Fiscal Year:	FY 2014	**Task Last Updated:**	FY 10/03/2014
PI Name:	Adelstein, Bernard Ph.D.		
Project Title:	Assessing and Mitigating the Impact of Transmission Delays on Teleoperations		
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Program/Discipline:	HUMAN RESEARCH		
Program/Discipline--Element/Subdiscipline:	HUMAN RESEARCH--Space Human Factors Engineering		
Joint Agency Name:		**TechPort:**	No
Human Research Program Elements:	(1) **SHFH**:Space Human Factors & Habitability (archival in 2017)		
Human Research Program Risks:	(1) **HSIA**:Risk of Adverse Outcomes Due to Inadequate Human Systems Integration Architecture		
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Space Biology Special Category:	None		
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Zip Code:	94035-1000	**Congressional District:**	18
Comments:			
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No. of PhD Candidates:		**No. of Master' Degrees:**	
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No. of Bachelor's Candidates:	5	**Monitoring Center:**	NASA JSC
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Key Personnel Changes/Previous PI:	None		
COI Name (Institution):	Ellis, Stephen (NASA Ames Research Center) Kaiser, Mary (NASA Ames Research Center)		
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Task Description:

The objective of the Directed Research Project (DRP) titled "Assessing and Mitigating the Impact of Transmission Delays on Teleoperations" is to examine coupled human-system performance in the presence of temporally varying communication delays between the human controller(s) and remotely operated robot(s), and to propose countermeasures for delay-induced performance decrements. This DRP will be conducted in support of the NASA Enabling Technology Development and Demonstration (ETDD) Program's Human Exploration Telerobotics (HET) Project, in which ground-station operators will control robotic assets on board the International Space Station (ISS). Specifically, the DRP will concentrate on the element led by NASA ARC that is focused on ground-to-orbit control of the "Synchronized Position, Hold, Engage, and Reorient Experimental Satellites" (SPHERES) free-flying robots on the ISS.
The DRP will focus on the range of time delays encountered in the ground-based control of the robotic assets on ISS, ranging from 20-50 ms (effectively for line-of-sight communication) up to 2-10 s for multiple satellite ground-station relayed (Tracking and Data Relay Satellite System, or TDRSS, and associated ground network) communication, and, in particular, as delay instantaneously varies because of real-time changes in communication paths and data buffering.

First, we will conduct human-in-the-loop (HITL) performance experiments using visual display of a dynamic simulation representative of a variety of SPHERES operations requiring different movement precision under this range of time-delay conditions. Next, we will examine HITL performance under these conditions employing mitigation techniques for short time delays such as prediction algorithms that generate compensatory in command signal lead and, for longer delays, predictive "feed-forward" graphical overlays that "look ahead" and provide a virtual view showing the future pose and location of the robot. The goal of the second of the studies is to understand the performance trades between these techniques in a wider variety of environmental and latency conditions than is usually achievable during in situ experimentation.

Finally, based on these empirical HITL results, we will design and test a strategy for combining and gracefully switching between mitigation techniques as telerobot system time delays vary across the millisecond to second range.

To conduct the DRP studies, we will build our experiment testbed derived from elements of the HET ground-to-orbit SPHERES task, encompassing ground operator user interfaces as well as computer-based simulations of the SPHERES robots and ground-ISS communication links. This strategy allows us to run HITL tests that will reduce the operating environment to offer sufficient flexibility and control for human performance experiments, yet still maintain salient features of the HET tasks key for face-validity and applicability of the results. The results from our experimental studies will help define more focused and scientifically revealing experiments that could subsequently be conducted on the ISS.

The aims of the proposed work are: 1) to employ human-in-the-loop (HITL) testing to empirically investigate the impact of variable communication delays, with latencies spanning from tens of milliseconds up to approximately five seconds, on coupled human-system performance for telerobotic systems; 2) to evaluate empirically the efficacy of existing time delay compensation schemes for this range of latencies for telerobotic tasks and control modes that have different required movement precision levels; and 3) to use the data resulting from these studies to identify the trade points between latency compensation schemes as a function of time delay and required task precision and then design and test strategies for gracefully switching between mitigation techniques as telerobot system time delays vary.

The guidelines, tools, mitigation techniques, and performance metrics developed from this research will help provide a rational basis for the design of teleoperation tasks to be carried out in the presence of communication delays. These products will in turn assist subsequent task, technology design, and validation experiment decisions regarding acceptable or desirable delay compensation techniques and define at what point to engage more autonomous operational modes.

Rationale for HRP Directed Research:

This research is directed because it contains highly constrained research, which requires focused and constrained data gathering and analysis that is more appropriately obtained through a non-competitive proposal.

Research Impact/Earth Benefits:

Potential Earth benefit from this work is for time-delayed teleoperation via the Internet or space satellite communication networks. Domains to which results of this work may ultimately be applied include telesurgery and remote piloting of unmanned autonomous vehicles (UAVs).

