Mahdi Tavakoli

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Summary

Mahdi Tavakoli is an assistant professor in the Department of Electrical and Computer Engineering at the University of Alberta, Canada. He received his BSc and MSc degrees in Electrical Engineering from Ferdowsi University and K.N. Toosi University, Iran, in 1996 and 1999, respectively. He then received his PhD degree in Electrical and Computer Engineering from the University of Western Ontario, London, ON, Canada, in 2005. In 2006, he was a post-doctoral research associate at Canadian Surgical Technologies and Advanced Robotics (CSTAR), London, ON, Canada. In 2007-2008, and prior to joining the Department of Electrical and Computer Engineering at the University of Alberta, Dr. Tavakoli was an NSERC Post-Doctoral Fellow with the BioRobotics Laboratory of the School of Engineering and Applied Sciences at Harvard University, Cambridge, MA, USA.

Specialties

Mahdi Tavakoli's research interests broadly involve the areas of robotics and systems control. Specifically, his research focuses on haptics and teleoperation control, medical robotics, and image-guided surgery. Dr. Tavakoli is the first author of the book "Haptics for Teleoperated Surgical Robotic Systems" (World Scientific, 2008).

Experience

Research Affiliate at Glenrose Rehabilitation Hospital, Edmonton
March 2010 - Present (3 years 8 months)

Assistant Professor at University of Alberta
September 2008 - Present (5 years 2 months)

NSERC Postdoctoral Fellow at Harvard University
January 2007 - August 2008 (1 year 8 months)

Postdoctoral Research Associate at Canadian Surgical Technologies and Advanced Robotics (CSTAR)
January 2006 - December 2006 (1 year)

Organizations

IEEE

ASEE

Projects

Haptic Teleoperation Control
Members:Mahdi Tavakoli

Haptic Interaction
Members:Mahdi Tavakoli

Human Factors in Haptics
Members:Mahdi Tavakoli

Robot-Assisted Surgery
Members:Mahdi Tavakoli

Robot-Assisted Therapy
Members:Mahdi Tavakoli

Robot-Assisted Rehabilitation
Members:Mahdi Tavakoli

Publications

Smith Predictor Based Robot Control for Ultrasound-guided Teleoperated Beating-heart Surgery
IEEE Journal of Biomedical and Health Informatics 2013
Authors: Meaghan Bowthorpe, E.I.T, Mahdi Tavakoli, Harald Becher, Robert Howe

Performing surgery on fast-moving heart structures while the heart is freely beating is next to impossible. Nevertheless, the ability to do this would greatly benefit patients. By controlling a teleoperated robot to continuously follow the heart's motion, the heart can be made to appear stationary. The surgeon will then be able to operate on a seemingly stationary heart when in reality it is freely beating. The heart's motion is measured from ultrasound images and thus involves a non-negligible delay due to image acquisition and processing, estimated to be 150 ms that, if not compensated for, can cause the teleoperated robot's end-effector (i.e., the surgical tool) to collide with and puncture the heart. This research proposes the use of a Smith predictor to compensate for this time delay in calculating the reference position for the teleoperated robot. The results suggest that heart motion tracking is improved as the introduction of the Smith predictor significantly decreases the mean absolute error, which is the error in making the distance between the robot's endeffector and the heart follow the surgeon's motion, and the mean integrated square error.

Teleoperation in the Presence of Varying Time Delays and Sandwich Linearity in Actuators
Automatica (A Journal of IFAC) 2013
Authors: Farzad Hashemzadeh, Iraj Hassanzadeh, P.Eng., Mahdi Tavakoli

In this paper, a novel control scheme is proposed to guarantee global asymptotic stability of bilateral teleoperation systems that are subjected to time-varying time delays in their communication channel and sandwich linearity in their actuators. This extends prior art concerning control of nonlinear bilateral teleoperation systems under time-varying time delays to the case where the local and the remote robots'

control signals pass through saturation or similar nonlinearities that belong to a class of systems we name sandwich linear systems. Our proposed controller is similar to the proportional plus damping (P+D) controller with the difference that it takes into account the actuator saturation at the outset of control design and alters the proportional term by passing it through a nonlinear function; thus, we call the proposed method as nonlinear proportional plus damping (nP+D).The asymptotic stability of the closed-loop system is established using a Lyapunov-Krasovskii functional under conditions on the controller parameters, the actuator saturation characteristics, and the maximum values of the time-varying time delays. To show the effectiveness of the proposed method, it is simulated on a variable-delay teleoperation system comprising a pair of planar 2-DOF robots subjected to actuator saturation. Furthermore, the controller is experimentally validated on a pair of 3-DOF PHANToM Premium 1.5A robots, which have limited actuation capacity, that form a teleoperation system with a varying-delay communication channel.

