MULTISENSORY REAL-TIME SPACE TELEROBOTICS. DEVELOPMENT AND ANALYSIS OF REAL-TIME TELEROBOTICS SYSTEMS FOR SPACE EXPLORATION

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ABSTRACT

We introduce a research project whose goal is the development and analysis of real-time telerobotic control setups for space exploration in stationary orbit and from deep-space habitats. We suggest a new approach to real-time space telerobotics - Multisensory Real-time Space Telerobotics - in order to improve perceptual functions in operators and surpass sensorimotor perturbations caused by altered gravity conditions. We submit that telerobotic operations, in such conditions, can be improved by offering enhanced sources of sensory information to the operator: combined visual, auditory, chemical and somatosensory stimuli. We will characterize and compare the effects of enhanced versus restricted sensory experiences, in operators' performance, during real-time telerobotic operations on Earth (ground-to-ground) and microgravity (space-to-ground) conditions. Specifically, we will evaluate cognitive and physical response (sustained attention/cognitive load; physical effort), efficacy and efficiency (including safety factors), in operators, while interacting with a telerobotic control station - used to control a remote rover on the Earth's surface (artificial space analogues).

1 INTRODUCTION

It was on April 1961 when, for the first time, the human body dispensed with the physical laws of linear acceleration and crossed the boundaries of Earth's atmosphere. Yuri Gagarin was the first human to achieve such an intrepid feat: completing an Earth orbit aboard the Vostok 1 spacecraft [12]. Once again, human biology was confronted with extreme environmental conditions - this time, in a relatively distant setting from Earth, thus far, only a by-product of human abstractions [13].

Three main motives have been raised in order to justify human presence in space environments: to ensure human survival, to develop the next evolutionary stages, and to create new ways to perceive novel environmental properties [9, 36]. Nevertheless, space environments are hostile for humans. Stressors such as altered gravity and pressure conditions, ionizing radiation, changes in day and night cycles, to mention a few variables, demand human biological adaptation, and disturb, in most cases, human performance [5].

One of the main goals of space telerobotics has been temporarily substitution of direct human exploration of space environments. The rationale in support of this later argument is the difficulties in achieving human exploration - due to current technical limitations on spacecraft and EVA technology (i.e., spacesuits) [31]. Another key goal of space telerobotics has been preparing direct human space exploration - terraforming planetary bodies in order to support human expedition and, ultimately, Earth-like life [34].

Lately, there has been a strong investment on the preparation of Crew Surface Telerobotics (CST) missions for space exploration - the crew remotely operates surface robots from a spacecraft or deep-space habitats [10]. These missions include Moon, Mars and Near-Earth Asteroid exploration [4, 16, 34]. CST missions include, for instance, the Human Lunar Exploration Precursor Project (HLEPP) from ESA [16] and the Exploration Mission-2 from NASA - expected to start in the opening half of 2020 [30]. One of the central goals of these missions is to explore the geological features of the Moon surface - the lunar farside - via robotic systems: a crew inside the Orion Multi-purpose Crew Vehicle (OMPCV) and/or the Deep Space Gateway (DSG), in stationary orbit (Near Rectilinear Halo Orbit - NRHO), will teleoperate robotic rovers on the Moon surface. ESA is also planning Moon surface exploration missions from surface pressurized rovers (mobile deep-space habitats) - a crew operates, e.g., robot arms attached to the pressurized rovers/rovers at distance.

A main objective of the previously mentioned CST missions is to collect geological samples from the South Pole-Aitkin Basin - namely, the Schrödinger Basin, in the lunar farside: an unexplored and geological-rich region enclosing rocks from older events in lunar history [8]. These samples are critical for investigating the cataclysm and ocean magma hypotheses.

According to ESA studies, the telerobotic tasks to be carried out in the Schrödinger basin, , include, for example: analyzing surface features and sample collection; preparing landing sites; deploying retro-reflectors/beacons or markers on landing sites and key geological areas; deploying storage/habitation systems on the surface; and monitoring landing locations [16].

