Deep Space & Haptic Encounters of The HRI Kind

Jeremy Bloom
Raphael Recanati
International School (IDC)
Herzliya, Israel
Jeremy.Bloom@post.idc.ac.il

ABSTRACT

Recent years have witnessed increasing global interest in space exploration and plans for interplanetary expansion. Operations in deep space are highly complex and require effective collaboration from several parties including ground control, robots and space crews. Manned missions conducted in EV (extravehicular) environments have added dangers and risks, including partial or full loss of communication with ground control or their space crew. Following technological advancements, there has been a rise of human-robot teams operating autonomously for such precarious missions. This paper describes several approaches in human-robot interactions, and then focuses more specifically on the ability of autonomous robots to remotely engage with their human teammates in deep space through diverse haptic interactions to enhance safety and spatial awareness. In addition a conceptual prototype is presented to demonstrate this HRI medium using a haptic feedback system embedded in the space suit of an astronaut.

KEYWORDS

Deep Space; Human-Robot Interaction;
Haptic Feedback; Space Exploration.

INTRODUCTION

Humanity's greatest accomplishment will be its expansion into a multi-planetary species. For mankind to achieve this goal, we must extend our knowledge in the processes involved with conducting space exploration. Momentum for space exploration and the pursuit of interplanetary expansion has been building in recent years, with the ambitious projection of the first landing of humans on the surface of Mars as early as 2033. Sending humans to live in space, however, poses both challenges and opportunities that go well beyond the technical and logistics of landing there [5]**.** These endeavors will require the enlistment and assistance of robots, machines and autonomous systems in the context of completing missions during operational spaceflight.

Deep Space

The deep space environment outside spacecraft is completely unforgiving and hostile to life. Surface temperatures can range from -180 C in darkness and 440 C in sunlight, with high radiation and no atmosphere [14]. Yet, astronauts must complete their missions in this environment, under high workload and high stress, sheltered inside bulky spacesuits. To limit the risks of space walks, the ability to perform physical actions remotely is crucial [14].

During spacewalks, various challenges arise from the nature of microgravity and unexpected meteoroid and space debris particles. EVAs are monitored remotely, so support ground personnel can look for anomalies to detect changes, anticipate incidents, and support remote decision making [1]. However, the remote nature of monitoring suffers communication delays and even blackouts where just minutes without monitoring of incoming hazards can be life or death. This presents a significant opportunity afforded to explore and conceptualize designs to augment the sensory perception and situational awareness of spacesuited humans carrying out Extra-Vehicular Activities (EVA) [1].

Human-Robot Interaction (HRI)

It is commonly held that human-robot interaction (HRI) is a subset of the field of human-computer interaction (HCI). The Special Interest Group on Computer-Human Interaction (SIGCHI) defines HCI as "a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them" [7]. And since robots are computing-intensive systems designed to benefit humans, it can be accepted that HRI can be informed by the research in HCI. Establishing methods to make human-robot interaction (HRI) effective, efficient, and natural is crucial for the success of the mission and safety of the astronauts. Human–robot teams bring together multiple types of agents, both human and robotic, with unique capabilities and capacities that complement each to promote mission success [5]. Unfortunately, many developed HCI and HRI techniques become obsolete in the context of extravehicular missions, requiring the astronaut to act on their own accord, with little to no support or communication from crew members or ground control. According to the 2013 evidence report issued by Nasa titled "Risk of Inadequate HCI", it's stated that "HCI has rarely been studied in operational spaceflight, and detailed performance data that would support evaluation of HCI have not been collected" [10]. Furthermore the report raises the concern that any potential or real issues to date may have been masked by the fact that crews have near constant access to ground control [9]. While developing HCI techniques such as the graphical user interface (GUI), voice user interface (VUI) and augmented reality (AR) have now become more established in the space domain, human-robot interaction (HRI) is still a relatively fresh field, playing a critical role as the central facet to astronaut autonomy and communication with their robotic accomplices. Generally for effective HRI, humans and robots must be able to: 1) communicate clearly about their goals, abilities, plans and achievements; 2) collaborate to solve problems, especially when situations exceed autonomous capabilities; and 3) interact via multiple modalities (dialogue, gestures, etc), both locally and remotely. To achieve these goals a number of HRIs must be addressed[11]. In this pursuit, the most effective HRI techniques must be established for effective communication during critical extravehicular missions such as space walks or operations on a planetary surface. Since resources such as data transmission are limited to just the communication bridge of the EVA suits, only the most efficient and communicative techniques should be employed in this critical context.

