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Project Title:	Sensory Manipulation as a Countermeasure to Robot Teleoperation Delays		
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Task Description:	Currently, most interactions with robots in space exploration are achieved through teleoperations. During future space teleoperations, communicating time delays associated with long distances may negatively affect performance if operators do not calibrate to it. The goal of this research is to test if sensory manipulation, especially providing virtual force cues via haptic device-generated feelings of touch and resistance (paired with delayed visual cues), can help mitigate the negative influence of teleoperation delays measured by perceived presence, neural efficiency, and task performance. This research aims to test the following hypothesis: Modifying haptic sensation alleviates the subjective perception of time delays and expedites operator's adaptation to stochastic delays in robot teleoperations. Human sensorimotor controls rely on multimodal sensory feedback, such as the visual, auditory, and tactile cues, to make sense of the consequence of the initiated action. Any latency between the action and the consequence creates a mismatch in motor perception and thus leads to perceptual-motor dysfunction. Literature has already found that sensory manipulation, i.e., providing additional sensory modalities as reinforcement cues, can modulate the effectiveness of motor learning and rehabilitation. The rationale of the proposed approach is that by simulating virtual force of physical interactions on the operator end, the delayed visual cues of teleoperation are reinforced by multimodal sensory feedback, mitigating the perception of time delays and improving performance. The two aims of this project are: Aim 1: Perform human-subject experiments to quantify how modified haptic stimulation expedites operator's adaptation to varying delays in teleoperations. The haptic simulation refers to reproducing the contact dynamics of the remote robotic system for operator via haptic devices. Note, the haptic simulation will be modified (in terms of timing and modes) to search for strategies for minimizing the subjective feeling of delays (primary outcome measure), ensuring accelerated adaptation to delays (secondary outcome measure), and ultimately, improving teleoperation performance (success metrics). Aim 2: Predict the short-term and long-term benefits and risks to the operators' functions based on neurobehavioral evidence. Neuroimaging data based on electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS), motion data, and performance data will be acquired to build a predictive model of human sensorimotor adaptation and performance with sensory manipulation in teleoperation tasks. The expected deliverables of this research include: (1) proof of concept evidence about the use of sensory manipulation in reducing the sense of time delays and expediting human adaptation to time-delayed robot teleoperations; (2) multimodal sensory feedback system design suggestions for human-robot interaction (HRI) in time-delayed teleoperations; and (3) quantitative models of functional and performance improvements in a variety of delay scenarios. This research proposes an innovative sensory manipulation approach to help reduce risks related to teleoperation delays. The neural, perception, and performance evidence contributes to the formulation of effective space teleoperation designs. The quantitative human models of perceptual and performance provide predictive models for NASA to perform risk and opportunity assessment for yet-to start missions that involve robot teleoperations. Lessons learned in this research will also inform a new training paradigm for both crewmembers and ground supports as for adapting to the changing environments in future deep space exploration with adaptive and assistive sensory augmentation. The data can also be transferred to other domains such as aviation and manufacturing industry with automation controls.
Rationale for HRP Directed Research:	
Research Impact/Earth Benefits:	This research project directly contributes to the HRR Human Factors and Behavioral Performance (HFBP) element, by narrowing the gap due to the inadequate design of human and robotic integration, via a new method and corresponding evidence pertaining to the design guidelines that take into account human capabilities and limitations with regards to management of automation or robotic asset(s) under time-varying communication latencies. Specifically, it proposes and tests an innovative, aggressive, while still technically feasible method of induced human adaptation to varying robot teleoperation latencies by sensory manipulation, i.e., modifying sensory stimulation paired with the motor actions in a way that (1) alleviates the subjective feeling of time delays and (2) expedites cognitive and behavioral adaptation to the delayed teleoperation. If warranted, the proposed method provides NASA with a new dimension of human-automation-robot-interaction (HARI) for time-varying communication latencies that differs from previous mitigation methods based on automation system design and training. The expected benefits include improved teleoperation performance, perceived higher comfort level and quality, with reduced training needs and simplified automation/robotic designs.
	The following progress has been made during the current reporting period: Aim 1: Develop a haptics-based sensory augmentation system for robot teleoperation. This aim proposed to develop a Virtual Reality (VR) and haptics-based simulator to support robot teleoperation with varying levels of delays (i.e., teleoperation latency). All proposed development has been completed, including the following components: a. A system that connected a real robot arm and a haptic controller (TouchX) was developed. Human operator could use the haptic device to control the remote robot in hand- picking tasks. b. Unity game engine was used to create a digital twin model of the remote robot and the workplace. Human operator could use a VR headset to visualize the remote workplace and the robot for coordinating the hand-picking tasks in an immersive way. c. Sensory augmentation system. Physical interactions, such as contact events, weight, texture, and momentum, were simulated via a physics engine, and were realized via the haptic controller. As such, the human operator could feel the enriched physical processes pertaining to the hand-picking task. To be noted, our system provides augmented haptic feelings (such as grabbing a weight in hands, or hitting a heavy object) in addition to regular tactile stimulations. d. Teleoperation delay simulation. We programmed the system to intentionally add three levels of latencies – 250ms, 500ms, and 750ms – to the visual or haptic feedback. As a result, we could test how different levels of latencies affected the teleoperation performance with our sensory augmentation system. Aim 2: Perform human-subject experiments (n=43) to explore the benefits of the proposed sensory augmentation system.

