, $\boldsymbol{\tau}_i = [\tau_{1_i}\ \tau_{2_i}]^T$, and $\bar{\boldsymbol{\tau}}_i = [\bar{\tau}_{1_i}\ \bar{\tau}_{2_i}]^T$ represent the joint angles, external (i.e., human/environmental) torques, and control inputs, respectively, for the master ($i = m$) and slave ($i = s$) robots. The 2×2 matrices $M_i(\mathbf{q}_i)$ and $C_i(\mathbf{q}_i, \dot{\mathbf{q}}_i)$ are the positive-definite inertia, and the centrifugal and Coriolis matrices, which are defined as

$$\begin{aligned} M_i(\mathbf{q}_i) &= \begin{bmatrix} \alpha_i & \beta_i \\ \beta_i & \gamma_i \end{bmatrix} \\ C_i(\mathbf{q}_i, \dot{\mathbf{q}}_i) &= \begin{bmatrix} \delta_i \dot{q}_{2_i} & \delta_i(\dot{q}_{1_i} + \dot{q}_{2_i}) \\ -\delta_i \dot{q}_{1_i} & 0 \end{bmatrix} \end{aligned} \tag{2}$$

where $\alpha_i = (0.834 + 0.150\cos(q_{2_i}))\ \mathrm{kg{\cdot}m^2}$, $\beta_i = (0.111 + 0.075\cos(q_{2_i}))\ \mathrm{kg{\cdot}m^2}$, $\gamma_i = (0.111)\ \mathrm{kg{\cdot}m^2}$, and $\delta_i = (-0.075\ \sin(q_{2_i}))\ \mathrm{kg{\cdot}m^2}$. For more details on the physical description of the manipulators, see [57].

As a remark, it should be mentioned that, for simplicity, reaction forces due to friction have been omitted in (1). However, in [51] and [58], it is shown that the manipulators suffer from bearing friction and its effect must be accounted for. In addition, the human and environmental torques ($\boldsymbol{\tau}_m$ and $\boldsymbol{\tau}_s$) are not directly measured. Instead, the human and environmental efforts are measured at the tip of the end-effectors (where they are actually applied) and are denoted by $\mathbf{f}_h$ and $\mathbf{f}_e$, respectively.

TABLE II
CHARACTERISTICS OF THE COMMUNICATION MODELS

Property		**Communication Model**												
		Time Constant Delay (TC)									**Time-Varying Delay (TV)**			
		TC1	**TC2**	**TC3**	**TC4**	**TC5**	**TC6**	**TC7**	**TC8**	**TC9**	**TV1**	**TV2**	**TV3**	**TV4**
One-way Delay (ms)	Minimum										68	468	48	448
	Mean	**4**	**80**	**480**	**4**	**80**	**480**	**4**	**80**	**480**	**80**	**480**	**80**	**480**
	Maximum										96	496	144	544
Standard Deviation of Delay (ms)		0	0	0	0	0	0	0	0	0	3	3	22	22
Packet Loss Rate (%)		**0**	**0**	**0**	**15**	**15**	**15**	**50**	**50**	**50**	**10-15**	**10-15**	**45-55**	**45-55**

They are related to the human and environmental torques by the Jacobian matrices $[J_i(\mathbf{q}_i)]$ of the system as $\boldsymbol{\tau}_m(t) = J_m^T(\mathbf{q}_m(t))\mathbf{f}_h(t)$ and $\boldsymbol{\tau}_s(t) = J_s^T(\mathbf{q}_s(t))\mathbf{f}_e(t)$ [56].

2) Communication Model: The coupling channel between the manipulators is a stochastic network model. The model is a Markov chain that switches between different transmitting conditions (e.g., delays and losses) enabling the designer to specify the characteristics of the network to be modeled and to simulate very different scenarios.

In this study, nine different constant-time-delay models and four different Internet-like models (i.e., time-varying) were simulated in order to compare the performance of the control schemes. Table II details the stochastic characteristics of each model for the forward (i.e., master to slave) and backward (i.e., slave to master) transmission lines. In each experiment, the forward- and backward-communication channels are simulated independently from each other; hence, at a given time, their characteristics are not necessarily the same.

As validation of the communication channels, it must be argued that Markov-based models have been broadly studied and exploited for network simulation (e.g., see [59] and [60]). Moreover, the characteristics presented in Table II for the time-varying-delay models are comparable with the results reported in [22], where real data from several different Internet connections are surveyed.

3) Transmission Protocol: The communication protocol was based on the User Datagram Protocol (UDP), which is a popular Internet protocol among real-time applications, including teleoperation [61], due to the generation of smaller round-trip time delays when compared with other communication standards. In UDP-based connections, data packets are continuously transmitted from both endpoints (i.e., master and slave) without confirmation of arrival or retransmission of lost packets. This nonconfirmation-based connection allows data to arrive out of order, duplicated, or go missing, thereby requiring an adequate management strategy at the receiving side.

The strategy designed to cope with data losses must preferably preserve passivity, which mainly depends on the information transmitted. Two common strategies are to hold the last sample and to assume a zero-valued packet. It is shown in [15] that, when communicating velocity–force wave variables, assuming a zero-valued packet, when it is missing, preserves the passivity of the communication block, while holding the previous value may not preserve the passivity. Therefore, for the WS and WP frameworks, the zeroing strategy was adopted. This strategy, however, is not well suited when position information is transmitted, which is the case for the PD, WI, and AC algorithms. Assuming a zero-position value may cause substantial jittering on the manipulators, which, in turn, may lead to instability[1] (a proof is omitted). Hence, the hold last sample solution was adopted until a new packet is received. As for the DD scheme, an interpolation strategy embedded on the control framework was applied [17].

Finally, duplicated packets and packets that were not in the right sequential order were considered as data losses.

4) Tuning the Controllers: In Section I, stability and transparency were described as two conflicting design goals. For instance, higher gains commonly contribute to smaller master-to-slave tracking errors and faster trajectory convergence. However, doing so may compromise the stability of the system [41] or increase the stiffness/inertia perceived by the operator [62]. Therefore, a tradeoff between stability and performance had to be experimentally established when tuning the gains and parameters of each controller.