Haptic Feedback

A general definition of haptic feedback is the use of touch to communicate with others. Physical touch and vibration as a haptic system help develop new interactional technologies in both scientific fields and humanities. It is commonly known that information can be encoded through haptic feedback, as we all own personal cellphones. The intimacy of the technology (needing to be physically in contact with the actuator) also reduces its invasion into the cognitive spheres of others[14]. One paper suggests that when haptic feedback is used as the appropriate form of communication, it can offload the visual sense, decreasing our own cognitive load [1]. Furthermore, research has shown that haptic feedback can even be used to complement other systems and to mediate the sensory filters imposed by the modern space suit while providing situational awareness [1].

Based on the presented evidence, in this study we want to examine if haptic feedback can be an effective communication method for robot-human teams to inform astronauts of surrounding stimuli, enhancing spatial awareness and safety during extra-vehicular activities.

RELATED WORK

The research conducted was primarily qualitative and exploratory, focusing on the evaluation of state-of-the-art HRI methods and benefits of remote haptic feedback systems when considered within the constraints of deep space environments. The literature review focused on all three topics (HRI, deep space and haptic feedback) as disparate entities, their intersections and the convergence of all three to best frame and evaluate the technical aspects and logistics involved in their relations.

Often times, autonomy is primarily used in space telerobots to provide safeguarding. This safeguarding includes, but is not limited to, collision detection, hazard avoidance, resource management and limit checking [5]. Several studies have shown there is strong evidence for human-robot collaboration (HRC) in cooperative tasks, maintaining safety procedures, and semi-autonomous procedures such as manufacturing or repairs [21]. Attached externally to the ISS (International Space Station) is the Canadarm2 robotic system, working as the principle SSRMS (Space Station Remote Manipulator System) during EVA space walks. While the Canadarm2 has been upgraded with force-moment sensors to provide a sense of touch to operators through direct manipulation, the primary method of informing astronauts of their surroundings is through viewing mounted manipulator-based cameras. These are challenging to use since the point of reference constantly changes during manipulator motion and the field of view is insufficient in providing a comprehensive representation of the work environment [13]. Additionally, “spatial awareness when using indirect viewing of teleoperation tasks can require significant cognitive demand if the mapping of translational and rotational axes between the scene and the control input devices is non-intuitive” [4,5]. The Canadarm3 is planned for arrival in space as early as 2026 and the addition of a remote haptic feedback system to convey spatial cues directly to the astronaut’s EVA suit could provide significant functional advantages while reducing visual cognitive load for its users.

Deep space imposes various environmental constraints that impede effective HRI, such as radiation, temperature extremes, illumination variations, micrometeoroids, micro gravity and planetary dust among other environmental factors [4]. One of the most important aspects of an EVA operation is to determine the exact location and velocity of objects in space while maintaining the right orientation to navigate and accomplish the mission efficiently. Existing solutions using advanced sensors, instruments and communication systems do not provide an infallible approach to address this problem [2]. New technologies and emerging scientific evidence surrounding the enhancement of spatial awareness via haptic systems are already prevalent, with recent studies aimed at translating auditory to tactile cues via sensory substitution. A recent study found that participants wearing a sensory substitution device could determine the identity of up to 95% and on average 70% of the auditory stimuli simply by the spatial pattern of vibrations on the skin [18]. An example of a proven haptic feedback system is the Neosensory Buzz [16]. The Buzz product is a wrist wearable that captures situational sounds and translates them into specific vibrotactile patterns that can be identified by the user (such as an approaching ambulance siren). It is developed by leading neuroscientists and aimed at enhancing auditory and spatial awareness among the deaf community.