The latest envisioned scenario encompasses two phases for Moon exploration: phase A - preparation for direct human lunar exploration - and phase B - human lunar surface exploration. During phase A (approximately one year), CST missions will be performed from Earth (ground control - 90% of the time) and stationary orbit (10% of the time - approximately 10 days). In phase B (approximately 42 days), humans will operate robotic systems from pressurized rovers [16].

The communication latency (two-way speed of light) between NRHO and the lunar farside is approximately 0.4 seconds [1] (including occasional signal interruptions); when considering phase B, the latency between surface pressurized rovers and robotic assets on the surface can be inferior to 0.4 seconds. These short communication latencies tolerate real-time (or on-line) remote control of robots on the lunar surface - allowing high-fidelity telepresence operations, translated in facilitation of such tasks as previously mentioned, from geological to lunar base development operations [23].

Research already indicates benefits that can be expected from robotic control under low-latency situation; e.g., "a factor of 2 improvement in speed operating from NRHO (~ 0.5 seconds) instead of Earth (…) when testing multiple users on a lunar driving simulator using varying latency" [16:40]. These results seem to be particularly relevant, given the fact that one of the main goals of lunar CST missions is achieving an as high as possible scientific return per capital investment for each mission.

Analyses and tests must be carried out in order to define the most critical operating setup for real-time remote control of space robots. We explain, in the following part of this paper, why these tests have to be performed in environmental conditions similar to those of the envisioned CST space missions, and why the feasibility evaluation should be also carried out aboard the International Space Station (ISS).

The central goal of the current research project is the development and analysis of real-time telerobotic control setups for space exploration in stationary orbit and from deep-space habitats. In this research project, we will specifically carry out CST feasibility experiments in micro-g (Low Earth Orbit - LEO) - aboard the ISS. Since lunar geological exploration/ surface preparation for direct human exploration are currently considered as priority missions to for the international space community, we decided to run CST feasibility experiments to control rovers on Earth from the ISS (analogue to crew in cislunar orbit controlling robots on the lunar surface) - including tasks, such as navigation, geological sample collection (e.g., rocks) and surface preparation for direct human exploration (e.g., preparing landing sites), in Moon analogues.

Earth-ground experiments will be carried out prior to CST feasibility experiments (in LEO) in order to refine the telerobotic control setups to be sent to the ISS as well as, accurately refine the experiments to be conducted in the ISS. This approach also makes it possible to compare operators' performance under Earth-ground and micro-g conditions - human factors.

In summary, the main goals of this research project are: the development and analysis of real-time telerobotic control setups for space exploration in stationary orbit and from deep-space habitats; investigate how Earth and micro-g conditions affect operator performance during telerobotic operations; investigate how short-, medium- and long-term exposure to micro-g affects operator performance during telerobotic operations - biological adaptation to altered gravity may affect operator performance.

2 PROBLEM AND HYPOTHESES

2.1 Real-time Space Telerobotics - The Segmented Human Body

Supervisory control methods are advantageous for telerobotic operations - allowing the operator to plan future steps to be taken, due to infrequent robot supervision (execution placed on the robot). This method has been proven to be effective for navigation tasks - allowing the operator to focus on scientific data instead of complex robot control in real-time [7]. Despite recent advances, autonomous control in robots is still in its infancy and is less effective and efficient at interacting with unstructured physical environments, compared to humans; mainly because robots are still endowed with rudimentary cognitive skills, e.g., less effective perceptual-motor, decision-making and planning skills [10, 34]. [10] showed that scouting missions were more successful, when operators could manually control a rover, compared to autonomous navigation.

An alternative approach to human-supervision methods has been explored, in order to surpass autonomy constrains and improve efficacy and efficiency during space telerobotic operations. We allude to the field of real-time (or on-line) space telerobotics via force-feedback (FFB) control: a method to be applied when the operator experiences low communication latencies between the control station and the remote environment (e.g., Moon orbit to Moon surface) - in order of milliseconds (500 to 800 milliseconds). This approach targets at facilitating tasks requiring control of complex robot motion in real-time (e.g., complex navigation tasks; fine motor control of a robot arm) [38].