A Passivity Criterion for Sampled-data Bilateral Teleoperation Systems
IEEE Transactions on Haptics 2013
Authors: Ali Jazayeri, Mahdi Tavakoli

A teleoperation system consists of a teleoperator, a human operator, and a remote environment. Conditions involving system and controller parameters that ensure the teleoperator passivity can serve as control design guidelines to attain maximum teleoperation transparency while maintaining system stability. In this paper, sufficient conditions for teleoperator passivity are derived for when position error based controllers are implemented in discrete-time. This new analysis is necessary because discretization causes energy leaks and does not necessarily preserve the passivity of the system. The proposed criterion for sampled-data teleoperator passivity imposes lower bounds on the teleoperator's robots dampings, an upper bound on the sampling time, and bounds on the control gains. The criterion is verified through simulations and experiments.

Absolute Stability Analysis of Sampled-Data Scaled Bilateral Teleoperation Systems
Control Engineering Practice (A Journal of IFAC) 2013
Authors: Ali Jazayeri, Mahdi Tavakoli

Stability of a bilateral teleoperation system may be jeopardized by controller discretization, which has been shown to involve energy leaks. This paper proposes a novel approach to analyzing the absolute stability of sampled-data bilateral teleoperation systems consisting of discrete-time controllers and continuous-time master, slave, operator, and environment. The proposed stability analysis permits scaling and delay in the master and the slave positions and forces. The absolute stability conditions reported here impose bounds on the gains of the discrete-time controller, the damping terms of the master and the slave, and the sampling time. A design-related application of these results is in proper selection of various control parameters and the sampling rate for stable teleoperation under discrete-time control. To explore the trade-off between the control gains and the sampling time, it is studied how large sampling times, which require low control gains for maintaining stability, can lead to unacceptable teleoperation transparency and human task performance in a teleoperated switching task. This shows that the effect of sampling time must be taken into account because neglecting it (as in the absolute stability literature) undermines both stability and transparency of teleoperation. The resulting absolute stability condition has been verified via experiments with two Phantom Omni robots.

Force Sensor Based Estimation of Needle Tip Deflection in Brachytherapy
Journal of Sensors (Special Issue on Sensors for Robotics) 2013
Authors: Thomas Lehmann, Mahdi Tavakoli, Nawaid Usmani, Ronald Sloboda

A virtual sensor is developed for the online estimation of needle tip deflection during permanent interstitial brachytherapy needle insertion. Permanent intestinal brachytherapy is an effective, minimally-invasive and patient-friendly cancer treatment procedure. The deflection of the needles used in the procedure however undermines the treatment efficiency and, therefore, needs to be minimized. Any feedback control technique to minimize the needle deflection will require feedback of this quantity, which is not easy to provide. The proposed virtual sensor for needle deflection incorporates a force/torque sensor, mounted at the base of the needle that always remains outside the patient. The measured forces/torques are used by a mathematical model, developed based on mechanical needle properties. The resulting estimation of tip deflection in real-time during needle insertion is the main contribution of this paper. The proposed approach solely relies on the measured forces and torques without a need of any other invasive/noninvasive sensing devices. A few mechanical models have been introduced previously regarding the way the forces are composed along the needle during insertion; we will compare our model to those approaches in terms of accuracy. In order to conduct experiments to verify the deflection model, a custom-built, 2-DOF robotic system for needle insertion is developed and discussed. This system is a prototype of an intelligent, hand-held surgical assistant tool that incorporates the virtual sensor proposed in this paper.