The gains of the controllers were adjusted such that, first, the system was guaranteed to be stable and, second, a similar average impedance was perceived by the operator in free motion (i.e., no environmental forces acting on the slave robot) when implementing any of the six control frameworks. The desired impedance was chosen to be $(Z_1, Z_2) = (13.0\ \mathrm{N{\cdot}m{\cdot}s/rad}, 7.5\ \mathrm{N{\cdot}m{\cdot}s/rad})$ for low one-way delays (i.e, 4 and 80 ms) and $(Z_1, Z_2) = (19.0\ \mathrm{N{\cdot}m{\cdot}s/rad}, 11.5\ \mathrm{N{\cdot}m{\cdot}s/rad})$ for larger delays (i.e., 480 ms), where Z_i correspond to the impedance values for the first ($i = 1$) and second links ($i = 2$). The use of a larger impedance value for the case of 480 ms was in order to allow the tracking error to be satisfactory, even under the presence of long delays.

Due to the dependence of the perceived impedance on the transmission delay [62], three sets of gains were chosen for each controller. The selection was based on the three constant-delayed, lossless communication channels (i.e., TC1, TC2, and TC3 given in Table II) and according to the following procedure.

S1) An initial arbitrary set of gains were assigned to the controllers.

[1]This premise excludes the WI scheme because it employs a reconstruction filter that preserves the passivity of the system independently of the adopted communication strategy.

TABLE III
CONTROL PARAMETERS

Scheme	Parameter	TC1 Link # 1	TC1 Link # 2	TC2 Link # 1	TC2 Link # 2	TC3 Link # 1	TC3 Link # 2
WS[a] DD	$b\ (Nsm)$	2.25	1.35	1.25	0.75	1.0	0.6
	$B\ (Nsm)$	2.25	1.35	1.25	0.75	1.0	0.6
	$K\ (Nm)$	18.0	13.5	10.0	7.5	8.0	6.0
WP[b]	$b\ (Nsm)$	20	40	20	40	20	40
	$B_{pd}\ (Nsm)$	20	40	20	40	20	40
	$K_{pd}\ (Nm)$	30	60	30	60	30	60
	$\alpha\ (1/s)$	5.5	5.5	4	4	1.5	1.5
	$\beta\ (1/Nm)$	7	7	5	5	1	1
	$\gamma\ (1/s)$	0.1	0.1	0.1	0.1	0.2	0.2
	$\delta\ (1/Nm)$	4	4	4	4	4	4
WI[a]	$b\ (Nsm)$	2.25	1.35	1.75	1.05	1.4	0.84
	$B\ (Nsm)$	2.25	1.35	1.75	1.05	1.4	0.84
	$K\ (Nm)$	18.0	13.5	14.0	10.5	11.2	8.4
	$\Delta t\ (ms)$	4	4	4	4	4	4
AC[c]	$b\ (Nsm)$	3.2	2.0	3.2	2.0	3.0	1.9
	$K\ (Nsm)$	3.2	2.0	3.2	2.0	3.0	1.9
	$\lambda\ (1/s)$	0.85	0.85	0.7	0.7	0.65	0.65
	Γ	$0.2I$[d]		$0.2I$		$0.2I$	
PD[e]	$K_p\ (Nm)$	10	8	4.0	2.8	1.8	1.0
	$K_v\ (Nsm)$	1.5	0.5	0.25	0.75	0.25	0.15
	$K_d\ (Nsm)$	0.19	0.15	0.34	0.24	0.87	0.48

[a]Notation, as in [16].
[b]Notation, as in [19] and [63]. The parameters used for the feedback linearization of (1) follow the model in Section III-A1 (for further detail, see [57]). The Kalman filter was constructed via the MATLAB built-in function *kalman*(). Matrices corresponding to the Kalman filter have been omitted.
[c]Notation, as in [52]. System parameters for feedback law follow the model in Section III-A1. Initial conditions for the adaptive law are omitted.
[d]I is the 3 x 3 identity matrix.
[e]Notation, as in [51].

S2) The operator exerted a nearly constant torque between 4 and 20 N·m on the ith link of the master robot in free motion for at least 3 s.

S3) The perceived impedance, which is given by $Z_i = \|\tau_{i_m}/\dot{q}_{i_m}\|$, was computed. If Z_i lied less than $\pm 20\%$ away from the desired impedance value, the process was concluded; otherwise, the gains were readjusted, and steps S2) and S3) were repeated.

This convention to set the gains provided a good initial trade-off between mobility and tracking error. A nearly complete list of the control gains and parameters employed is presented in Table III.

B. Taxonomy of Experiments and Maneuver Task (Trajectory)

The performance of the control frameworks, as discussed in Section II, were compared on a total of 26 experiments, which are listed in Table IV. Each experiment was distinguished by a particular communication model (see Table II) and a maneuver task (free-motion or restricted motion). In addition, the experiments were classified into ten experimental sessions according to the delay type, data-loss rate, and maneuver task. The next section will present more details on these experimental sessions.

As previously mentioned, there were two maneuver tasks: free motion and restricted motion. In free motion, the operator was asked to move the master manipulator over a fixed trajectory and then return it to the original configuration. In restricted motion, the operator was expected to manipulate the master robot until impacting an aluminum wall that is located in the slave's environment, then hold the slave robot against the wall for at least 6 s and, finally, return the master to the original position. The desired trajectories for both experiments are illustrated in Figs. 2 and 3. The left side of the figures illustrates joint motion, while the right side depicts Cartesian (x_i, y_i) motion, which are computed as

$$x_i = l_1 \cos q_{1_i} + l_2 \cos(q_{1_i} + q_{2_i})$$
$$y_i = l_1 \sin q_{1_i} + l_2 \sin(q_{1_i} + q_{2_i}) \qquad (3)$$

where $l_1 = l_2 = 0.30$ m are the length of both links.

TABLE IV
TAXONOMY OF EXPERIMENTS

Free Motion Exp. #	Free Motion Exp. Session	Free Motion Comm. Model	Restricted Motion Exp. #	Restricted Motion Exp. Session	Restricted Motion Comm. Model
1	ES1	TC1	14	ES6	TC1
2		TC2	15		TC2
3		TC3	16		TC3
4	ES2	TC4	17	ES7	TC4
5		TC5	18		TC5
6		TC6	19		TC6
7	ES3	TC7	20	ES8	TC7
8		TC8	21		TC8
9		TC9	22		TC9
10	ES4	TV1	23	ES9	TV1
11		TV2	24		TV2
12	ES5	TV3	25	ES10	TV3
13		TV4	26		TV4

C. Operator: Humans as Research Subjects

Human dynamics and capabilities play an important role in a teleoperation system. In any direct-controlled teleoperation system, the operator shares an energy-port channel with the system over which forces and velocities are exchanged. Hence, the energy exchange between the system and the human is limited by the operator's dynamics. Furthermore, an operator may act as a dissipative environment and mitigate unwanted behaviors, such as wave reflections and overshoot responses.