FFB aims at inducing to the operator a feeling/impression of contact with the remote environment - to increase operator's situational awareness [32, 46]. Real-time telerobotic operations via FFB typically proceed as follow: the operator receives visual feedback from the remote location (via a graphical user interface), at the same time he makes

[1] The maximum latency for real-time telepresence is approximately 0.5 seconds ("latencies within the cognitive window of the human reaction time") - beyond this point, perceptual functions are usually compromised [22:1].

use of a physical interface, providing FFB, (master, e.g., force reflective hand controllers) to control a desired trajectory on a slave robot (e.g., robot arm) in the remote location. The main goal of FFB is to provide back to the operator, the forces that the operator imposes on the task, while interacting with the remote environment. This is usually achieved via actuators that reflect torque forces back to the operator - e.g., gripper in the robot arm (e.g., while grasping an object).

Present-day FFB control interfaces (e.g., force reflective hand controllers; exoskeletons) mainly stimulate the following sensory organs in the human body: cutaneous (skin mechanoreceptors sensitive to pressure, vibration, slip and texture - respond to skin stretch and mechanical deformation; allowing detection of object size, shape, texture, motion and velocity via skin stretch); proprioceptors and vestibular system (information from muscle spindles, joints, vestibular system and eyes; encode information relative to self-motion and body schema, posture and balance) [15].

Several studies indicate that FFB improves telerobotic operations compared to no FFB (visual stimulus only), on Earth [32, 46:242] - "providing force feedback from the environment to the human operator yields a reduction in task completion time, energy consumption, error indices, the magnitudes of the contact forces, and the user's cognitive workload".

Research conducted by the Human-Robot Interaction Lab, at ESA, showed promising results regarding real-time telerobotics, via FFB control, in micro-g (LEO) - focusing on the suitability of FFB applied to a joystick controller (and not robot control per se). Studies indicated that there's a trend for no differences in human stiffness discrimination between Earth and micro-g conditions - astronauts were evaluated after a 3-month adaptation period to micro-g; FFB, at the level of a human, can be implemented with delays as high as 0.8 seconds (yet values are complexity-dependent) [38]. However, no studies were conducted to validate real-time teleoperation of surface robots via FFB control in micro-g (e.g., controlling rover navigation).

A study indicated that both tracking and control of movement impulses were deteriorated, in an astronaut, while manipulating a FFB joystick controller in micro-g (compared to Earth). The astronaut manipulated the joystick in an upright position, "stabilizing his body with a handle for the left hand and module rails for the feet". The astronaut had to control a 2-DOF robot located on Earth - manipulate a pointer (end effector) integrated on the robot, in order to accomplish tracking tasks. The astronaut was participating in his third space mission (total of 410 days spent in space). The study was conducted on the 45th flight-day [45:8].

Until now, it is still unknown if FFB control per se represents an advantage for real-time teleoperation of space robots in altered gravity conditions. Interestingly, researchers have indicated that FFB interfaces do not represent the full spectrum of natural haptic feedback from the environment, thus, compromising situational awareness - reason why, FFB tends to have limited benefit on overall telerobotics performance, on Earth conditions (improvements in order of 50%) [32, 33].

According to [32], it takes significantly more time to perform a task with a teleoperation interface integrated with FFB, compared to when the task is performed manually - teleoperation also tends to be more prone to error. The author performed a meta-analysis of FFB studies, indicating that there is increased risk to damage the material in the remote environment, due to lack of precise force regulation; FFB mechanisms to prevent excessive forces tend to degrade operator performance.