Is the human operator in a teleoperation system passive?
IEEE World Haptics Conference 2013 April 17, 2013
Authors: Matthew Dyck, Ali Jazayeri, Mahdi Tavakoli

Conventional approaches for stability analysis of bilateral teleoperation systems assume that the human operator does not inject energy into the system and behaves in a passive manner. Does this assumption hold for various tasks the human operator may execute in a teleoperation context? To answer this question, in this paper we measure the endpoint impedance (inertia, viscosity, and stiffness) of the human arm during two tasks: (1) relaxed grasping of a haptic device while the device imposes position perturbations, and (2) rigid grasping of a haptic device (posture maintenance) while the device imposes force perturbations. The human arm impedance is identified as a 2?x2 transfer function matrix and assessed for passivity over the frequency range characteristic of human motion. Our results agree with previous findings that the relaxed human arm behaves as a passive system. However, whether the rigid arm behaves as an active or passive system is found to depend on the magnitude of the force perturbations. We discuss why the passivity of the human operator is task dependent.

Measuring the dynamic impedance of the human arm without a force sensor
IEEE International Conference on Rehabilitation Robotics, 2013 June 25, 2013
Authors: Matthew Dyck, Mahdi Tavakoli

Conventional approaches for stability analysis of bilateral teleoperation systems assume that the human operator does not inject energy into the system and behaves in a passive manner. Does this assumption hold for various tasks the human operator may execute in a teleoperation context? To answer this question, in this paper we measure the endpoint impedance (inertia, viscosity, and stiffness) of the human arm during two tasks: (1) relaxed grasping of a haptic device while the device imposes position perturbations, and (2) rigid

grasping of a haptic device (posture maintenance) while the device imposes force perturbations. The human arm impedance is identified as a 2?x2 transfer function matrix and assessed for passivity over the frequency range characteristic of human motion. Our results agree with previous findings that the relaxed human arm behaves as a passive system. However, whether the rigid arm behaves as an active or passive system is found to depend on the magnitude of the force perturbations. We discuss why the passivity of the human operator is task dependent.

Introduction to Haptics for Neurosurgeons

Neurosurgery (Virtual Reality and Robotics in Neurosurgery Supplement) January 1, 2013

Authors: Rachael L'Orsa, Chris Macnab, Mahdi Tavakoli

Robots are becoming increasingly relevant to neurosurgeons, extending a neurosurgeon's physical capabilities, improving navigation within the surgical landscape when combined with advanced imaging, and propelling the movement toward minimally invasive surgery. Most surgical robots, however, isolate surgeons from the full range of human senses during a procedure. This forces surgeons to rely on vision alone for guidance through the surgical corridor, which limits the capabilities of the system, requires significant operator training, and increases the surgeon's workload. Incorporating haptics into these systems, ie, enabling the surgeon to "feel" forces experienced by the tool tip of the robot, could render these limitations obsolete by making the robot feel more like an extension of the surgeon's own body. Although the use of haptics in neurosurgical robots is still mostly the domain of research, neurosurgeons who keep abreast of this emerging field will be more prepared to take advantage of it as it becomes more prevalent in operating theaters. Thus, this article serves as an introduction to the field of haptics for neurosurgeons. We not only outline the current and future benefits of haptics but also introduce concepts in the fields of robotic technology and computer control. This knowledge will allow readers to be better aware of limitations in the technology that can affect performance and surgical outcomes, and "knowing the right questions to ask" will be invaluable for surgeons who have purchasing power within their departments.

Nonlinear Disturbance Observer Design For Robotic Manipulators

Control Engineering Practice (A Journal of IFAC) November 19, 2012

Authors: Alireza Mohammadi, Mahdi Tavakoli, Horacio J. Marquez, Farzad Hashemzadeh

Robotic manipulators are highly nonlinear and coupled systems that are subject to different types of disturbances such as joint frictions, unknown payloads, varying contact points, and unmodeled dynamics. These disturbances, when unaccounted for, adversely affect the performance of the manipulator. Employing a disturbance observer is a common method to reject such disturbances. In addition to disturbance rejection, disturbance observers can be used in force control applications. Recently, research has been done regarding the design of nonlinear disturbance observers (NLDOs) for robotic manipulators. In spite of good results in terms of disturbance tracking, the previously designed nonlinear disturbance observers can merely be used for planar serial manipulators with revolute joints [Chen, W. H., Ballance, D. J., Gawthorp, P. J., O'Reilly, J. (2000). A nonlinear disturbance observer for robotic manipulators. IEEE Transactions on Industrial Electronics, 47 (August (4)), 932–938; Nikoobin, A., Haghighi, R. (2009). Lyapunov-based nonlinear disturbance observer for serial n-link manipulators. Journal of Intelligent & Robotic Systems, 55 (July (2–3)), 135–153]. In this paper, a general systematic approach is proposed to solve the disturbance observer design problem for robotic manipulators without restrictions on the number of degrees-of-freedom (DOFs), the types

of joints, or the manipulator configuration. Moreover, this design method does not need the exact dynamic model of the serial robotic manipulator. This method also unifies the previously proposed linear and nonlinear disturbance observers in a general framework. Simulations are presented for a 4-DOF SCARA manipulator to show the effectiveness of the proposed disturbance observer design method. Experimental results using a PHANToM Omni haptic device further illustrate the effectiveness of the design method.

