Proceedings of IMECE'03
2003 ASME International Mechanical Engineering Congress
Washington, D.C., November 15–21, 2003

IMECE2003-43266

CURRENT CHALLENGES IN THE CONTROL OF HAPTIC INTERFACES AND BILATERAL TELEOPERATION SYSTEMS

John E. Speich

Mechanical Engineering
Virginia Commonwealth University
Richmond, VA 23284

Marcia K. O'Malley

Mechanical Engineering and Materials Science
Rice University
Houston, TX 77251

ABSTRACT

This paper presents a survey of current research focused on the control of haptic interfaces and bilateral teleoperation systems. Time delay is a significant control issue, along with the closely related topic of control via the Internet. Of key concern is the assurance of stability in the presence of constant or variable time delay. The transparency of bilateral systems, or the extent to which they accurately represent the feel of the environment to the operator, is another important control concern. The stability and transparency of haptic interface systems is also a significant research area. This paper presents a survey of the current state-of-the-art with regard to control in haptics and bilateral teleoperation.

1 INTRODUCTION

The objective of this paper is to summarize some of the recent advances in the control of bilateral telemanipulation systems and haptic interfaces. Since much of the latest work in haptics and teleoperation has not been presented at recent ASME IMECE conferences, the authors thought it would be beneficial to present this summary. This paper is primarily for engineers whose focus has not been in haptics or bilateral teleoperation. This paper provides a concise review of recent work in these areas.

A teleoperation system allows a human operator to interact with an environment without direct physical contact with the environment using a master-slave pair of manipulators. A teleoperation system is a bilateral system if it transmits the feel of the environment back to the human operator. Ideally, a bilateral telemanipulation system would transmit an undistorted, although possibly scaled, version of the environment to the human operator in a robustly stable manner. This paper provides a summary of some of the recent work in the development of control architectures for bilateral teleoperation systems.

Similarly, a haptic interaction system allows a human operator to interact with a virtual environment via force feedback that is computer controlled and sometimes displayed with other sensory modalities including visual and auditory feedback. Haptic systems are bimodal, measuring user motion (or force) input and displaying the corresponding force (or motion) feedback depending on the environment that is being displayed. The impedance model takes user motion and calculates the resultant force, while the admittance model of haptic interaction measures user force and displays the corresponding position. This paper provides a summary of some of the recent work in the development of control architectures for haptic systems.

2 CONTROL OF BILATERAL TELELOPERATION SYSTEMS

2.1 Bilateral Teleoperation Control Architectures

Various control architectures for bilateral telemanipulation systems have been developed to date. Some of the major distinctions between these architectures are the number and types of communication channels between the master and the slave, the types of local controllers used on the master and slave, and the manner in which the architecture addresses the stability and performance of the system.

Bilateral Control Architecture Design Goals

A bilateral control architecture should be designed such that the human-teleoperator-environment loop remains robustly stable, even when subjected to significant perturbations in the environment or human dynamics. The control architecture should also provide the desired quality of performance when transmitting the "feel" of the environment to the human operator. Ideally, the bilateral teleoperation system would completely preserve the feel of the environment with which the human operator interacts. In reality, however, the system cannot completely preserve this information. Instead, the system will filter and thus alter the perceived dynamic characteristics of the environment. The extent to which the manipulator system preserves the feel of the environment is characterized by the "transparency" of the system. A bilateral teleoperation system is perfectly transparent if it perfectly preserves the impedance, and thus the feel of an environment. Performance (transparency) and stability robustness are two primary considerations when selecting a bilateral teleoperation control system.

Two, Three and Four-Channel Architectures

The number of communication channels between the master and slave manipulators is often used to classify bilateral control architectures. A number of two, three and four-channel architectures have been developed and compared in recent years.

Hannaford [1] assessed the performance of both a two-channel and a four-channel bilateral control architecture. In his "forward flow" architecture, the velocity imposed by the operator is fed forward from the master as input to the velocity-controlled slave, and the force experienced by the slave is fed back as input to the force-controlled master. This is in essence a two-channel control architecture, since only two channels of information (i.e., master velocity and slave force) are exchanged between the master and slave systems. Hannaford's "bilateral impedance" architecture feeds both the force and velocity of the operator forward to the slave and similarly feeds both the force and velocity of the environment back to the master. The master force and velocity are utilized to estimate the impedance of the human, and these variables are then used as the commanded impedance into the slave impedance controller. Similarly, the slave force and velocity are utilized to estimate the environment impedance, which is used as input to the master impedance controller. The bilateral impedance control structure is essentially a four-channel control architecture, since four channels of physical information (i.e., master and slave forces and velocities) are exchanged between the two manipulators.