To regulate the effect of the operator in the comparison study, each experimental session was performed by three different subjects, where each experimental session consisted of two time-varying-delay or three time-constant-delay experiments, as defined in Table IV. At the beginning of a session, the operator was instructed in the use of the manipulators and was given a reasonable time to practice. The participant was then required to manipulate the master robot using a particular controller over a fixed trajectory, as described in Figs. 2 and 3, and was then asked to repeat the same procedure with the remaining five schemes. The order of the controllers and the order of the experiments in each session were varied to avoid biased data due to learning effects. Each participant was requested to repeat the same experiment once. After completing the requested two trials of

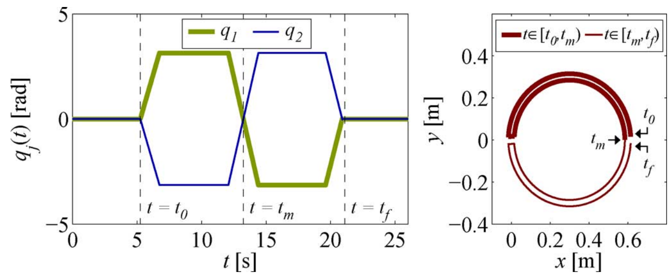

Fig. 2. Desired free-motion trajectory for the master and slave robots. The left and right plots illustrate the desired joint and Cartesian motion for the manipulators, respectively.

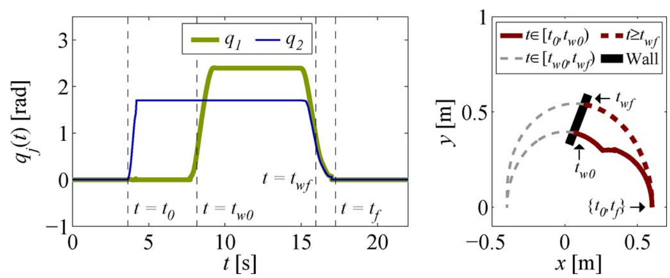

Fig. 3. Desired restricted-motion trajectory. The left plot illustrates the desired motion in the joint space for the manipulators. The right plot depicts the corresponding Cartesian motion. The dashed gray line represents the section of the trajectory that is admissible to the master robot but inadmissible to the slave due to the restriction imposed by the wall (portrayed by the solid black line).

his/her first experiment, the operator was asked to do the same procedure for the remaining experiments in his/her experimental session. For instance, an operator that was initially asked to perform experiment #18, was later requested to repeat the procedure for experiments #17 and #19 corresponding to the experimental session ES7.

In total, 18 individuals (five women and 13 men), who voluntarily participated in this study, were distributed among the ten experimental sessions with no operator participating in more than two sessions. The experimental protocol was reviewed and accepted by the Institutional Review Board of the University of Illinois, and each participant signed an informed consent.

D. Comparison Criteria

Stability and performance constitute the two main criteria in the experimental comparison study. For stability, it is meant that the system must have a human–environment *stable* and safe interaction and achieve an equilibrium state when no forces are applied. By performance, some following concepts are considered:

1) a low tracking error between master and slave in transient and steady-state conditions;
2) a faithful transmission of force information (i.e., the operator should perceive the same net of forces applied to the slave at the remote side);
3) a perceived high stiffness when the slave's motion is restricted.

For comparison purposes, it is easier to fold the criteria in a single measure that properly ranks the performance of the controllers. For the free-motion experiments, the criteria for evaluation must be based on transient and steady-state position errors (recall that all control frameworks were designed such that a similar impedance was transmitted to the operators in unrestricted motion). Therefore, consider the following performance measure Φ, which is defined as

$$\Phi = \left(\sum_{k=t_0}^{t_f} \|\mathbf{e}(k)\|^2 \Delta_T \right)^{1/2} + \|\mathbf{e}(t_f)\| \tag{4}$$

where $\mathbf{e}(k) = \mathbf{q}_m(k) - \mathbf{q}_s(k)$ is the coordination error, t_0 is the time at which the operator starts manipulating the master robot, t_f is the time at which the system reaches a steady state in its final configuration, and $\Delta_T = 0.004$ is the sampling time given in seconds. Note that (4) is the sum of the ℓ_2 norm of the transient and steady-state position errors; hence, a higher valued Φ implies an undesirable performance.

For the restricted-motion experiments, the comparison criteria are based on the steady-state position error, the stiffness perceived by the operator, and the mean force error. Accordingly, consider the following performance measure for contact experiments Ψ, which is defined as

$$\Psi = \frac{\text{MFE} + 1}{\text{MST}} + \|\mathbf{e}(t_f)\| \tag{5}$$

where

$$\text{MFE} = \frac{1}{t_{w_f} - t_{w_0}} \sum_{k=t_{w_0}}^{t_{w_f}} \|\mathbf{f}_h(k) - \mathbf{f}_e(k)\| \Delta_T \tag{6}$$

and

$$\text{MST} = \frac{1}{t_{w_f} - t_{w_0}} \sum_{k=t_{w_0}}^{t_{w_f}} \left\| \frac{\mathbf{f}_h(k)}{\mathbf{e}(k)} \right\| \Delta_T \tag{7}$$

denote the mean absolute force error and mean absolute stiffness values, respectively. The time variable t_{w_0} represents the instant at which the slave robot contacts the wall, while t_{w_f} represents the time at which it retreats from it. The summation with one prevents Ψ from becoming zero when achieving perfect force-matching and steady-state-position convergence, which is independent of the value of MST. Note that, in its domain, Ψ is an increasing function with respect to the absolute force error and absolute steady-state position error, but a decreasing function with respect to the mean absolute stiffness; therefore, a high value is an indicator of a poor performance.

It can be argued that other performance metrics may be formulated; however, (4) and (5) appear to be two natural and well-suited measures.