Bilateral Control of a Nonlinear Pneumatic Teleoperation System with Solenoid Valves

IEEE Transactions on Control Systems Technology July 17, 2012

Authors: Minh Quyen Le, Minh Tu Pham, Mahdi Tavakoli, Richard Moreau, Jean-Pierre Simon, Tanneguy Redarce

In past research on the control of pneumatic actuators, typically proportional servovalves have been used for achieving high-performance control of the mass flow rate. In this brief, we instead use fast-switching ON/OFF valves due to their distinct advantages in terms of low cost and small size. Accurate control of pneumatic actuators with ON/OFF solenoid valves is a challenge since the system dynamics is both discrete input and highly nonlinear. In this brief, we apply a hybrid control algorithm to a pneumatic actuator with ON/OFF valves. Such a control approach is developed for choosing the best control vector at each sample time to track the reference state (i.e., desired force) in the inner force control loop within a bilateral teleoperation system. Experimental results show that good teleoperation transparency is achieved despite all the
obstacles such as discrete input and nonlinear behavior of the
pneumatic-actuated teleoperation system.

Adaptive Control for State Synchronization of Nonlinear Haptic Telerobotic Systems with Asymmetric Varying Time Delays

Journal of Intelligent and Robotic Systems April 2012

Authors: Farzad Hashemzadeh, Iraj Hassanzadeh, Mahdi Tavakoli, Ghasem Alizadeh

In this paper, we introduce a new adaptive controller design scheme for nonlinear telerobotic systems with varying time delays where the delays and their variation rates are unknown. The designed controller has the ability to synchronize the state behaviors of the local and the remote robots. In this paper, asymptotic stability in the presence of varying time delays is of interest. Using the proposed controller, asymptotic stability of the bilateral telerobotic system subject to any bounded yet unknown varying delay with a bounded yet unknown rate of change can be guaranteed. Besides the varying time delay, the proposed adaptive controller has the ability to adapt to the parameter variations in the local and the remote robots' dynamics. It is shown that position and velocity errors between the local and the remote manipulators converge to the zero asymptotically, thus ensuring teleoperation transparency. Experimental and simulation results with a pair of PHANToM haptic devices and a pair of planar manipulators under varying time delays in the communication channel demonstrate the effectiveness of the proposed scheme.

A New Method for Bilateral Teleoperation Passivity under Varying Time Delays

Mathematical Problems in Engineering April 2012

Authors: Farzad Hashemzadeh, Iraj Hassanzadeh, Mahdi Tavakoli, Ghasem Alizadeh

In this paper, a new framework is proposed to mitigate the adverse effect of time-varying time delays on the passivity of a teleoperation system. To this end, the communication channel with time-varying delays is

modeled as a constant-delay channel along with additive output disturbances. Then, disturbance estimator blocks are added in each of the feedforward and feedback paths to estimate these disturbances and to compensate for them. In the disturbance estimator block, there is a need for a virtual time-varying delay block such that the overall communication channel can be seen as one with a constant delay. We also propose a method for determining this virtual delay. Two PHANToM haptic devices connected through a communication channel with time-varying delays are considered for a case study. Simulation and experimental results confirm the efficiency of the proposed method in terms of passivating the teleoperation system in the presence of time-varying delays.