Hannaford [1] used two-port network modeling techniques to characterize the transparency of the forward flow and bilateral impedance architectures. He defined ideal teleoperator performance (i.e., transparency) in terms of the two-port hybrid parameter matrix and utilized this framework to show that both the forward flow and bilateral impedance architectures depart from ideal performance only to the extent that the dynamics of the manipulators are not canceled by feedback control. Anderson and Spong [2] introduced the use of a four-channel architecture to guarantee the passivity (stability) of the communication link between two manipulators in the presence of time delay, but they did not specifically address the issue of transparency.

Lawrence [3] incorporated a network model approach similar to Hannaford's to assess both the performance and the stability characteristics of a four-channel architecture. The four-channel control architecture proposed by Lawrence provides perfect transparency in the absence of uncertainty and noise, but requires the measurement of accelerations. Lawrence utilized the two-port hybrid parameter matrix to show that, given his architecture, teleoperative transparency cannot be obtained without the use of all four information channels. Lawrence continued his analysis by incorporating passivity concepts to derive expressions for filters that, when incorporated into his architecture, enhance the stability of the human-teleoperator-environment loop. Lawrence further demonstrated by example that transparency and robust stability (passivity) are conflicting design goals in this architecture. Hashtrudi-Zaad and Salcudean [4] subsequently modified the architecture presented by Lawrence with local force feedback. The modification enables the same degree of transparency with three communication channels rather than four.

Loop-Shaping Techniques

Fite, Goldfarb and Speich [5-7] developed a modified two-channel position-force architecture that can enable a simultaneous increase in the transparency and stability robustness of a teleoperation system. This bilateral architecture was developed from a frequency-domain loop-shaping perspective instead of from the hybrid two-port network-based perspective. This change in perspective enables the use of classical compensation techniques to provide transparency in the bandwidth of interest while maintaining the gain and phase margins necessary for robust stability. Compensation can be provided at specific frequencies, which allows simultaneous improvements in the transparency and stability robustness. This approach offers an alternative to the more conservative passivity approach, in which some degree of stability robustness (passivity) is traded for improved transparency. This architecture has been implemented on a 3-DOF scaled master-slave telemanipulation system [7]. The experimental results demonstrate that significant transparency improvements could be achieved using this technique without decreasing the stability robustness of the system. This work is currently being extended to multivariable controller design.

Flemmer *et al.* [8] also used loop-shaping techniques to design a control architecture for teleoperation for surgical applications. They demonstrated the stability of a three-channel architecture that handles parameter uncertainty within a local master control loop. They also compared a two-channel and a three-channel control architecture for the case when the teleoperation system is in contact with a stiff environment. In these experiments, the two-channel controller was unstable, while the three-channel controller was stable.

Hirche and Buss [9] proposed a new method for impedance matching filter design by optimization in the frequency domain to achieve passivity of the teleoperator/environment and transparency of position-force controlled telepresence systems. Numerical, simulation, and experimental results showed that the proposed approach improves performance with respect to stability, tracking, and transparency.

Hybrid Position/Force Control
Another important aspect of the control of bilateral teleoperation systems is the use of hybrid position/force control. It is sometimes used in applications in which the slave frequently switches between unconstrained motion and contact with a stiff environment. Yamano *et al.* [10] explored a bilateral control algorithm that switches between position and force control. They provided force-feedback using an elastic element and a mechanical clutch instead of the typical electric motor. Ni and Wang [11] used position error rather than force data for cost effective bilateral teleoperation. However, this position-position architecture provided poor transparency with fixed PD controllers. Therefore, they introduced a gain-switching control scheme based on the detection of the impedance change at the slave site. Their experimental results verified that transparency was improved based on observation of position responses and verbal comments from the human operators. Ni and Wang [12] also examined the issue of chattering when a position-controlled bilateral telemanipulation system contacts a stiff environment. They found conditions for selecting gains that maintain stability in this situation. Future work may consider time delay.