Since space is in a vacuum and incoming space debris would not make an audible sound, our methods would rely on deployed robotic AI systems to process various non-auditory stimuli (visual, chemical, radioactivity, etc) and then deliver identifiable dynamic patterns of vibrations to the EVA suit to inform the astronaut of a new stimulus and their orientation to it. Following this direction, qualitative studies and a conceptual prototype have been developed on the topic of haptic feedback systems in EVA suits. Specifically, on the possibilities of exploring the language of haptic feedback to complement other systems and to mediate the sensory filters imposed by modern space suits [1]. In a relevant study, a described Periphery Cap prototype is equipped with six vibration motors to encode sensory information into haptic feedback, in order for wearers to better interact with their environment, equipment and crew members.

While the above approach to haptics is intriguing, we hypothesize that haptic information delivered specifically to the head of the user could be irritating and counterproductive in reducing cognitive load under stressful conditions. There is also no description of using haptics in delivering spatial information via robot-human interaction within the realm of autonomous human-robot space teams.

In addition, the results of a paper describing the mapping of a robotic haptic interface to a remote manipulator to assist individuals with disabilities performing vocational task suggest that the introduction of these haptic capabilities offer special benefit to motion-impaired users by augmenting their performance on job-related tasks [17]. As astronauts performing space walks in microgravity are not only motion-impaired but disoriented in their spatial awareness, these findings provide promise for haptic methods to aid astronauts in their missions without creating additional stress.

OUR APPROACH

As a result of the complexity of EVA missions, space crew are expected to interact with highly automated systems and to perform these interactions with often little prior training, or on an infrequent or sporadic basis [15]**.** As such, it can be deduced that there is strong demand for improving mediums of communicating information in a natural manner between human-robot teams in space.

We propose a unilateral interaction method utilizing haptic feedback to leverage robot-to-human interaction for autonomous deep space missions, to help improve the spatial awareness, productivity and safety of the astronaut. Human-robot teams can be supported across multiple spatial ranges, but due to the latency constraint associated with limited communications bandwidth, the relevant methods are shoulder-to-shoulder proximity (e.g., astronaut and robot in a shared space) and line-of-sight interaction (crew in habitat, robot outside). The main purpose of the prototype is to boost the efficiency of HRI communication channels, by providing the robot a non-intrusive but intuitive medium of informing the astronaut of situational awareness, directional goals and high priority alerts (such as incoming space debris). This physical touch interaction technique will mainly serve a functional use, but in a broader sense represents a step toward more natural human-robot interactions. While auditory and visual signals emitted by robots can be effective interaction methods, we suggest that haptic feedback through multi vibrational modes can deliver informative cues while providing a more natural feeling of communication to the human recipient.

The Proposed System

The intention of the conceptual prototype is to explore the abilities of haptic feedback in providing effective communication to the user as a sub-system embedded in their space suit.

The first iteration prototype will include an Arduino Nano microcontroller connected to four vibration motors. To represent left and right awareness, a vibration motor will be placed on the top exterior portion of each hip. To represent the upward direction a vibration motor will be placed at the posterior top of the neck and another placed at the lower back to represent the downward direction. A second Arduino Nano microcontroller will be used to represent the autonomous robot, that would deliver the vibration cues to the receiving controller, fitted on the innermost layer of clothes of the user. Testing will be performed to ensure the various vibrations can be accurately felt and recognized when placed within an operational EVA space suit. Both microcontrollers will be equipped with a HC05 Bluetooth module capable of short range communication to deliver the vibration cues. Five different vibration signatures will be devised based on their duration, pattern and level of intensity.

Each vibration signature will be mapped to a particular stimulus: three negative (negative, hazardous) and two positive (affirmative, directional goal).