IV. Experimental Results

In this section, the experimental results for the six controllers are presented. First, the effects of delays and data losses on the evaluation criteria for the free- and restricted-motion experiments are addressed. Then, a comparison between the

TABLE V
GENERAL EFFECTS FOR FREE-MOTION EXPERIMENTS

Factor (f)	Criteria (g)	
	Transient Position Error	Steady-State Position Error
Schemes	Y	Y
Schemes + Delays[a]	Y	Y
Schemes + PL[b]	Y	Y
Schemes + Delays + PL	–	–
Schemes + TV[c]	–	Y
Delay	△	–
PL	△	△
Delay + PL	N	N
TV	△	△

[a]Symbol "+" stand for combine (for iteract) with.
[b]PL stands for packet loses.
[c]TV stands for time-varying delay.

TABLE VI
EFFECTS OF DELAYS AND DATA LOSSES FOR FREE-MOTION EXPERIMENTS

Factor (f)	Transient Position Error (g)					
	WS	WP	DD	WI	AC	PD
Delay	△	△	△	△	△	△
PL	△	N	△	N	N	△
TV	△	△	△	△	–	△
Factor (f)	**Steady-State Position Error (g)**					
	WS	WP	DD	WI	AC	PD
Delay	–	N	–	△	△	△
PL	△	N	△	–	–	N
TV	△	–	△	△	–	–

performance of the six controllers is given, which is based on the performance measures.

A. Effect of Delays and Data Losses

One of the main objectives of this study is to identify the effects of delays and data losses in the performance of the compared controllers. In order to achieve this objective, two common statistical methods, namely, multivariate linear regression and analysis of variance (ANOVA) [64], were applied to the collected data.

Conclusions in the statistical analysis were drawn based on a 99.5% confidence level (equivalent to a p-value of 0.005, and due to the relatively small number of trials per experiment, i.e., (6)). This confidence level means that if an observation had a p-value less or equal to 0.005, the effect was accepted. If in contrast, the observation was over the threshold p-value, it was said that the result had no statistical significance under a 99.5% confidence level, and therefore, no conclusion could be established. In total, there were five possible qualitative outcomes from the statistical analysis, i.e., either

1) g depended (Y) on f;
2) g did not depend (N) on f;
3) g increased proportional (△) to f;
4) g decreased proportional (▽) to f;
5) no conclusion (–) could be established, i.e., $p > 0.005$;

where g corresponds to the dependent variable (e.g., tracking error, stiffness, and force error), and f corresponds to the independent variable (e.g., delay and data losses). For convenience, the set of symbols {Y, N, △, ▽, –} will be utilized to tabulate the results.

1) Free Motion: The general effects of delays and data losses in the transient and steady-state position errors between master and slave for the free-motion experiments are reported in Table V. The statistical analysis indicated that both tracking errors depend on the use of the controllers, i.e., the transient and steady-state errors vary among control schemes. Similarly, the results evidenced that the tracking errors depend on the interaction of the control scheme with the data-loss rate and the mean size of the delay, thereby suggesting that some control frameworks are more affected by unreliabilities of the communication channel than others.

In general, delays were also reported to proportionally increase the transient position error, while data losses seemed to increase both the transient and steady-state position errors. However, there was no significant effect in the tracking error due to the interaction of the delay with the data-loss rate, i.e., the effect of the size of the delay in the position error is independent of the rate of data losses, and *vice versa*. In addition, time-varying-delay experiments were reported to gather larger tracking errors when compared with constant-delay cases.

The effects of delays and data losses were also evaluated for the controllers individually and are summarized in Table VI. As previously reported, the transient position error was found to increase proportional to the mean size of the delay for all schemes. In contrast, the effect of data losses was not common among control frameworks; reporting an increase in the transient position error when implementing the WS, DD, and PD schemes, while having no significant effect for all other controllers. Time-varying-delay experiments, on the other hand, were reported to yield higher transient tracking errors when compared with their counterpart, except when implementing the AC scheme, for which no trend could be concluded.

Concerning the steady-state position error for the free-motion experiments, Table VI suggests a trend for the error to increase proportional to the delay for the WI, AC, and PD schemes. For the WS, WP, and DD architectures, a tendency could not be established, or there was not a statistically significant effect from the delay. Packet losses were found to increase the steady-state position error when employing the WS and DD schemes, while the variance of the delay appears to adversely affect the WS, DD, and WI controllers.

2) Restricted Motion: The effect of delays and data losses was also evaluated for the restricted-motion experiments employing multivariate linear regression and ANOVA. The general results are presented in Table VII. Overall, the statistical analysis indicated that the steady-state position error, mean stiffness value, and mean force error vary among controllers. The results also indicated a decrease in the stiffness perceived by the operator while in contact with the wall due to larger mean delays and a negative effect in the general criteria (excluding the force error) due to higher packet loss rates. However, there does not

TABLE VII
GENERAL EFFECTS FOR RESTRICTED-MOTION EXPERIMENTS

Factor (f)	**Criteria** (g)		
	Steady-State Error	**Mean Stiffness**	**Mean Force Error**
Schemes	Y	Y	Y
Schemes + Delays	–	Y	–
Schemes + PL	Y	Y	–
Schemes + Delays + PL	–	Y	–
Schemes + TV	–	Y	–
Delay	–	▽	–
PL	△	▽	▽
Delay + PL	N	Y	N
TV	–	▽	△

TABLE VIII
EFFECTS OF DELAYS AND DATA LOSSES FOR RESTRICTED-MOTION EXPERIMENTS

Factor (f)	**Steady-State Position Error** (g)					
	WS	**WP**	**DD**	**WI**	**AC**	**PD**
Delay	–	–	–	△	N	△
PL	△	N	△	△	▽	–
TV	–	–	△	△	△	–
Factor (f)	**Perceived Stiffness** (g)					
	WS	**WP**	**DD**	**WI**	**AC**	**PD**
Delay	▽	▽	▽	▽	–	▽
PL	▽	–	▽	–	–	▽
Delay + PL	Y	N	–	N	N	N
TV	▽	▽	▽	▽	–	▽
Factor (f)	**Mean Force Error** (g)					
	WS	**WP**	**DD**	**WI**	**AC**	**PD**
Delay	–	–	–	–	–	–
PL	–	–	–	▽	▽	▽
TV	–	–	–	△	–	–

appear to be a significant effect in the criteria due to the interaction between delays and packet losses save for the stiffness values. As for the effect of variations of the delay, the statistical analysis suggested an adverse impact in the average stiffness (decrease) and in the mean force error (increase).