Force Assistance
Kim and Hamel [13] also explored strategies to improve the performance of a telemanipulation system as it comes into contact with an object in its environment. They developed a force-assistance function that modifies the operator's commands using a set of fuzzy rules to reduce contact force and improve surface tracking ability. Pernalete *et al.* [14] used a force assistance function to control a teleoperation system for assisting persons with disabilities.

Passivity
As previously discussed, passivity techniques can be used to examine the stability robustness of teleoperation systems. Ryu *et al.* [15] implemented a "Passivity Observer" and a "Passivity Controller" within a two-port control architecture for a bilateral teleoperation system. The controller maintained stability by sacrificing performance, but only in the amount necessary to guarantee stability. Ryu *et al.* demonstrated the effectiveness of this architecture during hard wall contact with a 2-DOF teleoperation system. Future work may include adapting the "Passivity Controller" for use in systems with communication time-delay. In other work, Park *et al.* [16] used the passivity-based approach and added specific constraints for micro-teleoperation.

Lee and Li [17, 18] developed a passivity-based control architecture for nonlinear bilateral telemanipulation systems. They achieved coordination between the manipulators with feed forward cancellation using fictitious energy storage while maintaining the energetic passivity of the system [19]. Their experimental results showed that the passive control implementation structure ensures energetic passivity of the closed-loop teleoperator robustly, regardless of the accuracy of force sensing and model uncertainties. The structure limited the amount of energy generated by the controller even in the presence of severely corrupted force sensing (delays of 35 and 350 msec).

Bilateral Teleoperation under Rate Mode
Salcudean *et al.* [20] investigated the issue of transparency for a four-channel architecture under position and rate control. Transparent teleoperation under rate mode has proven to be difficult to achieve in terms of stability, performance, and implementation. This is mainly due to the need for the exchange of the derivatives and the integrals of measured positions and forces. Hashtrudi-Zaad *et al.* [21] proposed a number of control architectures based on the use of local force feedback and environment impedance reflection. While they were not able to recommend a unique control architecture for all different operational conditions, in the case of negligible delays, any one of their architectures can be used, when operating at low frequencies.

2.2 Time Delay and Bilateral Teleoperation via the Internet

The presence of communication time delay is a major challenge in the control of some bilateral teleoperation systems. Anderson and Spong [2] introduced the use of a four-channel architecture to guarantee the passivity of the communication link between two manipulators in the presence of time delay. Lozano *et al.* [22] used the scattering formalism of Anderson and Spong, which preserves passivity of the communication channel for constant delay. They demonstrated the loss of passivity in the case of time-varying transmission delay. They also showed that a suitable time-varying gain inserted in the transmission path can recover passivity provided that a bound on the rate of change of delay is known. Tracking performance can be further improved through the use of a velocity saturation command received at the slave side, within the limits of the master velocity.

Wave Variables
Niemeyer and Slotine [23] used a wave variable approach to time-delayed bilateral teleoperation. Later they added wave variable filters to the existing wave variable architecture [24]. This work showed that stability can be preserved through the systematic use of specially designed wave-variable reconstruction filters. Munir and Book [25, 26] also incorporated wave variables in the control of teleoperation. They addressed the serious issue of performance degradation during variable time delay by incorporating a Smith-type wave predictor, a Kalman filter, and an energy regulator. Their experimental results verified that stability is maintained even in the presence of large model uncertainties.

Yokokohji *et al.* [27] also used wave variables; but introduced an energy input/output balance monitoring mechanism that limits the energy that the system can generate. Simulations with a 1-DOF system were performed to validate the approach under a limited set of time delay conditions. They experimentally implemented the wave variable approach with energy input/output balance monitoring and proposed a method for dealing with communication blackout on a LAN (local area network) [28]. The approach was to recharge the energy margin and correct the position error that had grown during the communication blackout. In the future, this work may be extended to a WAN (wide area network) and the Internet.

Model-Based Teleoperation

Several researchers have developed model-based architectures for time-delayed teleoperation. These control architectures use feedback generated from a virtual environment, ideally matched to the remote environment, for force-reflection rather than feeding back data directly from the remote environment. Bejczy *et al.* [29] used a predictive graphics display overlay on the camera view of a remote site to improve operator performance in a tapping task. This work did not use simulated forces from a virtual site, but instead used the standard bilateral force feedback from the slave. Kotoku [30] proposed a predictive display system to provide force feedback to the operator in a telemanipulation system with time delay. In this work, the operator was shown a visual display of the slave environment and received force feedback from a virtual slave and environment. The operator was able to generate a plan for the slave with the master/virtual system, and therefore was not controlling the virtual and remote robots simultaneously.