Stimulus	Vibration signature	Vibration duration
Negative (-)	Mildly intense vibration	1 short pulse
Affirmative (+)	Mild vibration	2 short pulses
Hazard Detected (-)	Highly intense vibration	1 long pulse
Incoming Hazard (-)	Mildly intense vibration	5 long pulses
Directional Goal (+)	Mild vibration	2 long pulses

Table 1: Proposed mappings between vibration modality and stimulus sentiment.

The Proposed Evaluation

The experiment will be conducted with 12 participants (6 men and 6 females) who are all active or retired astronauts, of various ages, between 30-70 years old. Each participant will have had experience with wearing a spacesuit in microgravity, either in deep space or in simulated environments. Before the experiment, each participant will have the prototype equipped to their body, under their regular clothes. A standard EVA space suit will also be placed on them. For a short period of time, the participant will be trained on the prototype, making sure the different vibration modes are felt and recognized correctly. A between subject study design would be conducted, with half the participants split as the control group and half with the working prototype (both groups with equal number of males and females and balanced ages). In order to simulate the cognitive strain of the extended period of time of a space walk, the study will be conducted over a period of 4 hours. During the experiment, each participant will be suspended in a simulated microgravity environment at a certified testing facility. A typical spacewalk task will be replicated for the participant to complete with a robot prop placed in the scene to simulate the robot-human interaction. The spacewalk task will require the active viewing of multiple GUIs, while periodically a simulated stimulus alert will be introduced. While both groups will be notified visually of an approaching stimulus on a GUI screen, the test group will receive the haptic feedback associated with that particular stimulus. After the study, the average observed reaction times of both groups will be recorded and analyzed. Two qualitative questionnaires, the Likert and HRI Trust Scale [22], will then be conducted to evaluate the participants' positive and negative aspects of their experience with the prototype and if/how it affected their ability to complete the space tasks.

SUMMARY

Modern times have observed a higher frequency of manned space exploration missions and as a plan for the first landing of humans on Mars begins to unfold, the number of space operations within human-robot teams will continue to increase. These missions are dangerous and run additional risks when conducted in EV environments. While numerous studies seek to improve communication mediums within the field of HRI, this paper focuses on a novel conceptual prototype as a means for autonomous robots to remotely engage with their human teammates through a diverse set of haptic interactions. The proposed haptic feedback mechanism is considered non-intrusive while effectively delivering critical information to enhance safety and spatial awareness. Next steps would include an additional literature review into the topics of HRI in space and novel haptic feedback mechanisms, a development of the conceptual prototype and pilot study to validate or invalidate its effectiveness. In future iterations, the use of more complex vibration motors to deliver directional vibrations that indicate the motion or speed or an incoming object, could be a valuable addition to more precisely inform where hazards or areas of interest could be in relation to the user. Following this, a more comprehensive study with a larger number of participants and added measures could be conducted to further validate or invalidate our prototype.

REFERENCES

[1]Torstein Hågård Bakke and Sue Fairburn. 2019. Considering Haptic Feedback Systems for A Livable Space Suit.TheDesign Journal22, sup1 (2019), 1101–1116.

[2] Tiziano Bernard, Andrea Gonzalez, Vincenzo Miale, Kushal Vangara, Lucas Stephane, and Winston E Scott. 2017. Haptic feedback astronaut suit for mitigating extra-vehicular activity spatial disorientation. InAIAA SPACE and Astronautics Forum and Exposition. 5113

[3] Christopher E Carr, Steven J Schwartz, and Ilia Rosenberg. 2002. A wearable computer for support of astronaut extravehicular activity. InProceedings. Sixth International Symposium on Wearable Computers,. IEEE, 23–30.

[4] Terrence Fong and Illah Nourbakhsh. 2005. Interaction challenges in human-robot space exploration.Interactions12, 2(2005), 42–45.