[33:164] performed an analysis on haptic interfaces for telerobotic operations, in which it was concluded that: "A tele-manipulator is typically not able to represent the full spectrum of natural haptic feedback from the environment as it filters and degrades the position and force information that passes through. The quality of the feedback is often referred to as the transparency of the tele-manipulator and can be indicated by e.g. the transmitted impedance of the remote environment that is felt by the operator. The transparency of tele-manipulators is still imperfect and has many unresolved issues (…) limited transparency already improves task performance substantially compared to no transparency. Further system oriented improvements in transparency (…) tend to have limited additional benefit on the overall task performance".

Hence, FFB control per se, may not be sufficient to improve situational awareness in operators.

Studies in micro-g (LEO) indicate impairments in sensorimotor functions, in astronauts, during short-term spaceflight, compared to Earth-ground conditions: fine manual control decrements (reduced speed and accuracy of movements); degraded postural control (including balance) and sensing of limb position - both affecting spatial perception. Sensorimotor impairments have been a primary cause of accidents in space [6, 25].

The previous results are particularly concerning for telerobotic operations in real-time, which require accurate motor control from operators. Degraded sensorimotor functions, in altered gravity, may also change how operators perceive FFB information - decreased ability to discriminate vibrotactile frequencies and their relation to physical action; may be highly disturbing for short-term telerobotics space exploration missions (e.g., the ESA CST lunar missions are projected to last up to 10 to 42 days).

We suggest a new approach to real-time space telerobotics - Multisensory Real-time Space Telerobotics (MRTST) - in order to improve perceptual functions in operators and surpass sensorimotor perturbations caused by altered gravity conditions. We argue that telerobotic operations, in altered gravity conditions, can be improved by offering enhanced sources of sensory information to the operator.

The sensory organs in the human body encode information from the physical environment. Multisensory integration regards the integration of multiple sources of sensory information in the nervous system, in order to generate coherent percepts from the environment and to facilitate goal-directed behavior within it. Perception refers to the identification, organization and interpretation of sensory information (to represent the environment) [37, 40]. Combined sources of sensory information (e.g., visual, auditory and somatosensory) tend to facilitate perception and goal-directed behavior in the physical world [40, 41].

Exposing humans to a limited number of sources of sensory information (e.g., visual, or visual and somatosensory) may reduce situational awareness (closed communication between sensory organs and the environment), and thus, goal-directed behavior in the physical world. We decided to employ a metaphor do describe this idea: *the segmented human body*.

MRTST aims at optimizing real-time telerobotic operations, in altered gravity conditions - improve efficacy, efficiency and safety - by optimizing perceptual functions and motor control as well as reducing mental and physical fatigue in operators. This approach encourages the development of telerobotic control setups in synergy with the human body, via (see fig. 1):

- Enhanced sensory experiences - stimulating multiple sensory systems in the human body (visual, auditory, chemical, somatosensory);
- Biocybernetically Adaptive Interfaces that adapt to the biological response of each operator - e.g., real-time detection and maintenance of alertness levels/reduction of physical load (e.g., detection of cognitive states via a brain-machine interface/physical load via metabolic interfaces) - future work.

Our approach will be detailed in the next subchapter.

Figure 1: Conceptual MRTST on the Moon.

2.2 Multisensory Real-time Space Telerobotics

Enhanced sensory experiences provide the operator different and complementary sources of information about the remote environment - what may improve situational awareness in operators.

We hypothesize that:
H_0: Enhanced sensory experiences (combined visual, auditory, chemical, cutaneous and somatosensory stimuli) increase operator's efficacy and efficiency, in real-time space telerobotic operations, compared to restricted sensory experiences (unimodal or bimodal stimulation - e.g., stimulating the visual senses; visual and somatosensory senses; or the visual and auditory senses).

We will start by evaluating if combined visual, auditory and somatosensory stimuli represents an advantage for space telerobotic operations. We put forward two main arguments - I/II - in support of the previous hypothesis.

I - Enhanced sensory experiences may improve perceptual functions in operators, in altered gravity conditions

Hominids evolved during millions of years actively exploring multiple sources of sensory information in the physical environment. Hence, it seems no coincidence that humans are better at encoding multisensory events compared to restricted sensory events - perception is made easier when combining information from multiple sensory modalities. For instance, visual inputs "have been shown to enhance the sensitivity of neurons to sound location" [17].