Sayers and Paul [31] proposed a system for bilateral telemanipulation in the presence of time delay that attempts to predict the operator's actions and then actively assist in task execution. Rather than feeding back interaction forces between the slave and the remote environment, synthetic fixtures were displayed to properly guide the operator to perform one of a set of predefined tasks, depending on the motion of the operator. The system monitored the operator's motion command, and then selected the correct motion for the remote site. Examples of synthetic fixtures available for force reflection to the master are point fixtures and surface fixtures.

Tsumaki *et al.* [32, 33] and Yoon *et al.* [34] proposed a model-based bilateral teleoperation architecture that tolerated geometrical errors. This system used two control modes for each arm (master, slave, and simulated arm). Contact was detected using force data, and the arms were configured such that they were able to independently and automatically change their control mode depending on the environment. In this work, the slave and virtual arms were controlled by a velocity command only, which is derived from the operator's force command. Finally, Owaki *et al.* [35] proposed a system for virtually touching real objects. This system used active vision data transformed to the haptic mode to generate reaction forces. While this system mimicked the master/virtual telemanipulation scheme, there was no remote environment or slave to be controlled.

What has not yet been demonstrated is a direct model-based teleoperation system in which the operator simultaneously controls the position of the virtual slave and the remote slave while receiving forces from the virtual environment. Previous work relies on predictive displays, teleprogramming techniques, or combined velocity and force control in order to create a robust bilateral teleoperation system in the presence of time delay. The next step will be to develop new methods for model-based force generation that maintain operator position-control of the slave robot, while tolerating geometric errors, time delays, and limited bandwidth.

Internet-Based Teleoperation

A number of researchers have worked to develop and improve Internet-based bilateral teleoperation. Mirfakhari and Payandeh [36] developed a method for improving performance by decreasing the errors between the master and slave forces and velocities. This technique used an autoregressive model to predict variable time delay in the teleoperation system based on previous delays. Using the predicted delay, controller gains found using wave integral techniques were selected from a look-up table. They concluded that data should be sent as fast as possible, but sending data too fast caused extra queuing delay; therefore, in some situations the data rate should be reduced slightly to prevent queuing delay.

Liu *et al.* [37] explored the issue of data packet loss in Internet-based teleoperation. Instead of using autoregressive and moving average models (ARMA) to predict packet loss, they developed an adaptive algorithm for delay boundary prediction using the maximum entropy principle (MEP). Their experiments demonstrated the improved performance of the MEP algorithm over the ARMA algorithm when predicting roundtrip time delay. Fung *et al.* [38] used Quality-of-Service (QoS) parameters to adjust the controller gains of an Internet-based teleoperation system with network delay. Preliminary experiments showed faster task completion times using this control scheme, which provided haptic feedback through a force feedback joystick. In other work, Perusche *et al.* [39] developed a generic framework for coupling haptic devices in an Internet-based telepresence system using a Common Object Request Broker Architecture (COBRA).

Elhajj *et al.* [40] used event-based planning and control of Internet-based teleoperation systems. In this approach, new position commands were not generated and sent until the most up-to-date status of the robot force was received. At the same time, a new force was not fed back until a new velocity was received. Elhajj *et al.* [41] also considered the feedback of supermedia, or a collection of several sensory feedback mechanisms. This teleoperation system provided feedback of force, video and temperature. Experimental results demonstrated that an event-based control system could provide "event-transparency" and "event-synchronization" even with some time delay.

Chopra and Spong [42] were able to recover passivity and tracking performance by implementing a controller with time-varying gains in the scattering transformation and the feed forward position controller. They experimentally implemented their techniques on a 1-DOF master/slave system and the results supported the theoretical claims. It is important to note that no bounds on tracking error were defined, and the approach requires some knowledge of the delay in order to set the gains.