[5] Terrence Fong, Jennifer Rochlis Zumbado, Nancy Currie, Andrew Mishkin, and David L Akin. 2013. Space telerobotics:unique challenges to human–robot collaboration in space.Reviews of Human Factors and Ergonomics9, 1 (2013), 6–56.

[6] Gernot Groemer, Alexander Soucek, Norbert Frischauf, Willibald Stumptner, Christoph Ragonig, Sebastian Sams, ThomasBartenstein, Sandra Häuplik-Meusburger, Polina Petrova, Simon Evetts, et al.2014. The MARS2013 Mars analog mission.Astrobiology14, 5 (2014), 360–376.

[7] Ewald Heer and Henry Lum. 1988. Machine intelligence and autonomy for aerospace systems. (1988).

[8] Thomas T Hewett, Ronald Baecker, Stuart Card, Tom Carey, Jean Gasen, Marilyn Mantei, Gary Perlman, Gary Strong,and William Verplank. 1992.ACM SIGCHI curricula for human-computer interaction. ACM.

[9] Kritina Holden. [n.d.]. Evidence Report: Risk of Inadequate Human-Computer Interaction. ([n. d.]).

[10] Ph D Holden. 2013.K., Ezer. Ph.D. Dissertation. Ph. D., N., & Vos, Ph. D., G.

[12] Jinguo Liu, Yifan Luo, and Zhaojie Ju. 2016. An interactive astronaut-robot system with gesture control.Computationalintelligence and neuroscience2016 (2016).

[13] Rod McGregor and Layi Oshinowo. 2001. Flight 6A: deployment and checkout of the space station remote manipulatorsystem (SSRMS). InProceedings of the 6th International Symposium on Artificial Intelligence, Robotics and Automation inSpace (i-SAIRAS).
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[14] Scott D Novich and David M Eagleman. 2015. Using space and time to encode vibrotactile information: toward an estimateof the skin’s achievable throughput.Experimental brain research233, 10 (2015), 2777–2788.

[15] Julie Payette. 1994. Advanced human-computer interface and voice processing applications in space. InHUMAN LANGUAGETECHNOLOGY: Proceedings of a Workshop held at Plainsboro, New Jersey, March 8-11, 1994.

[16] Neosensory. (2018). NeoSensory | Buzz. Retrieved November 14, 2018, from https://neosensory.com/buzz/

[17] Norali Pernalete, Wentao Yu, Rajiv Dubey, and Wilfrido Moreno. 2002. Development of a robotic haptic interface to assistthe performance of vocational tasks by people with disabilities. InProceedings 2002 IEEE International Conference onRobotics and Automation (Cat. No. 02CH37292), Vol. 2. IEEE, 1269–1274.

[18] Michael V Perrotta, Thorhildur Asgeirsdottir, and David M Eagleman. 2021. Deciphering sounds through patterns ofvibration on the skin.Neuroscience(2021).

[19] Sandra Robla-Gómez, Victor M Becerra, José Ramón Llata, Esther Gonzalez-Sarabia, Carlos Torre-Ferrero, and JuanPerez-Oria. 2017. Working together: A review on safe human-robot collaboration in industrial environments.IEEE Access5 (2017), 26754–26773.

[20] Jane Shi, Glenn Jimmerson, Tom Pearson, and Roland Menassa. 2012. Levels of human and robot collaboration forautomotive manufacturing. InProceedings of the Workshop on Performance Metrics for Intelligent Systems. 95–100.

[21] Jeffrey Too Chuan Tan, Feng Duan, Ye Zhang, Kei Watanabe, Ryu Kato, and Tamio Arai. 2009. Human-robot collaborationin cellular manufacturing: Design and development. In2009 IEEE/RSJ International Conference on Intelligent Robots andSystems. IEEE, 29–34.

[22] Rosemarie E Yagoda and Douglas J Gillan. 2012. You want me to trust a ROBOT? The development of a human–robotinteraction trust scale.International Journal of Social Robotics4, 3 (2012), 235–248