This directed research project addressed the current the risk of "Inadequate Design of Human and Automation/Robotic Integration," specifically targeting the current gap SHFE-HARI-04 "What are the effects of delays of different mission regimes on teleoperation and how do we mitigate these effects?"
Under this project, we studied the influence of latency due to transport delays on telerobotic user manual performance as a function of task control difficulty. For this series of experiments we first established a task that allows direct manipulation of the amount of control difficulty by the introduction of generalized rotations of the users' control frames of reference with respect to their viewing frames. Such rotations are typical of the non-optimal viewing conditions experienced when remote teleoperation cameras are not appropriately oriented with respect to the telerobot's end effectors or work environment. Employing sets of display-to-control rotations in three experimental investigations has allowed us to impose equivalent levels of difficulty for a highly generalized, three-dimensional, Fitts-like movement task that we studied in a high-fidelity virtual-environment simulation of a telerobotic reaching task.

In Experiment I, a wide range of rotations that varied in twist, i.e., rotation, magnitude, and axis orientation were studied using a wide range of body-referenced movement directions. In this experiment the rotation axes were aligned with the body's canonical axes. The resulting precise measurement of what we call the Misalignment Effect Function (MEF) has allowed development of a theoretically derived explanation for part of this function's range. It is based on pure pursuit tracking and is most parsimoniously described in terms of a proposed natural measure called normalized Path Length (nPL). This theoretical explanation, that we named the Secant Rule, has been shown accurate in predicting measured nPL for twists up to ~65 degrees. Using higher-order statistical moments of recorded normalized movement path lengths, we have shown how task performance transitions from our well characterized Secant Rule behavior to a still uncharacterized process for larger input-to-display rotations.

By repeating Experiment I with more generically oriented rotation axes Experiment II provided evidence for initially establishing nPL-based equivalence classes of rotations that could be quantitatively assigned to three known levels of control difficulty. A selection of rotation conditions from Experiment II were in turn used in Experiment III to investigate directly the interaction of latency and imposed control difficulty in a highly generalized way. Both nPL and

Task Progress:	targeting movement completion times were used in turn in a study of the interaction of control difficulty and latency. Our analysis of participants' ability in Experiment III to make movements in a wide variety of body-referenced target directions revealed a purely multiplicative interaction between latency and task difficulty. We showed that this interaction depends upon accounting for an internal human processing latency of ~250 ms, which parallels the interaction derived by E.R. Hoffmann (Ergonomics, 35, 1992) from experiments on Fitts' Law. Moreover, our data suggest that the interaction varies nonlinearly with rotationally imposed task difficulty in a manner quantitatively consistent with Hoffmann's results for Fitts' Index of Difficulty (ID). Further analysis has led us to propose a theoretically based quantitative model in the form of an additive pair of two-way multiplicative interactions that may predict overall task performance, as represented by movement time, for targeting movements in arbitrary directions subject to arbitrary input-to-display rotations, demands on movement precision (i.e., Fitts ID), and communication delays. One of the two-way model interactions is identical to Hoffmann's product of latency multiplied by Fitts ID. The other two-way interaction is the product of latency and the MEF resulting from our experimentally imposed input-to-display rotation. Up to this point we have only tested and demonstrated one of the proposed model's multiplicative two-way interactions, the one between rotation and delay. Assessing whether the pair of two-way interactions indeed does provide a valid description of the interaction between rotation, delay, and precision will require further empirical data from new studies in which all three of these factors are experimentally manipulated. These experimental studies should consider the full span of misalignment rotation angles up to 180 degrees, with specific focus both on angles where the Secant Rule applies and on larger angles where operator movement transitions to still undefined processes. Furthermore, these studies should also consider a more extensive range of time delays beyond the 800 ms we tested in Experiment III as well as a broad range of Fitts ID employed by Hoffmann rather than a single value. The testing of alternative models, including plausible purely multiplicative three-way interactions between these factors, should also be considered in the studies' design. Exploring the breadth of the proposed three-factor experimental parameter space would be useful in determining how far the quantitative theoretical model that we proposed could be extended. Data analyses should consider not only average operator responses but also higher statistical moment (variance, skew, kurtosis) to elucidate stochastic "noise" processes underlying teleoperator performance. Even when general closed-form mathematical descriptions cannot be expressed, the resulting experimental data, at minimum, would populate a look-up table that could provide a trade-space to weigh the relative impacts of, and the interactions between, input-to-display rotation, required precision, and communication delays for teleoperation applications as well as afford predictions of potential performance outcomes. Future work should also include more detailed analyses of movement trajectories of individual users' responses to stressed operation in the presence of latency. In particular, attention should be paid to different types of trajectory change points such as temporal pauses and spatial discontinuities that delimit submovements and may be indicators of underlying transitions in operator strategy and performance. Potentially, these analyses could lead to more dynamic-process models that would reveal deeper interrelations between MEF measures such as nPL and movement time as a function of teleoperation task conditions such as task difficulty (e.g., input-to-display rotation), required precision (i.e., Fitts ID), and communication latencies. This project narrowed the gap SHFE-HARI-04 by revealing a multiplicative interaction between latency and task difficulty experimentally imposed by input-to-display rotation in a manner analogous to that reported for task precision imposed by Fitts ID. Thus our results provide a basis for establishing requirements for reference tasks in which latency may be traded off against rotational or other types of difficulty in a manner analogous to what has been shown by Hoffmann for latency versus the task precision tradeoffs modeled by the Fitts ID. The project did not close the gap because it has not yet demonstrated how this new understanding can be applied to improve existing latency mitigation techniques, for example, for teleoperation systems using rate control. Consequently, because of the maturity of this work, new specifications or guidelines for teleoperation latency mitigation strategies cannot yet be offered.
Bibliography Type:	Description: (Last Updated: 04/13/2017)
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