An Application of Time-Delayed Teleoperation: Telesurgery
To conclude this discussion of time-delayed teleoperation, an example of a control algorithm for telesurgery applications is presented. Ottensmeyer *et al.* [43] developed a telesurgery testbed for investigating the effects of time delay on controller stability and on the performance of surgical tasks. They developed and implemented a fuzzy sliding control (FSC) algorithm on a pair of PHANToM haptic interfaces (SensAble Technologies, Inc.). The FSC algorithm provided stability in the bilateral system and overcame a position drifting problem present when a passive compensation control scheme was implemented. The FSC teleoperation system was used to perform a variety of inanimate surgical tasks with synchronous and asynchronous feedback time delays. The results showed that performance could be improved by providing feedback as soon as it is available and not synchronizing feedback from different sensory modes, in this case audio/visual and force. As researchers continue to develop enhanced control techniques, the areas in which time-delayed teleoperation is applied are certain to grow.

3 CONTROL OF HAPTIC INTERFACE SYSTEMS

Haptic systems differ from bilateral teleoperation systems in that the remote environment is computer-generated rather than real. Important issues for a haptic system are performance evaluation and controller design for providing a high-precision and stable system. Hayward and Astley [44] discussed some of the performance measurements that exist in the field of haptics. Transparency, a performance measure introduced in bilateral teleoperation by Lawrence [3], is a suitable measurement for both teleoperation and haptic systems. Transparency measures the degree of distortion of the feeling between the operator and the remote environment, and is used in teleoperation work by Fite *et al.* [6] and Hashtrudi-Zaad and Salcudean [4]. Sirithanapipat [45] has applied this performance measure to haptic interface systems.

Stability is another primary concern in feedback control systems. In haptic simulations, instability can cause an undesirable feeling to the user, distorting the transparent interaction with the virtual environment, or can be dangerous if the manipulator can output a sudden high force. Stability is linked to the system loop gain, which is a function of the stiffness of a virtual environment. The quality of a haptic system is often described in terms of the maximum stiffness that can be achieved by the system. Clearly, stability and transparency are two key issues when determining the quality of a haptic device.

3.1 Passivity and Stability in Haptic Interface Systems

Virtual Coupling
Adams and Hannaford [46] addressed stability and performance issues associated with haptic interaction. The two-port mapping of network theory approach provided a framework for the unification of different models of haptic interaction. They implemented the concept of a virtual coupling network, an artificial connection between a haptic display and a virtual world, with both the impedance and admittance models of haptic interaction. The virtual coupling network guaranteed the stability of the combined haptic interface for arbitrary passive human operator and environmental admittances. Basing their work on Llewellyn's stability criteria, necessary and sufficient conditions led to an explicit procedure for the design of the virtual couplings. If the virtual environment is passive, the virtual coupling network design is independent of the impedance or admittance causality of the virtual environment model.

Energy-Based Methods
In other work, Hannaford and Ryu [47] proposed an energy-based method for controlling a haptic interface system to ensure stable contact under a wide variety of operating conditions. In this work, system stability was analyzed in terms of the time-domain definition of passivity. A Passivity Observer (PO) was defined, which measures energy flow in and out of one or more subsystems in real-time software. Active behavior was indicated by a negative value of the PO at any time. Also defined was a Passivity Controller (PC), an adaptive dissipative element that absorbs exactly the net energy output measured by the PO. Totally stable operation was achieved under conditions such as stiffness greater than 100 N/mm or time delays of 15 msec. The PO/PC method requires very little additional computation and does not require a dynamic model to be identified.

Frequency Domain Methods
Colgate and Schenkel [48] considered the passivity of systems comprised of a continuous time plant and a discrete time controller, as is the case with haptic systems. Necessary conditions for passivity were found via a small gain theorem, and sufficient conditions were found via an application of Parseval's theory and a sequence of frequency domain manipulations.

Physically-Based Methods
Goldfarb and Wang [49] proposed a physically-based approach to ensuring passive behavior in a haptic simulation of a stiffness by coupling a rate-independent hysteresis with the pure stiffness. Experimental results indicated that the proposed approach demonstrates significantly better stability for a given stiffness and sampling rate, and that the approach enables stable simulation of significantly larger stiffness for a given sampling rate, and simulation at a significantly lower sampling rate for a given stiffness.

Other Virtual Coupling Approaches
Kawai and Yoshikawa [50] proposed a haptic device with an analog circuit, which is placed between the computer and the haptic device and works as a system of springs and dampers. The control system can specify the stiffness and the damping coefficients and their equilibrium. For displaying virtual objects that can move in virtual environment, they proposed two methods to utilize the device, Continuous-time Coupling Impedance (CCI) method and Continuous-time Object's Impedance (COI) method. They also analyzed the passivity of each method for a 1-DOF display system. They also showed the validity of the approach with experimental results from a two-dimensional virtual environment.