Input projections from different sensory modalities (unisensory afferents) converge on individual multisensory neurons in the brain - that simultaneously process multiple sources of sensory information (e.g., visual, auditory, somatosensory). Multisensory neurons have been detected in multiple brain areas, e.g., the superior colliculus, posterior thalamic nuclei, cerebellum, amygdala and higher-order association cortex. These areas work cooperatively to generate coherent percepts from the physical environment [40].

Humans react faster to trimodal stimulus (combined visual, auditory and somatosensory) compared to unimodal or bimodal stimuli (visual; visual plus auditory/somatosensory) - e.g., faster manual reaction time - observed when trimodal stimulus are presented simultaneously, or with small delays [18, 43].

Synchronized trimodal stimulus (visual, auditory, somatosensory) optimizes human perception - interactions between two modalities are modulated by the signal in the third modality; synchronized stimuli tends to improve perception - e.g., when temporal synchrony unites the motion of an object with sound [24, 48]. Conflicting presentation of sensory information tends to compromise perception (also at semantic level - e.g., auditory distractors during a task).

According to [48:9], the visual system has less temporal precision than the auditory and tactile systems. Humans better perceive (identify)/react faster to auditory compared to visual and tactile stimuli [15].

Telerobotics research (e.g., control of robot arms) showed that bimodal experiences (combined visual and somatosensory or auditory stimuli) - tend to optimize operators' performance, compared to unimodal experiences (visual stimulus only), in Earth-ground conditions - improvements translated in decreases in task completion times/error rates, lower peak force, less variability and less damaging contact forces [26, 27].

[26] showed that replacing FFB information with auditory information - representing forces through sound (sensory substitution) - provided a significant advantage in perception of contact forces in operators. Auditory stimulus was also an advantage for telerobotic tasks with high temporal delays - where FFB was no useful due to increased operational errors (operators were also unable to complete tasks).

Studies comparing the effects of trimodal experiences in operators' performance are scarce. Researchers in telesurgery found that trimodal stimulus (combined visual, auditory and somatosensory) improved situational awareness in operators [27].

The previous results suggest that enhanced sensory experiences tend to improve perception in humans (including reaction time), compared to restricted sensory experiences, in Earth-ground conditions. No micro-g studies have evaluated this relation. In similar fashion, we reason that enhanced sensory experiences may improve perception in operators (including reaction time), compared to restricted sensory experiences, in altered gravity conditions - e.g., combined visual, auditory, somatosensory versus visual/visual plus auditory or somatosensory stimuli. In turn, perceptual improvements may optimize space telerobotic operations.

As previously mentioned, studies indicate impairments in sensorimotor functions (e.g., manual control) in astronauts during short-term spaceflight (also observed during Moon exploration). Visual function seems also to be degraded in micro-g (LEO), namely during initial stages of spaceflight - e.g., degraded visuo-motor performance, reduced contrast sensitivity, decrements in near vision acuity (difficulties in evaluating distances, object's size and shape) [5].

The previous outlined biological changes will affect the use of any kind of telerobotic interface - degraded sensorimotor and visual functions (perceptual-motor skills) may disturb motor control, inducing more errors during teleoperation.

Auditory function seems no to be altered in micro-g (LEO) conditions [5].

As previously mentioned, Earth-ground research showed that humans are faster reacting to auditory, compared to visual and tactile stimuli. [3] found that auditory signals facilitate tactile perception. Hence, auditory stimulus may be a determinant factor for optimizing space telerobotic operations - the operator can rely on auditory information to better/faster perceive and act in the remote environment, when experiencing sensorimotor and visual degradation.

FFB interfaces tend to not represent the full spectrum of natural haptic feedback from the environment. The previous factor, added with sensorimotor and visual degradation, in micro-g, may contribute to decrease situational awareness in operators - contributing to less accurate mental models of the remote environment - worsening action control within it. Auditory stimulus can work as a perceptual facilitator - compensating for gaps on haptic feedback and sensorimotor/visual degradation - by providing additional sources of information, from the remote environment, to the operator (e.g., perception of robot motion can be facilitated by uniting robot motion with sound - friction/ stiction noises for better/safest robot motion control).