This aim proposed to collect experimental data on how modified haptic stimulation expedites operator's adaptation to varying delays in teleoperation. The haptic simulation refers to reproducing the contact dynamics of the remote robotic system (e.g., resistance, torque, nominal weight, etc.) for operator via haptic devices. Based on how the haptic simulation was modified (in terms of timing and modes), four conditions were tested:

Condition 1: Control condition, where haptic feedback and visual feedback happen immediately after an action initiated by the human operator, i.e., in real time without any delay.

Condition 2: Anchoring, where the haptic feedback happens immediately after an action, i.e., in real time, while the visual feedback is delayed for 250ms, 500ms, or 750ms.

Condition 3: Synchronous, where the haptic feedback and visual feedback are both delayed synchronously after an action for 250ms, 500ms, or 750ms.

Condition 4: Asynchronous, where the haptic feedback and visual feedback are both delayed after the action, and the amounts of delays of the two feedbacks are different.

Our hypothesis is that modifying haptic sensation along with the visual feedback alleviates the subjective perception of time delays and expedites operator's adaptation to stochastic delays in robot teleoperation. We call this method sensory manipulation.

We successfully recruited 43 healthy subjects to test the hypothesis. A VR model was created to simulate a replace and repair (R&R) task in a low gravitational environment. The task involves picking up, moving, and placing four objects with different masses as fast as and as accurately as possible. The experiment was designed as a within-participant experiment, i.e., each participating subject experienced four conditions. To avoid learning effects, the sequence order was shuffled for each subject. The performance data (time and accuracy), motion data (moving trajectory), eye tracking data (gaze focus and pupillary size), and neurofunctional data (measured by Functional Near-Infrared Spectroscopy, or fNIRS) were collected.

Task Progress:

Aim 3: Data analysis to quantify the impacts of the proposed sensory augmentation method on teleoperation performance and human function.

This aim proposed to analyze the experiment data to better understand if the proposed system can improve teleoperation performance while reducing the perceived delays. The analysis is still ongoing with the following preliminary findings:

a. The augmented haptic feedback indeed improves the teleoperation performance. The anchoring condition, i.e., providing haptic cues coupled with the action, significantly improved the hand-picking task in terms of time, independent of the visual delays. It could be because human subjects could rely more on haptic feedback when it was available to coordinate the teleoperation actions. The benefit of providing a real-time haptic stimulation boosted the performance to a level similar to the control condition (i.e., no delay). To be noted, we did not observe significant differences across the four conditions in terms of picking and dropping accuracy. This could be due to the overall level of difficulty; e.g., if the designed task was not challenging enough.

b. The augmented haptic feedback can reduce subjective feeling of teleoperation delays. As for the perceived visual delays, the data shows that under the anchoring condition, the overall average perceived visual delay in teleoperation was significantly lower than the synchronous condition. And the perceived visual delay seemed to be the highest under the asynchronous condition. About 18% of the test subjects reported a perceived visual delay that was actually smaller than the actual one under the anchoring condition. For example, when the actual visual delay was 750ms, a subject reported 100ms as the perceived delay. It means that coupling real-time haptic feedback with the action during teleoperation can mitigate the subjective feeling of delays. As for the perceived haptic delays, the data shows a little different pattern. Subjects seemed to report a lower perceived haptic delay under the synchronized condition. This makes sense because the coupled haptic and visual feedback may help a better estimate of the haptic delay. As for the visuomotor delay perception, it shows that under the anchoring condition, a significant amount of subjects reported a delay smaller than the actual one. All these results confirmed the perceptual benefits of having haptic feedback synchronized with the action.

c. The augmented haptic feedback can reduce cognitive load. When analyzing the overall cognitive load over the entire course of the task, the synchronized condition shows the lowest cognitive load. Surprisingly, the anchoring condition and the control condition don't show a lower load as expected. This might suggest an increased cognitive load does not often lead to a worse performance. It deserves a further investigation. In addition, we analyzed the cognitive load changes from the beginning of the task to the end of the task. It shows that across the four conditions, there is a general trend of cognitive load increasing. It may suggest that participating subjects experienced a continuously increasing load during the task. This trend is confirmed by the preliminary fNIRS analysis.

The human-subject experiment (n=43) confirmed a variety of benefits of the proposed sensory manipulation method in teleoperation tasks with delays. It generally confirmed that providing haptic cues along with the initiated action could significantly reduce teleoperation time, no matter how much visual delay presented. It was also found that participating subjects tended to perceive a smaller visual delay when real-time haptic cues were provided. The preliminary findings suggest that the anchoring method, i.e., providing real-time haptic feedback, has multiple performance and functional benefits. The cognitive load analysis found that the synchronized condition led to the lowest cognitive load, followed by the anchoring condition. A further analysis is needed to explain the divergence between the cognitive load data and the performance data.

In the next reporting period, we expect to complete the analysis of the experimental data and provide concrete human performance and functional data (neural, physiological, and self-reports) to model the implications of multimodal sensory stimulation in teleoperation with varying levels of time delays. In addition, we propose to add some additional experiments with longer delay levels (i.e., 3s) and a more difficult hand-picking task (i.e., a longer moving distance). Although the planned new experiments are out of the proposed scope of this research, we believe that they will help us better understand the boundary of the preliminary discoveries, and the applicable scenarios of the proposed method.

Targeting on the time delays issues in robot teleoperation, this research proposes the third way, in addition to automation design and training: induced human adaptation. Inspired by the motor learning and rehabilitation literature, this research hypothesizes that modified (time points, frequency, modality, and magnitude) sensory stimulation, paired with the motor actions, helps alleviate the subjective feeling of time delays, and expedite human functional adaptation to time-delayed

	teleoperation, without the need for excessive trainings, or sophisticatedly designed automation/robotic systems.
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