3.2 Transparency in Haptic Interface Systems

Just as passive interactions between a human user and haptic interface system are desired, so are transparent interactions. Transparency refers to the degree of distortion between the user and the virtual environment, and can be degraded by such things as backlash, friction, or high inertia in the hardware system, or by computational delays due to complex virtual environment scenes. A couple of control approaches for maximizing transparency are discussed in this section.

Eom *et al.* [51] suggested a controller design methodology for multi-axis haptic display considering transparency and robust stability. To exclude the coupling effect existing in multi-axis haptic display, the equivalent disturbance in Cartesian space including modeling uncertainties and a coupling effect was derived and can be effectively removed using a disturbance observer. As a result, the multi-axis haptic system could be simplified into several 1-DOF haptic device models by employing such a disturbance observer. A performance index for the transparency-optimized haptic interface was defined from the viewpoint of admittance matching, and the optimal solution for minimizing the performance index was obtained by solving the H_2 optimization problem. Additionally, a robust stabilizing condition using an H_∞ norm was described.

Frequency Domain Methods

Classical loop shaping methods offer several clear advantages over conventional network theory and energy-based (passivity) approaches for designing and analyzing the transparency and stability of haptic systems. Sirithanapipat [45] treated the haptic system as a single feedback loop, including the human operator, haptic interface, and virtual environment, which could then be analyzed and compensated using classical control techniques. In this framework, a single compensator affects both the stability and performance of the loop. The stability can be addressed by the gain cross-over frequency, and the rest of the frequency domain can be used to improve the performance of the haptic system. This approach showed promising results, allowing Sirithanapipat to achieve the same levels of stability and transparency robustness in an open-loop-plus-compensator system as is typically achieved with a closed-loop system. He also showed that adding a compensator to a closed-loop system further improves the stability and transparency robustness.

4 FUTURE DIRECTIONS

Future directions in the control of bilateral teleoperation systems may include the development of more robust methods to address the nonlinear nature of time delay; the development of model-based force generation that maintains operator position-control of the slave robot yet tolerates geometric errors, time delays, and limited bandwidth; and the development of autonomous techniques to overcome time delay. Other work may include the continued development of force assistance functions; the extension of control architectures used on 1-DOF and 2-DOF systems to 3 or more DOF, and experimental implementation and validation of theoretical approaches presented in this paper. *Additional directions in the control of haptic* interfaces and bilateral teleoperation systems may include the addition of more DOF; the expansion of controller robustness to include greater ranges of users and environments and the development of less conservative approaches to stability to push the limits of performance.

5 CONCLUSIONS

This paper provides a survey of current research focused on the control of bilateral teleoperation systems and haptic interfaces. Several types of bilateral control architectures are presented and the issues of stability, transparency and time delay are discussed. A number of control methodologies for haptic interface systems are also presented, with a focus on issues of stability, passivity, and transparency in haptic interaction.

REFERENCES

[1] Hannaford, B., 1989, "A Design Framework for Teleoperators with Kinesthetic Feedback," IEEE Transactions on Robotics and Automation, **5**(4), pp. 426-434.

[2] Anderson, R. and Spong, M., 1989, "Bilateral Control of Teleoperators with Time Delay," IEEE Transactions on Automatic Control, **34**(5), pp. 494-501.

[3] Lawrence, D., 1993, "Stability and Transparency in Bilateral Teleoperation," IEEE Transactions on Robotics and Automation, **9**(5) pp. 624-637.

[4] Hashtrudi-Zaad, K. and Salcudean, S., 1999, "On the Use of Local Force Feedback for Transparent Teleoperation," Proceedings of the IEEE Conference on Robotics and Automation, pp. 1863-1869.

[5] Speich, J., Fite, K. and Goldfarb, M., 2000, "A Method for Simultaneously Increasing Transparency and Stability Robustness in Bilateral Telemanipulation," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 2671-2676.

[6] Fite, K., Speich, J. and Goldfarb, M., 2001, "Transparency and Stability in Two-Channel Bilateral Telemanipulation," ASME Journal of Dynamic Systems, Measurement and Control, **123**(3), pp. 400-407.