As previously mentioned, synchronized sensory stimuli tends to improve perception - e.g., the consequence of a motor action (object's motion) must be immediately perceived by the operator in order to perform effective, efficient and safe interactions with the remote site. According to [39:235], sensory feedback delays result in performance degradation (e.g., delays in visual feedback significantly increase manipulation performance times - 1 to 3 seconds).

Humans react faster to trimodal stimuli - faster manual reaction time, which is critical for the control of remote robots, via physical interfaces. This response was observed when stimuli are presented simultaneously, or with small delays. Hence, trimodal stimulus may improve reaction time in operators, even when experiencing temporal asynchronies between sources of sensory information. Faster reaction time to auditory stimuli may improve motor control of remote robots and decrease operational errors, in operators, when experiencing delays relative to visual and somatosensory information - the operator may faster perceive (interpret) and act in the remote environment (better connection of segmented time events for the prospective attainment of a goal, e.g., continuous motion of a robot arm).

[20] found that 40 sleep-deprived subjects had faster reaction time to auditory compared to visual stimuli. Astronauts suffer from chronic sleep loss during spaceflight - linked to mental and physical fatigue, which in turn is linked to performance decrements and operational errors [29]. Faster reaction time to auditory stimuli may increase safety during telerobotic operations, by improving motor performance and decreasing operational errors in fatigued astronauts.

In effect, we also hypothesize that enhanced sensory experiences may reduce cognitive and physical fatigue in humans, compared to restricted sensory experiences, in altered gravity conditions. In turn, decreases in cognitive and physical fatigue may improve operators' performance during space telerobotic operations.

II - Enhanced sensory experiences may reduce cognitive and physical fatigue in operators, in altered gravity conditions

Space environments are considered extreme environments - "which demand complex processes of physiological and psychological adaptation". Extreme environments increase cognitive and physical fatigue in humans - converting relatively simple tasks into complex tasks [21:15]. Significant increases in fatigue denote cognitive and/or physical exhaustion [42], which is, in most cases, linked to cognitive and physical performance decrements - in both, Earth and micro-g (LEO) conditions [2, 14, 29].

Chronic sleep loss, circadian desynchronization and work overload contribute to increased fatigue in astronauts - linked to decreases in alertness, increases in cognitive load and performance decrements [29].

Studies indicate that cognitive and physical fatigue tends to be associated with sensorimotor performance degradation in micro-g (LEO) - including increased risk of accidents [11, 25, 28]. Space telerobotics missions have been subject to incidents due to crew fatigue - several incidents have occurred during the control of the Canada arm (control errors and a near collision) [47].

Time-on-task tends to impair operators' performance on Earth (subject to interindividual variation) [14] - no studies evaluated this relation in space conditions.

Real-time CST lunar missions are predicted to last up to 42 days (from surface pressurized rovers) - including long-term teleoperation of robots - 6-8 hours (also from orbit), which will probably increase cognitive and physical fatigue in operators. Furthermore, astronauts may not have appropriate time to adapt to the new environment.

The previous results are concerning for space telerobotics missions, which require optimal cognitive and physical performance from the operator in order to be successful.

Cognitive performance decrements are, in most cases, associated with decreases in alertness (sustained attention) and increases in cognitive load [1, 2]. We argue that enhanced sensory experiences may optimize attention and memory functions in operators, in altered gravity conditions - translated in increases in alertness and decreases in cognitive load, respectively.

Alertness concerns the ability to respond to events in the environment and is characterized as a continuous function - maintaining focus during a task in the presence of distracting stimuli [35]. Researchers have emphasized that alertness relies on bottom-up sensory input [2]; increased sustained attention tends to facilitate perception in humans [35].