Sliding-Mode Bilateral Teleoperation Control Design for Master-Slave Pneumatic Servo Systems
Control Engineering Practice June 2012
Authors: Richard Moreau, Minh Tu Pham, Mahdi Tavakoli, Minh-Quyen Le, T. Redarce

This paper presents a novel bilateral control design scheme for pneumatic master–slave teleoperation systems that are actuated by low-cost solenoid valves. The motivation for using pneumatic actuators in lieu of electrical actuators is that the former has higher force to mass ratio than the latter and is inert to magnetic fields, which is crucial in certain teleoperation applications such as MRI-guided, robot-assisted surgery. A sliding mode approach, called the three-mode control scheme, is incorporated into a two-channel bilateral teleoperation architecture, which can implement a position–position, force–force, or force–position scheme. An analysis of stability and transparency of the closed-loop teleoperation system is carried out. The proposed control design performance is experimentally verified on a single-degree-of-freedom pneumatic teleoperation system actuated by on/off valves. Experimental results show high accuracies in terms of position and force tracking under free-space motion and hard-contact motion in the teleoperation system. Another purpose of this paper is to demonstrate the possibility to improve the valve lifetime by increasing the number of control levels. To do this, a new control design, called the five-mode control scheme, is developed and compared with the three-mode scheme in time domain as well as in frequency domain.

Improved Tracking and Switching Performance in Position-Controlled Nonlinear Pneumatic-Actuated Robots
Mechatronics February 2012
Authors: Sean Hodgson, Minh Quyen Le, Mahdi Tavakoli, Minh-Tu Pham

For robotic systems that use on/off (solenoid) pneumatic actuators, a sliding mode control law for precise position control and low switching (open–close) activity of the valves is presented in this paper. Given a pneumatic actuator with two chambers and four solenoid valves, there are sixteen possible input combinations defined directly from the state of the four on/off valves present in the system; however, only seven of these discrete operating modes are considered both functional and unique. Therefore, we introduce a novel seven-mode sliding controller that minimizes the position tracking error using modes that have both the necessary and sufficient amounts of drive energy and, thus, involve reduced switching activity. An analysis of the closed-loop system stability is carried out. The performance of the proposed control design is experimentally verified on a single pneumatic actuator setup comprising of two chambers with four on/off valves.

Adaptive Control of Teleoperation Systems with Linearly and Nonlinearly Parameterized Dynamic Uncertainties

Journal of Dynamic Systems, Measurement and Control February 2012
Authors: Xia Liu, Mahdi Tavakoli

Existing work concerning adaptive control of uncertain teleoperation systems only deals with linearly parameterized (LP) dynamic uncertainties. Typical teleoperation system dynamics, however, also posses terms with nonlinearly parameterized (NLP) structures. An example of such terms is friction, which is ubiquitous in the joints of the master and slave robots of practical teleoperation systems. Uncertainties in the NLP dynamic terms may lead to significant position and force tracking errors if not compensated for in the control scheme. In this paper, adaptive controllers are designed for the master and slave robots with both LP and NLP dynamic uncertainties. Next, these controllers are incorporated into the 4-channel bilateral teleoperation control framework to achieve transparency. Then, transparency of the overall teleoperation is studied via a Lyapunov function analysis. Simulation studies demonstrate the effectiveness of the proposed adaptive scheme when exact knowledge of the LP and NLP dynamics is unavailable.

Disturbance Observer-Based Control of Nonlinear Haptic Teleoperation Systems
IET Control Theory & Applications December 2011
Authors: Alireza Mohammadi, Mahdi Tavakoli, Horacio Marquez

Teleoperation systems are subject to different types of disturbances. Such disturbances, when unaccounted for, may cause poor performance and even instability of the teleoperation system. This study presents a novel non-linear bilateral control scheme using the concept of `disturbance observer-based control' for non-linear teleoperation systems. Lumping the effects of dynamic uncertainties and external disturbances into a single disturbance term enables us to design a disturbance observer to suppress these disturbances and alleviate their adverse effects on the teleoperation system. A disturbance observer-based control law is proposed for non-linear teleoperation systems which will guarantee global asymptotic force tracking and global exponential position and disturbance tracking when the bilateral teleoperation system is experiencing slow-varying disturbances. In the case of fast-varying disturbances, the tracking errors are shown to be globally uniformly ultimately bounded, with an ultimate bound that can be made as small as desired using the design parameters. Simulations are presented to show the effectiveness of the proposed approach.