The independent effects of delays in each control scheme are summarized in Table VIII. It was found that the magnitude of the delay increases the convergence error for the WI and PD controllers, whereas for all other control frameworks, it has either no effect or an inconclusive trend. Likewise, the variance of the delay was observed to increase the steady-state position error when employing the DD, WI, and AC controllers, while for all other frameworks, a specific effect could not be established.

The effects in the steady-state position error during restricted-motion experiments due to data losses are also reported in Table VIII. Packet losses appear to affect the WS, DD, and WI controllers negatively, while having either an inconclusive or an insubstantial effect in the PD and WP schemes. The results also evidenced a reduction in the steady-state error for the AC controller. An explanation for this singular behavior is attempted in the next section.

From Table VII, it is evident that the stiffness perceived by the operators is the most sensitive criterion. Table VIII suggests that higher delays as well as higher fluctuations (i.e., variance) decrease the mean stiffness perceived by the operator for all control schemes with the exclusion of the AC scheme for which the results were inconclusive. Similarly, losses in the communication channel were found to decrease stiffness values for the WS, DD, and PD controllers.

As for the mean force error, statistical trends of behavior were mostly inconclusive, as indicated in Table VIII. Yet, time-varying delays appear to increase the force error for the WI controller, while packet losses appear to reduce the force error for the PD, WI, and AC schemes. The last result will be addressed later in Section V.

B. Performance Measures

The performance of the controllers under different delays and data losses was subject to comparison using the performance measures formerly defined in Section III-D. At this point, the reader should recall that lower Φ and Ψ values are indications of satisfactory performances.

1) Free-Motion Performance Measure (Φ): Fig. 4 illustrates the average free-motion performance measure Φ for each control framework under time-constant-delayed communication lines. In general, the results suggest a common trend in Φ to increase proportional to the delay. Yet, its impact widely varied among control architectures. For instance, under no data losses, a change on the one-directional delay from 4 to 480 ms generated a 36%[2] (i.e., 1.21 rad) increase in Φ for the AC framework,[3] while the same change in the delay produced a 1380% (i.e., 7.66 rad) increase when employing the PD control. Data losses, on the other hand, were found to affect the WS, DD, and PD controllers the most, with increments of 2580%[4] (7.40 rad), 710% (1.99 rad), and 154% (0.85 rad), respectively, when data-loss rates rose from 0% to 50%. No evident effect for the WP and WI schemes was obtained and a linear trend for the AC framework could not be established. Yet, the AC framework showed an increase of nearly 9% in Φ when data-loss rates were set to 15% in comparison with the 0% and 50% rates. Overall, the lowest Φ measurements were achieved with the DD framework for the lossless case, and with the WI and WP schemes once data losses were introduced.

Average free-motion performance measures for time-varying-delayed channels are presented in Fig. 5. Similar overall results to the time-constant-delay case were attained: Average Φ values were found to be proportional to the size of the delay, and data losses incremented the average measurements when using the WS and DD algorithms. However, it can be observed that time-varying-delay results tended to be higher in magnitude for the

[2]Percentage of Increase due to the delay is given by $(\Phi(480\text{ ms}, 0\%) - \Phi(4\text{ ms}, 0\%))/\Phi(4\text{ ms}, 0\%) \times 100\%$.

[3]It should be mentioned that AC's values were relatively large when compared with most controllers.

[4]Percentage of Increase due to data losses is given by $(\Phi(4\text{ ms}, 50\%) - \Phi(4\text{ ms}, 0\%))/\Phi(4\text{ ms}, 0\%) \times 100\%$.

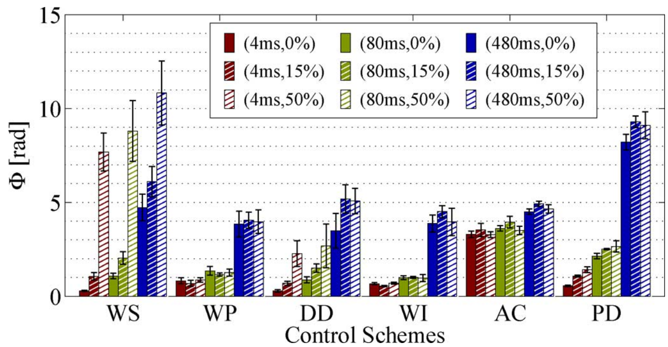

Fig. 4. Average free-motion-performance measure Φ for time-constant-delay experiments. The legend on the plot indicates one-way delay values followed by data-loss rates. The vertical lines above bars represent ± 1 standard deviation from the average Φ.

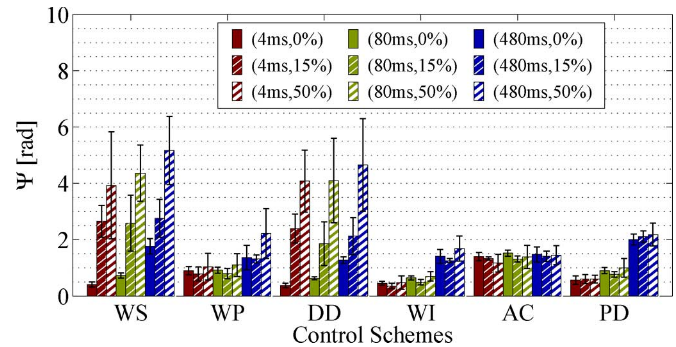

Fig. 6. Average restricted-motion performance measure Ψ for time-constant-delay experiments. The legend on the plot indicates one-way delay values followed by data-loss rates. The vertical lines above bars represent ± 1 standard deviation from the average Ψ.

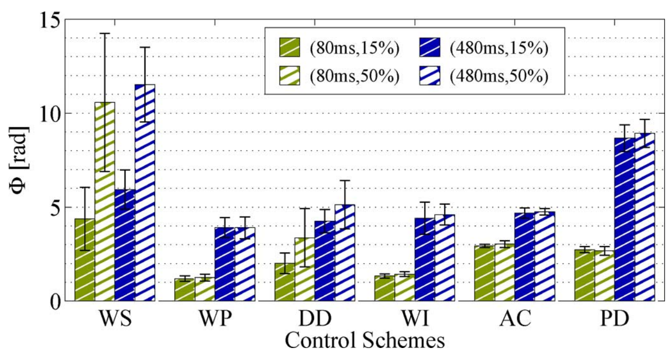

Fig. 5. Average free-motion performance measure Φ for time-varying-delay experiments.