Hence, we suggest that enhanced sensory experiences (e.g., combined visual, auditory and somatosensory stimuli) may increase alertness levels in operators, compared to restricted sensory experiences (e.g., visual; visual plus auditory or somatosensory), in altered gravity conditions. In turn, increased alertness may improve situational awareness in operators by contributing to accurate mental representations (in the working memory system) of the remote environment where teleoperation occurs - increased awareness about elements/event sequences (e.g., landscape; robot motion) in the remote site, thus, facilitating action-related functions (including decision-making improvements through upholding of accurate information in the working memory system).

General studies in micro-g (LEO) showed that subjective alertness appears to decline over time during spaceflight (17-days mission) [28] - what may compromise telerobotic operations. Studies evaluating alertness and space telerobotic operations are missing.

Working memory capacity is evaluated by accessing cognitive load levels [1, 2]. According to [1:165], "Cognitive workload has been conceptualized as the allocation of mental resources or effort required to maintain adequate performance on one or more tasks". Enhanced sources of sensory information tend to reduce load in the working memory system, because information load is spread over multiple sensory modalities - facilitating processing of information [41].

Exposure to enhanced sensory experiences can decrease cognitive load in operators and thus increase their working memory capacity - benefiting the retention/maintenance of information in the working memory system and facilitating perceptual functions.

Increases in working memory capacity are particularly relevant in space conditions - operators may have increased difficulties in processing visual and somatosensory information, due to ongoing space adaptation. Disturbances in information processing may overload the operator's working memory system and, thus, compromise perception during teleoperation. Additional sensory sources - auditory (beyond visual and somatosensory) - may facilitate information processing. By doing so, they free up space in the working memory system for the processing of visual and somatosensory information.

Micro-g studies (subjective assessment) showed increased cognitive load to be associated with motor performance decrements - e.g., degraded joystick control on an aiming task and motor accuracy on a tracking task [11, 25]. A LEO study [4] evaluated cognitive load levels in an astronaut during telerobotic operations (subjective assessment). It was observed that 3-D views of rover activity and state reduced cognitive load in the operator.

Improvements in cognitive performance - attention and memory functions - may optimize space telerobotic operations - translated in increased efficacy and efficiency (improved motor control/reduced task-completion times) and less performance errors (due to increased situational awareness) during teleoperation.

Improved motor control caused by improvements in cognitive performance, may also reduce operator's physical effort. Increases in physical load, during telerobotic operations, may happen due to lack of efficacy and efficiency in motor control - e.g., lack of motor efficiency during running tasks is linked to increased metabolic costs in humans [19]. Improved motor control may reduce physical effort and thus errors/accidents.

3 SUMMARY AND OUTLOOK

In summary, improvements in the mental and physical state of operators should enable better control over robotic systems and, thus, reduce mission completion times - greater efficacy, efficiency and safety during telerobotic operations (hence, lowering mission costs).

The present research work aims at evaluating if offering enhanced sources of sensory information to the operator, is an option, or if it represents a critical aspect for real-time space telerobotic operations. No studies have evaluated this topic.

There are further advantages of enhanced sensory experiences for humans in altered gravity conditions.

Enhanced sensory experiences can contribute to the overall maintenance of physical and mental health in astronauts - reducing overall physical and mental fatigue. Because biological adaptation to space environments may require more intervention of the body's energy sources (metabolic energy), decreased physical and mental fatigue may also facilitate adaptation processes - by releasing more energy for the restructuring of biological structure and functions.

Furthermore, we suggest that, depriving humans from enhanced sensory experiences, during long-term space missions, may degrade or eliminate the integrative capacity of multisensory neurons in the human brain - degrading multisensory abilities, as observed in Earth-ground studies [44]. This may be particularly concerning for astronauts who must maintain their sensory capabilities to the maximum, e.g., to transit in extreme environmental conditions - e.g., transiting from a spacecraft (micro-g) to Mars (increased gravitational forces compared to micro-g). The ability to integrate multiple sources of sensory information facilitates action in the physical environment.

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