[7] Speich, J. and Goldfarb, M., 2002, "Implementation of Loop-Shaping Compensators to Increase the Transparency Bandwidth of a Scaled Telemanipulation System," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 2886-2993.

[8] Flemmer, H., Ericksson, B. and Wikander, J., 2002, "Control Design for Transparent Teleoperators with Model Parameter Variation," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 2956-2961.

[9] Hirche, S. and Buss, M., 2003, "Passive position controlled telepresence systems with time delay," Proceedings of the American Control Conference, pp. 168-173.

[10] Yamano, I., Takemura, K., Endo, K. and Maeno, T., 2002, "Method for Controlling Master-Slave Robots using Switching and Elastic Elements," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 1717-1722.

[11] Ni, L. and Wang, D., 2002, "A Gain-switching Control Scheme for Position-error-based Force-reflecting Teleoperation," Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS, pp. 239-246.

[12] Ni, L. and Wang, D., 2002, "Contact Transition Stability Analysis for a Bilateral Teleoperation System," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 3272-3277.

[13] Kim, S. and Hamel, W., 2002, "Force Assistance Function For Human Machine Cooperative Telerobotics Using Fuzzy Logic," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 2165-2170.

[14] Pernalete, N., Yu, W., Fritz, B. and Dubey, R., 2002, "Development of a Telerobotic System to Assist Persons with Disabilities," Proceedings of the ASME International Mechanical Engineering Congress and Exposition, pp. 1-8.

[15] Ryu, J., Kwon, D. and Hannaford, B., 2002, "Stable Teleoperation with Time Domain Passivity Control," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 3260-3265.

[16] Park, K., Chung, W. and Youm, Y., 2002, "Obtaining Passivity of Micro-Teleoperation Handling a Small Inertia Object," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 3266-3271.

[17] Lee D. and Li, P., 2002, "Passive Coordination Control of Nonlinear Bilateral Teleoperated Manipulators," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 3278-3283.

[18] Lee D. and Li, P., 2002, "Passive Tool Dynamics Rendering for Nonlinear Bilateral Teleoperated Manipulators," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 3284-3289.

[19] Lee, D. and Li, P., 2003, "Toward Robust Passivity: A Passive Control Implementation Structure for Mechanical Teleoperators," Proceedings of the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS, pp. 132-139.

[20] Salcudean, S., Zhu, M., Zhu, W. and Hashtrudi-Zaad, K., 2000, "Transparent Bilateral Teleoperation under Position and Rate Control," International Journal of Robotics Research, **19**(12), pp. 1185-1202.

[21] Hashtrudi-Zaad, K., Mobasser, F. and Salcudean, S., 2003, "Transparent implementation of bilateral teleoperation controllers under rate mode," Proceedings of the American Control Conference, pp. 161-167.

[22] Lozano, R., Chopra, N. and Spong, M., 2002, "Passivation of Force Reflecting Bilateral Teleoperators with Time Varying Delay," Mechatronics '02, Entschede, Netherlands, June 24-26.

[23] Niemeyer, G. and Slotine, J., 1991, "Stable Adaptive Teleoperation," IEEE Journal of Oceanographic Engineering, **16**(1), pp. 152-162.

[24] Niemeyer G. and Slotine, 1998, "Towards Force-Reflecting Teleoperation over the Internet," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 1909-1915.

[25] Munir S. and Book, W., 2002, "Wave Variables and Prediction," IEEE/ASME Transactions on Mechatronics, **7**(2), pp. 124-133.

[26] Munir, S. and Book, W., 2003, "Control techniques and programming issues for time delayed Internet based teleoperation." ASME Journal of Dynamic Systems, Measurement and Control, **125**, pp. 205-214.

[27] Yokokohji, Y., Imaida, T. and Yoshikawa, T., 2000, "Bilateral Control with Energy Balance Monitoring under Time-Varying Communication Delay," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 2684-2689.

[28] Yokokohji, Y., Tsujioka, T. and Yoshikawa, T., 2002, "Bilateral Control with Time-Varying Delay Including Communication Blackout," Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS, pp. 285-292.

[29] Bejczy, A., Kim, W. and Venema, S., 1990, "The Phantom Robot: Predictive displays for teleoperation with time delay," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 546-551.

[30] Kotoku, T., 1992, "A Predictive Display with Force Feedback and its Application to Remote Manipulation System with Transmission Time Delay," Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 239-246.