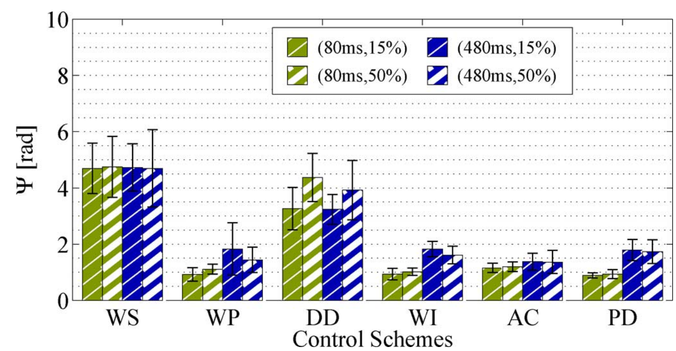

Fig. 7. Average restricted-motion performance measure Ψ for time-varying-delay experiments.

WS and, to some extent, the WI frameworks when compared with constant-delay cases. For all other controllers, either there was not a significant difference, or a trend could not be identified. Overall, the WP framework showed the best performance (i.e., $\Phi(80\text{ ms}, 15\%) = 1.19$ rad, $\Phi(80\text{ ms}, 50\%) = 1.25$ rad, $\Phi(480\text{ ms}, 15\%) = 3.91$ rad, and $\Phi(480\text{ ms}, 50\%) = 3.90$ rad) followed by the WI scheme (i.e., 1.33, 1.43, 4.41, and 4.60 rad). The least satisfactory performance accounting for most time-varying-delay scenarios was obtained when implementing the WS framework (i.e., 4.37, 10.57, 5.9, and 11.51 rad).

In addition, it is worth mentioning that higher delays and data-loss rates were found to generate larger variations in Φ values as indicated by the vertical lines on the plots, which represent ± 1 standard deviation from the mean values.

2) Restricted-Motion Performance Measure (Ψ): Similar to free-motion experiments, an average performance measure Ψ was computed for the six controllers when executing the restricted-motion trajectory. Fig. 6 depicts the average Ψ values for the case of constant communication delays. Note that Ψ showed a tendency to increase proportional to the delay. However, the increase in Ψ was not equal among controllers. For instance, the AC scheme was robust to increments in the delay by reporting a small gain of 5.6%[5] (0.078 rad) in the mean Ψ values when evaluating the lossless case, while the WS and PD controllers documented larger increments of 335% (1.35 rad) and 252% (1.43 rad), respectively. Data losses, on the other hand, were found to increase the average Ψ values when using the DD (993%,[6] 3.71 rad) and WS (868%, 3.52 rad) controllers. For the WP, WI, and PD frameworks, either there is a negligible effect, or a trend could not be supported. In the case of the AC scheme, a small reduction in Ψ values due to data losses was obtained. This coincides with the results reported in Table VIII, where the steady-state position error for the AC framework was found to decrease proportional to the rate of data losses. For the lossless case, the DD scheme reported the lowest Ψ values, while for all other scenarios, the best responses were attained, in general, with the WI scheme. In lossy communication channels, the highest average Ψ were obtained with the WS and DD controllers.

The average restricted-motion performance measures for time-varying-delayed communication channels are presented in Fig. 7. Similar to the time-constant-delay experiments, Ψ was reported to increase proportional to the size of the delay for all controllers, except for the WS scheme for which Ψ values remained nearly constant. Increments of Ψ due to data losses were clearly seen when implementing the DD scheme. For all other frameworks, no trend or effect can be established. Overall, the best restricted-motion performances under

[5]Percentage of Increase due to the delay is given by $(\Psi(480\text{ ms}, 0\%) - \Psi(4\text{ ms}, 0\%))/\Psi(4\text{ ms}, 0\%) \times 100\%$.

[6]Percentage of Increase due to data losses is given by $(\Psi(4\text{ ms}, 50\%) - \Psi(4\text{ ms}, 0\%))/\Psi(4\text{ ms}, 0\%) \times 100\%$.

time-varying-delay conditions were attained when employing the WP ($\Psi(80 \text{ ms}, 15\%) = 0.93$ rad, $\Psi(80 \text{ ms}, 50\%) = 1.11$ rad, $\Psi(480 \text{ ms}, 15\%) = 1.82$ rad, $\Psi(480 \text{ ms}, 50\%) = 1.44$ rad), WI (0.94, 1.02, 1.82, and 1.61 rad), AC (1.15, 1.20, 1.37, and 1.36 rad), and PD (0.89, 0.93, 1.79, and 1.73 rad) algorithms.

V. Discussion

A. Stability

As previously mentioned in Section II, stability for the teleoperation system with time-varying transmission delays is not guaranteed when employing the AC and PD controllers. Yet, the teleoperator under both controllers proved experimentally to remain stable for all tested communication scenarios.

The AC and PD controllers were designed under passivity constraints, which frequently yield conservative conditions for stability. In fact, a nonpassive system may still be stable, since even though passivity implies stability, the reverse is not always true. Moreover, in order for the closed-loop teleoperation system in (1) to be passive, it has to satisfy the following passivity condition:

$$E_{\text{in}} \geq E_{\text{out}} - E_d \tag{8}$$

where $E_{\text{in,out},d}$ are the input, output, and dissipated energy in the system, respectively. The dissipated energy E_d depends on the dynamics of the systems, which, more than often, is uncertain, and therefore, it is omitted, in practice. Such omission renders (8) into $E_{\text{in}} \geq E_{\text{out}}$, which is a stronger sufficient condition for stability. In the case of the manipulators employed in the experiments, the dissipated energy due to Coulomb and viscous frictions was ignored. If considered, it might have allowed the AC and PD schemes to afford some variance in the transmission delay while guaranteeing passivity.