Adaptive Inverse Dynamics 4-Channel Control of Uncertain Nonlinear Teleoperation Systems
Advanced Robotics 2011
Authors: Xia Liu, Mahdi Tavakoli

Most of the methods to date on bilateral control of nonlinear teleoperation systems lead to nonlinear and coupled closed-loop dynamics, even in the ideal case of perfect knowledge of the master, the slave, the human operator and the environment. Consequently, the transparency of these closed-loop systems is difficult to study. In comparison, inverse dynamics controllers can deal with the nonlinear terms in the dynamics in a way that, in the ideal case, the closed-loop systems become linear and decoupled. In this paper, for multi-d.o.f. nonlinear teleoperation systems with uncertainties, adaptive inverse dynamics controllers are incorporated into the four-channel bilateral teleoperation control framework. The resulting controllers do not need exact knowledge of the dynamics of the master, the slave, the human operator or the environment. A Lyapunov analysis is presented to prove the transparency of the teleoperation system. Simulations are also presented to show the effectiveness of the proposed approach.

Performance Analysis of a Haptic Telemanipulation Task under Time Delay
Advanced Robotics 2011
Authors: Michael Yip, Mahdi Tavakoli, Robert D. Howe

There is ample research on the effect of haptic teleoperation under delayed communication channels in terms of stability and system performance. Little attention, however, has been paid to the effect of delayed force feedback on users' task performance and whether force feedback is beneficial under significant communication delays. This paper investigates whether force feedback improves user's task performance in delayed teleoperation. We study peg-in-the-hole insertion/retraction, dexterous manipulation tasks involving high degrees of freedom and high forces at certain points during task execution. A user study involving unilateral (without force feedback), bilateral (with force feedback) and graphical feedback teleoperation under various delays is presented. We observed that for all feedback modalities, task completion times increase as delay increases. Haptic feedback helps reduce contact forces and the occurrence of large robot/environment forces. Furthermore, graphical feedback helps users maintain the lowest range of forces at the cost of higher task completion times. With users mindful of minimizing contact forces, haptic/graphical feedback causes the task to take more time than unilateral control. Therefore, when short completion times are crucial given a tolerance for larger forces, force feedback only serves to increase the time required to perform the task; thus, unilateral control may be sufficient.

Haptic Effects of Surgical Teleoperator Flexibility
International Journal of Robotics Research October 2009
Authors: Mahdi Tavakoli, Robert D. Howe

Minimally invasive surgery systems typically involve thin and cable-driven surgical instruments. This introduces link and joint flexibility in the slave robot of a master—slave teleoperation system, reducing the effective stiffness of the slave and the transparency of teleoperation. In this paper, we analyze transparency under slave link and joint flexibility (tool flexibility). We also evaluate the added benefits of using extra sensors at the tip of the flexible robot. It is shown that tip velocity (or position) feedback improves free-space position tracking performance in the presence of robot flexibility. Also, when the interaction forces with an environment are measured by a force sensor and fed back to the user’s hand, tip velocity feedback improves hard-contact force tracking performance. During a hard contact task, tip velocity feedback can also eliminate the transmission of robot flexibility to the user’s hand.

Discrete-Time Bilateral Teleoperation: Modeling and Stability Analysis
IET Control Theory & Applications June 2008
Authors: Mahdi Tavakoli, Arash Aziminejad, Mehrdad Moallem, Rajni V. Patel

Discretisation of a stabilising continuous-time bilateral teleoperation controller for digital implementation may not necessarily lead to stable teleoperation. While previous research has focused on the question of passivity or stability of haptic interaction with a discretely simulated virtual wall, here the stability of master-slave teleoperation under discrete-time bilateral control is addressed. Stability regions are determined in the form of conditions involving the sampling period, control gains including the damping introduced by the controller and environment stiffness. Among the obtained stability conditions are lower and upper bounds on the controller damping in addition to upper bounds on the sampling period and the environment stiffness, implying that as the sampling period is increased, the maximum admissible stiffness of the environment with

which a slave robot can stably interact is reduced. An outcome of the paper is a set of design guidelines in terms of selection of various control parameters and the sampling rate for stable teleoperation under discrete-time control. Because of the sampling period-environment stiffness tradeoff and the stability-transparency tradeoff, the obtained stability boundaries are of particular importance for hard-contact teleoperation or when the teleoperation system has near-ideal or ideal transparency. The results of the stability analysis are confirmed by a simulation study in which the bilateral controller is realised by z-domain transfer functions while the master, the slave and the environment are simulated in the s-domain.