[31] Sayers, C. and Paul, R., 1993, "Synthetic Fixturing," Proceedings of the ASME DSC-Vol. 49, Advances in Robotics, Mechatronics, and Haptic Interfaces, pp. 37-46.

[32] Tsumaki, Y., Hoshi, Y., Naruse, H. and Uchiyama, M., 1996, "Virtual reality based teleoperation which tolerates geometrical modeling errors," Proceedings of the IEEE International Conference on Intelligent Robots and Systems, pp. 1023-1030.

[33] Tsumaki, Y., and Uchiyama, M., 1997, "A Model-Based Space Teleoperation System with Robustness Against Modeling Errors," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 1592-1599.

[34] Yoon, W., Goshozono, T., Kawabe, H., Kinami, M., Tsumaki, Y., Uchiyama, M., Oda, M. and Doi, T., 2001, "Model-Based Teleoperation of a Space Robot on ETS-VII using a Haptic Interface," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 407-412.

[35] Owaki, T., Nakabo, Y., Namiki, A., Ishii, I. and Ishikawa, M., 1999, "Real-time system for virtually touching objects in the real world using modality transformation from images to haptic information," Systems and Computers in Japan, **30**(9), pp. 17-24.

[36] Mirfakhrai T. and Payandeh, S., 2002, "A Delay Prediction Approach for Teleoperation over the Internet," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 2178-2183.

[37] Liu, P., Meng, M., Ye X. and Gu,, J., 2002, "End-to-End Delay Boundary Prediction Using Maximum Entropy Principle (MEP) for Internet-Based Teleoperation," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 2701-2706.

[38] Fung, W., Xi, N., Lo W. and Liu, Y., 2002 "Improving Efficiency of Internet based Teleoperation using Network QoS," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 2707-2712.

[39] Preusche, C., Hoogen, J., Reintsema, D., Schmidt G. and Hirzinger, G., 2002, "Flexible Multimodal Telepresent Assembly using a Generic Interconnection Framework," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 3712-3718.

[40] Elhajj, I., Xi, N., Song, B., Yu, M., Lo W. and Liu, Y., 2002, "Transparency and Synchronization in Supermedia Enhanced Internet-Based Teleoperation," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 2713-2718.

[41] Elhajj, I., Xi, N., Fung, W., Liu, Y., Li, W., Kaga, T. and Fukada, T., 2001, "Haptic Information in Internet-Based Teleoperation," IEEE/ASME Transactions on Mechatronics, **6**(3), pp. 295-304.

[42] Chopra, N. and Spong, M., 2003, "Bilateral teleoperation over the Internet: the time varying delay problem," Proceedings of the American Control Conference, pp. 155-160.

[43] Ottensmeyer, M., Hu, J., Thompson, J., Ren, J. and Sheridan, T., 2000, "Investigations into Performance of Minimally Invasive Telesurgery with Feedback Time Delays," Presence, **9**(4), pp. 369-382.

[44] Hayward V. and Astley, O., 1996, "Performance Measures for Haptic Interfaces," Robotics Research: The 7th International Symposium/Georges Giralt and Gerhard Hirzinger, Eds., pp. 195-207.

[45] Sirithanapipat, T., 2002, "Haptic Interface Control Design for Performance and Stability Robustness," Ph.D. Thesis, Vanderbilt University, Nashville, TN.

[46] Adams, R., and Hannaford, B., 1999, "Stable haptic interaction with virtual environments. IEEE Transactions on Robotics and Automation, **15**(3), pp. 465-474.

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

[48] Colgate, J. and Schenkel, G., 2002, "Passivity of a class of sample-data systems: Application to haptic interfaces," Journal or Robotic Systems, **14**(1), pp. 37-47.

[49] Goldfarb, M. and Wang, J., 1999, "Passive Stiffness Simulation with Rate-Independent Hysteresis," American Society of Mechanical Engineers, International Mechanical Engineering Congress and Exposition, Dynamic Systems and Control Division DSC Vol. 67, pp. 345-350.

[50] Kawai, M. and Yoshikawa, T., 2002, "Haptic Display of Movable Virtual Object with Interface Device Capable of Continuous-Time Impedance Display by Analog Circuit," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 229-234.

[51] Eom, K., Suh, I. and Yi, B., 2000, "A Design Method of Haptic Interface Controller Considering Transparency and Robust Stability," Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 961-966.