B. Effect of Delays

Aside from stability, the effect of delays in the performance criteria was evaluated. It was found that large delays in the transmission lines will increase the transient position error independently of the controller. Naturally, a time delay in the transmitted signal means that at a certain time t_*, one of the manipulators has no knowledge of the current information (e.g., force, position, velocity, etc.) regarding the opposite manipulator until an interval of time equal to the delay T_d has elapsed. Consequently, the manipulator's controller will not react until $t \geq t_* + T_d$, which is the time at which the states of the opposite manipulator, such as position, might have diverged substantially from the previous values at t_*. Larger tracking position errors due to the delay would be mostly observed in the transient response, since for finite-delayed communication channels, the error should eventually converge to zero once the system reaches a rest (i.e., $\dot{\mathbf{q}}_i = 0$, $\mathbf{q}_i(t) = \mathbf{q}_i(t - T_d)$, and $\boldsymbol{\tau}_i = 0$). Despite this reasoning, Table VI shows that the delay indeed affected the steady-state position error for the WI, AC, and PD controllers, even though the three schemes provide explicit position compensation. This result can be attributed to the general use of lower control gains required to keep a desired low impedance during free motion when transmission delays are large in magnitude. Since the teleoperation system suffered from friction, lower gains could have been insufficient to compensate for static friction and guarantee, accordingly, position convergence.

In addition to the effects in the position error, large delays were reported to lower the transmitted stiffness to the operator when the slave was in contact with the environment. As discussed previously, higher delays tend to increase the position error between master and slave. Therefore, by definition of the mean absolute stiffness (7), the result that it is inversely proportional to the position error and, hence, inversely proportional to the delay, should become evident.

C. Effect of Data Losses

Packet losses in the communication channel were found to affect almost exclusively the WS, DD, and to some extent, the PD algorithms in every criterion. However, from Figs. 4 and 6, it can be noted that the effect of data losses is more substantial for the WS and DD schemes than for the PD algorithm. This conclusion is in agreement with Section II, since the WS and DD controllers do not provide explicit position-feedback information, and the WS scheme does not compensate for data losses.

On a side note, in Table VIII, it is reported that data losses decreased the steady-state position error for the AC control framework. The singularity of this positive result in the presence of data losses should be carefully considered since, at the extreme case in which all packets are dropped, the position of the master and slave should arbitrarily diverge. The observed trend may partially respond to a favorable effect from the hold-last-sample strategy employed whenever a packet was missing. As the system approaches steady state, the signals $(\ddot{\mathbf{q}}_i, \dot{\mathbf{q}}_i, \boldsymbol{\tau}_i) \rightarrow 0$ and, therefore (by definition [52]), the wave variables also converge to zero. Therefore, every previous sample of the wave variable should be, in general, higher in magnitude than the next. Holding the last sample may then result in a larger ephemeral control input to the system of what it actually should be, potentially forcing (*pushing*) the position of the teleoperators slightly closer to zero by overruling the system's static force friction.[7]

Similarly, in Table VIII, it is reported that data losses tend to decrease the mean force error for the WI, AC, and PD controllers. This statement should not be interpreted as a positive consequence of packet losses in the communication channel. For example, in the case where the master and slave are disconnected (i.e., a packet loss rate of 100%), there would be, of course, no exchange of force and position information and, therefore, no

[7]Although the hold-last-sample strategy was adopted for the WI and PD schemes, these frameworks do not necessarily suffer from the same effect. The WI scheme employs an energy-based reconstruction filter that preserves the passivity of the communication channel by choking its output according to the net energy flow. This means that the output of the filter may not be the previous sample but a reconstructed wave output that satisfies the passivity condition. As for the PD scheme, it transmits explicit position and velocity information that do not necessarily translate to the same interpretation of push-and-pull commands as in wave-based approaches (see [16]).

sense of telepresence. In addition, force-magnitude measurements were observed to be generally lower under the presence of packet losses, which means that low-magnitude values for the force error can be expected.

D. Time-Varying Delays

The last communication-based phenomenon to be evaluated in this study is the effect of time-varying delays on the performance of the system. The statistical analysis of the previous section suggested a negative impact from time-varying delays to virtually all criteria and controllers. Yet, when inspecting Figs. 4–7, the most notably affected algorithm was arguably the WS approach. In this study, the WS approach is the only technique that provides neither compensation for time-varying delays nor position convergence. The results also evidence robustness from all other controllers to the variance of the delay.

E. Overall Performance

Overall, to determine which controller provides the best performance is a difficult task, since the results greatly varied among experiments. For instance, when there are no losses on the communication channel, the best performance for free and contact motion is achieved with the DD scheme, followed closely by the WS (when delays are small), WI, and WP techniques. Once data losses are introduced, the error for the DD and WS schemes increases, and the lowest Φ and Ψ values are obtained with the WP and WI control frameworks. Therefore, choosing the optimal control will require knowledge of the operational conditions, such as the data-loss rate and task.

VI. Measure of Complexity

Apart from stability and performance criteria, control engineers are concerned about implementation, sensitivity, and optimality. How easy is the control scheme to design and implement? How is the system affected by changes, and uncertainties on the robot dynamics, task, or workspace? Is it efficient, or can something simpler accomplish the same task? An approach to partly answer these questions is to measure the complexity of the control schemes. Intuitively, a simple control scheme should be easy to implement, be efficient, and be compact.

To measure the complexity of a system is a quite ambitious topic. In the literature, there are many different approaches to define and categorize a complex system (for examples, see [65] and [66]). Yet, a major consensus is that *complexity* must involve the size, organization, and behavior of the system. In this section, an attempt to measure the complexity of the teleoperation frameworks is given, which is based on structural and computational complexity. It is argued that the combination of both measures appeals to the most common and general understanding of complexity.

A. Static Complexity

Static (or structural) complexity refers to how well the components of a system are connected [67]. Analyzing the connectivity patterns and understanding the information-passing topology inside a code can provide information about efficiency, adaptability, and optimality of the design [68]. In this paper, a systematic method based on polyhedral dynamics is used to evaluate the structural complexity of the control frameworks. Polyhedral dynamics, which is also known as Q-analysis, is an approach based on algebraic topology for studying the inherent structure of a system and the relationship of its components. It was originally developed as a mechanism to analyze the structural characteristic of social systems [68], however, has expanded to other research fields, such as ecology [69], transportation [70], geography [71], communications [72], and project management [73]. Since a concise and excellent description of the Q-analysis can be found in [67], [71], and [74], a discussion of the method will be omitted. For further reading, see [75], where a detailed example using one of the compared controllers is presented.