Stability and Performance in Delayed Bilateral Teleoperation: Theory and Experiments
Control Engineering Practice November 2008
Authors: Arash Aziminejad, Mahdi Tavakoli, Rajni V. Patel, Mehrdad Moallem

In the presence of communication latency in a bilaterally controlled teleoperation system, stability and transparency are severely affected. In this paper, based on a passivity framework, admittance-type and hybrid-type delay-compensated communication channels, which warrant different bilateral control architectures, are introduced. Wave transforms and signal filtering are used to make the delayed-communication channel passive and passivity/stability conditions are derived based on the end-to-end model of the teleoperation system with and without incorporating force measurement data of the master and the slave manipulators' interactions with the operator and the remote environment in the control configuration. Based on analogies of the hybrid parameters of the teleoperation systems, it is demonstrated that using force sensor measurements about hand/master and/or slave/environment interactions in the control algorithm can significantly improve teleoperation transparency. Experimental results with a soft-tissue task for a hybrid-type architecture and for round-trip delays of 60 and 600 ms further substantiate the hypothesis that using slave-side force measurements considerably enhances the matching of the master and the slave forces and consequently the transparency compared to a position error-based configuration.

Transparent Time-Delayed Bilateral Teleoperation Using Wave Variables
EEE Transactions on Control Systems Technology May 2008
Authors: Arash Aziminejad, Mahdi Tavakoli, Rajni V. Patel, Mehrdad Moallem

Besides stability, a high degree of transparency is also an essential requirement in order to enable operators to safely and precisely perform bilateral teleoperation tasks. An existing approach based on the wave transformation technique can make a two-channel teleoperation system insensitive to time delays by making the time-delayed communication channel passive. In this paper, we propose a novel method for incorporating this technique in a four-channel architecture, which is the optimal architecture from a transparency point of view, and derive the corresponding absolute stability condition. It is analytically demonstrated that the proposed teleoperation architecture is capable of providing ideal transparency when transmission delays are present, and criteria for its stable operation are derived. We also show that a three-channel variant of the proposed four-channel control architecture can offer a comparable performance with less implementational complexity. Experimental results in support of the developed theory are provided.

High-Fidelity Bilateral Teleoperation Systems and the Effect of Multimodal Haptics
IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics December 2007
Authors: Mahdi Tavakoli, Arash Aziminejad, Rajni V. Patel, Mehrdad Moallem

In master-slave teleoperation applications that deal with a delicate and sensitive environment, it is important to provide haptic feedback of slave/environment interactions to the user's hand as it improves task performance and teleoperation transparency (fidelity), which is the extent of telepresence of the remote environment available to the user through the master-slave system. For haptic teleoperation, in addition to a haptics-capable master interface, often one or more force sensors are also used, which warrant new bilateral control architectures while increasing the cost and the complexity of the teleoperation system. In this paper, we investigate the added benefits of using force sensors that measure hand/master and slave/environment interactions and of utilizing local feedback loops on the teleoperation transparency. We compare the two-channel and the four-channel bilateral control systems in terms of stability and transparency, and study the stability and performance robustness of the four-channel method against nonidealities that arise during bilateral control implementation, which include master-slave communication latency and changes in the environment dynamics. The next issue addressed in the paper deals with the case where the master interface is not haptics capable, but the slave is equipped with a force sensor. In the context of robotics-assisted soft-tissue surgical applications, we explore through human factors experiments whether slave/environment force measurements can be of any help with regard to improving task performance. The last problem we study is whether slave/environment force information, with and without haptic capability in the master interface, can help improve outcomes under degraded visual conditions.

A Haptic Interface for Computer-Integrated Endoscopic Surgery and Training
Virtual Reality 2006
Authors: Mahdi Tavakoli, Rajni V. Patel, Mehrdad Moallem

Haptic feedback has the potential to provide superior performance in computer-integrated surgery and training. This paper discusses the design of a user interface that is capable of providing force feedback in all the degrees of freedom (DOFs) available during endoscopic surgery. Using the Jacobian matrix of the haptic interface and its singular values, methods are proposed for analysis and optimization of the interface performance with regard to the accuracy of force feedback, the range of applicable forces, and the accuracy of control. The haptic user interface is used with a sensorized slave robot to form a master–slave test-bed for studying haptic interaction in a minimally invasive environment. Using the master–slave test-bed, teleoperation experiments involving a single degree of freedom surgical task (palpation) are conducted. Different bilateral control methods are compared based on the transparency of the master–slave system in terms of transmitting the critical task-related information to the user in the context of soft-tissue surgical applications.