B. Computational Complexity

Besides the structural organization of a system, another source of complexity that control engineers need to consider in the design is the amount of time and memory storage demanded by the system to execute the particular control algorithm (i.e., computational load). For instance, a teleoperator may be required to be small, power-saving, light, or just inexpensive. These limitations usually imply smaller processors and faster computations. Hence the need for simpler, shorter, and faster control frameworks.

Computational complexity refers to the time and size required by a computer to execute a particular algorithm [76]. Traditionally, the runtime cost and memory size of an algorithm are estimated by counting its total number of operations and instructions [77]. Therefore, the time and memory space demanded by the control framework can be rudimentarily estimated by measuring the code length of the control architecture.

When evaluating the computational complexity of the teleoperation control schemes, it is assumed that the control algorithms are irreducible in size. In addition, the measures are normalized by the shortest code such that the simplest algorithm has a unitary value. This rudimentary measure satisfies the fundamental axioms of complexity, which are defined by Casti [67]. For more details on this, see [75].

C. Results on Complexity

The results of the structural (i.e., static) complexity measure are illustrated in Fig. 8. The simplest control scheme was found to be the PD controller, followed by the WS scheme. The control technique with the highest level of structural complexity was found to be the WP scheme. The results seem to agree with the fact that both PD and WS frameworks consist of the exclusive interconnection of their controllers with the communication channel and the manipulators. In contrast, the WP framework employs a relatively large number of additional components (e.g., energy filters, estimators, predictor, etc.) that create a larger interactional network.

As for the computational complexity measure, the results were normalized by the code length of the WS scheme and

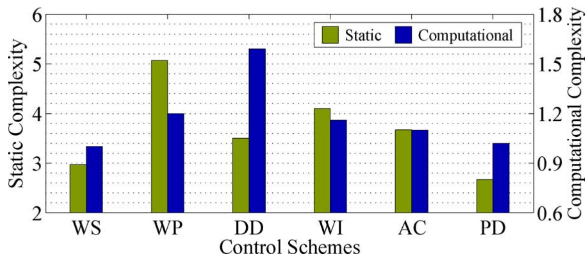

Fig. 8. Complexity results.

are plotted in Fig. 8. The WS scheme had the lowest number of instructions, and therefore, it was used as the shortest code (i.e., unitary value). The results follow a similar trends as for structural complexity, thereby showing that the PD and WS algorithms are the simplest, while the DD and WP have the largest computational load. Once again, the results reflect the fact that the WS and PD controllers require fewer computations when contrasted with either the DD or WP schemes.

VII. Conclusion and Final Remarks

A. Conclusions

In this study, six motion–force controllers for bilateral teleoperators were compared based on stability, tracking error, transparency, and complexity for different delays, data losses, and environmental constraints. The following is a summary of the most relevant results and remarks obtained from the evaluation.

1) *Stability*: The six controllers under evaluation were experimentally found to be stable for the constant- and time-varying-delay experiments, which are characterized in Section III. This demonstrates robustness to variations in the delay and data losses for all controllers, even for those that do not explicitly enforce time-varying-delay stability, i.e., PD and AC controllers.
2) *Effect of delays*: Larger delays were reported to adversely affect the transient error and the transmission of contact information for all controllers. In fact, a proportional increase in the transient position error and a weaker perception of contact surfaces (i.e., stiffness values) were reported with an increase in the delay.
3) *Time variance of the delay*: Time-varying delays were found to increase the tracking error, to decrease the stiffness perceived by the operator during contact, and to increase the force error for nearly all controllers when contrasted with the constant case. Yet, the impact of delay variations was almost negligible for most controllers, except for the WS architecture, for which the performance was notably worse.
4) *Effect of data losses*: Data losses were reported to mainly affect negatively the WS and DD schemes in all criteria. For all other controllers, the effect of data losses was less critical (if any) than the effect of delays.
5) *Interaction of data losses with delays*: The study showed no significant effect on the evaluation criteria due to the interaction between data losses and delays. The negative effects in the tracking position error and the transmitted contact information due to data losses and delays seem to be decoupled.
6) *Overall performance*: The best performance was achieved with the WI scheme, followed by the WP control framework. For lossless and low-delayed communication channels, the DD and WS architectures exhibited the best results on the basis of tracking error, stiffness, and force error. However, as data losses are introduced, the response of both controllers gradually deteriorates. In fact, for data losses, the WS framework was reported to have the least satisfactory performance.
7) *Complexity*: The WS and PD controllers are the simplest algorithms in terms of structural and computational complexity. The most complex schemes were the WP and DD frameworks.
8) *Other considerations*: The study demonstrated that the preference for a particular control algorithm mostly depends on the information available about the communication channel (e.g., delays and losses), the remote environment (e.g., rigid surface or free motion), the robot dynamics (e.g., inertia, physical dimensions, and nonlinearities), and the hardware and software limitations on the design (e.g., sensors, computational speed, weight, among others). For instance, the DD and WS controllers outperformed most controllers for low-delayed and lossless transmission lines but suffered from large tracking errors and low stiffness values when data losses were present. Likewise, the WI and WP schemes showed the best responses under data losses and high delays, but their computational requirements are higher than those of the PD and WS controllers. Therefore, the selection of a control architecture will depend on the information that is available to the designer, the task to be executed, and the level of performance and complexity that may be demanded.

B. Further Research

There are many research extensions to this comparison study. Among them, an immediate extension would be to evaluate the performance and preference of the operator under different controllers and communication conditions. How satisfactorily (on the basis of task completion time and performance errors) does the operator accomplish the planned trajectory or task? What are the effects of delays and data losses on the environmental perception from the operator's opinion? Which controller does the operator prefer?

Finally, another significant extension to this study would be to evaluate the performance of the controllers when interacting with different remote environments (i.e., surfaces with different stiffness). Can the operator discern between different material compliances? How do delays and data losses affect the operator's ability to identify different materials? These are some fundamental questions that can potentially lead to more comprehensive design guidelines.

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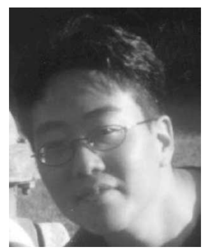

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