Methods and Mechanisms for Contact Feedback in a Robot-Assisted Minimally Invasive Environment
Surgical Endoscopy 2006
Authors: Mahdi Tavakoli, Arash Aziminejad, Rajni V. Patel, Mehrdad Moallem

Providing a surgeon with information regarding contacts made between instruments and tissue during robot-assisted interventions can improve task efficiency and reliability. In this report, different methods for feedback of such information to the surgeon are discussed. It is hypothesized that various methods of contact feedback have the potential to enhance performance in a robot-assisted minimally invasive environment. To verify the hypothesis, novel mechanisms needed for incorporating contact feedback were designed, including a surgeon–robot interface with full force feedback capabilities and a surgical end-effector with full force

sensing capabilities, that are suitable for minimally invasive applications. These two mechanisms were used to form a robotic “master–slave” test bed for studying the effect of contact feedback on the system and user performance. Using the master–slave system, experiments for surgical tasks involving soft tissue palpation were conducted. The performance of the master–slave system was validated in terms of criteria that assess the accurate transmission of task-related information to the surgeon, which is critical in the context of soft tissue surgical applications. Moreover, using a set of experiments involving human subjects, the performance of several users in carrying out the task was compared among different methods of contact feedback.

Haptic Interaction in Robot-Assisted Endoscopic Surgery: A Sensorized End Effector
International Journal of Medical Robotics and Computer Assisted Surgery 2005
Authors: Mahdi Tavakoli, Rajni V. Patel, Mehrdad Moallem

Conventional endoscopic surgery has some drawbacks that can be addressed by using robots. The robotic systems used for surgery are still in their infancy. A major deficiency is the lack of haptic feedback to the surgeon. In this paper, the benefits of haptic feedback in robot-assisted surgery are discussed. A novel robotic end-effector is then described that meets the requirements of endoscopic surgery and is sensorized for force/ torque feedback. The endoscopic end-effector is capable of non-invasively measuring its interaction with tissue in all the degrees of freedom available during endoscopic manipulation. It is also capable of remotely actuating a tip and measuring its interaction with the environment without using any sensors on the jaws. The sensorized end-effector can be used as the last arm of a surgical robot to incorporate haptic feedback and/or to evaluate skills and learning curves of residents and surgeons in endoscopic surgery.

Identification and Robust H# Control of the Rotational/Translational Actuator System
International Journal of Control, Automation, and Systems 2005
Authors: Mahdi Tavakoli, Hamid D. Taghirad, Mehdi Abrishamchian

The Rotational/Translational Actuator (RTAC) benchmark problem considers a fourth-order dynamical system involving the nonlinear interaction of a translational oscillator and an eccentric rotational proof mass. This problem has been posed to investigate the utility of a rotational actuator for stabilizing translational motion. In order to experimentally implement any of the model-based controllers proposed in the literature, the values of model parameters are required which are generally difficult to determine rigorously. In this paper, an approach to the least-squares estimation of the parameters of a system is formulated and practically applied to the RTAC system. On the other hand, this paper shows how to model a nonlinear system as a linear uncertain system via nonparametric system identification, in order to provide the information required for linear robust H# control design. This method is also applied to the RTAC system, which demonstrates severe nonlinearities due to the coupling from the rotational motion to the translational motion. Experimental results confirm that this approach can effectively condense the whole nonlinearities, uncertainties, and disturbances within the system into a favorable perturbation block.

Skills & Expertise

Robotics
Science
Matlab

Signal Processing
Biomedical Engineering
Haptics
Algorithms
Labview
Machine Learning
LaTeX
Electrical Engineering
Teaching
Control Theory
Image Processing
Computer Vision
Simulink
Simulations
Control Systems Design
Mathematical Modeling
Sensors
Artificial Intelligence
Numerical Analysis
Pattern Recognition
Physics
Experimentation

Education

The University of Western Ontario
PhD, Electrical and Computer Engineering, 2001 - 2005

K.N. Toosi University
MSc, Electrical Engineering, 1996 - 1999

Ferdowsi University of Mashhad
BSc, Electrical Engineering, 1992 - 1996

Interests

Robotics and Telerobotics, Haptics, Teleoperation Control, Surgical and Therapeutic Robotics, Image-Guided Surgery

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