Development of Methodologies, Metrics, and Tools for Investigating Human-Robot Interaction in Space Robotics

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Abstract

Human-robot systems are expected to have a central role in future space exploration missions that extend beyond low-earth orbit [1]. As part of a directed research project funded by NASA's Human Research Program (HRP), researchers at the Johnson Space Center have started to use a variety of techniques, including literature reviews, case studies, knowledge capture, field studies, and experiments to understand critical human-robot interaction (HRI) variables for current and future systems. Activities accomplished to date include observations of the International Space Station's Special Purpose Dexterous Manipulator (SPDM), Robonaut, and Space Exploration Vehicle (SEV), as well as interviews with robotics trainers, robot operators, and developers of gesture interfaces. A survey of methods and metrics used in HRI was completed to identify those most applicable to space robotics. These methods and metrics included techniques and tools associated with task performance, the quantification of human-robot interactions and communication, usability, human workload, and situation awareness. The need for more research in areas such as 'natural' interfaces, compensations for loss of signal and poor video quality, psycho-physiological feedback, and common HRI testbeds were identified. The initial findings from these activities and planned future research are discussed.

Keywords- end-effectors; human robot interaction; space technology; robots; robot control; telerobotics; teleoperation; user interface

I. INTRODUCTION AND GOALS OF THE CURRENT WORK

Human-robot interaction (HRI) is a research area that seeks to understand, design for, and evaluate the complex relationships among variables that affect the way humans and robots work together to accomplish goals [2]. HRI research is critical to improving NASA's current human-robots systems (e.g., the International Space Station's Special Purpose Dexterous Manipulator, Robonaut 2, and Mars Exploration Rover) as well as future systems, which are expected to have central roles in space exploration missions. These future roles may include transporting cargo on planetary surfaces; collecting and handling samples (e.g., soil or rocks); grappling other space vehicles, satellites, or asteroids; collaborating with extravehicular human crewmembers; assembling and servicing habitats; and performing in-vehicle inspections [1, 3].

The characteristics of space robots are vast and diverse. For example, The Robonaut 2 system was recently launched on the STS-133 mission to the International Space Station (ISS) to investigate dexterous manipulation in zero gravity. After initial experiments, its purpose is envisioned to offload housekeeping and other chores from crewmembers and work side-by-side with them as a teammates in repair and maintenance tasks [4-5]. Operators from the ground will control it using a telepresence system with head mounted displays, stereo visual feedback, force and tactile feedback gloves, and posture trackers. In contrast, the Mars Exploration Rovers (Spirit and Opportunity), which have been operating on Mars since January 2004, are typically commanded once per Martian solar day. Operators from Earth send commands telling the rovers where to go (either with or without autonomous driving capabilities such as terrain assessment), what images and data to collect, and which way to position the robotic arm [6]. Communication between operators and robots is limited by time delays (which can be upwards of 40 minutes) and constraints on bandwidth. Finally, consider the Special Purpose Dexterous Manipulator (SPDM), a robot with two symmetrical seven degree-of-freedom (DOF) arms used to change-out Orbital Replaceable Units (ORUs), actuate mechanisms, support extravehicular activities (EVA), and manipulate and inspect payloads on the Space Station's exterior [7]. Although originally designed for on-orbit control, operators on the ground command SPDM by following pre-planned procedures, sending discrete commands to position the robot, and monitoring camera views and telemetry (Observations of SPDM operation, December 2010).

From these three space robotic system examples – Robonaut 2, Mars Exploration Rovers, and SPDM – it is clear that the nature of the human-robot interaction from one system to the next is very different. Yet, each system relies on the appropriate design of tasks, displays, controls, and communication between humans and robots. The human is always an integral part of the success or failure of the system.

A. Research Goals

Researchers at NASA's Johnson Space Center, funded under the Human Research Program (HRP), have begun a multi-year effort to survey the existing field of space robotics and carry out a series of studies to address gaps in research which are applicable to both space robotics and the HRI field in general. The goals of the current work are to use a variety of techniques (e.g., literature reviews, knowledge capture, case studies, field studies, interviews, observations, and experiments) to understand critical HRI variables and their effects on task performance, task efficiency, and user satisfaction. The intention is that results will support the development of HRI requirements, standards, and design guidelines.

II. REVIEW OF HRI METHODOLOGIES, METRICS, AND TOOLS

The work began with a literature review of methods and metrics in HRI and in related fields such as human-computer interaction, aviation, automation, teamwork, and artificial intelligence. Over 350 peer-reviewed journal articles and proceedings were reviewed. The goal of this review was to categorize general and space-specific ways of studying and measuring HRI. Research gaps and the lack of common methods, metrics, and tools emerged from this review and provided impetus for the development of research questions for future studies. A select set of findings is presented in this paper.

A. The Need for Methods and Metrics

The first finding that emerged from the review was the need for methods and metrics that can answer questions about HRI across many applications and systems. Several researchers have commented about the lack of a comprehensive set of valid and replicable metrics and the methods to aid in design and evaluation of human-robot systems [8-11]. Some have attributed this to the newness of the field and the tendency of robot developers and researchers to use metrics that are biased towards a specific application rather than answer basic, but critical, research questions. In a workshop of fifty-six leading HRI researchers and robotics developers, the need for HRI methods and metrics was identified as one of the major needs for future advancement of the field[12]. Metrics identified as critical included those associated with robot autonomy, mission complexity, human-robot coordination and collaboration, task performance, sensory processing, human intervention, operator workload, logistics, control station attributes, and ease-of-use. User experience, social acceptance, and social impacts are additional critical factors that require HRI metric development [11].

B. Task and Performance Metrics

A task in HRI is defined as a discrete activity that the human-robot system has to complete within an environment via an interface [13]. Tasks involves the human obtaining information about the current state of the robot and environment, synthesizing this information in a meaningful way, choosing an action or response to the situation, implementing the action, and then evaluating the outcome. Different task metrics provide different information about success or failure of the human-robot system during each of these task steps.

Teleoperation of space robotic arms, robotic urban search and rescue (USAR), and robotic explosive ordnance disposal (EOD), are three areas in HRI that have developed a number of objective measures of task performance. Measures of task performance for control of space robotic arms have included metrics associated with collision avoidance, selection of optimal camera views, and appropriate control inputs. For example [14] investigated task performance with alternative camera configurations, by analyzing the location and orientation of the end effector, time to capture a simulated node, and time to dock the node. These were used to determine human task performance, which included: time from start of trial to first controller input, time to complete the task, percent motion (i.e., percent of total time the end effector was moving), percent of multiple DOF inputs, angular DOF movements, and docking position offset. Other researchers have defined human task performance for a space robotic arm alignment task as control movements that reach limits or singularities, translational (X, Y, Z) and rotational (Pitch, Yaw, Roll) accuracy, number of forbidden configurations, control effort (as measured by taking the root mean square value of control movements along all axes multiplied by maneuver duration), path efficiency (as measured by taking the root mean square value of the distance between current robot position and target multiplied by maneuver duration), sum of distances in direction opposite to the target, command velocity, maximum velocity, and number of operator head movements as a measure of visual search [15-17]. Although these measures of human task performance allow for comparisons among display configurations for different space arms robots, the heavy reliance of measurements from hand controller inputs (e.g., angular DOF movements) may make them difficult to apply to robots that use different types of control inputs, a problem highlighted later in this paper.

Researchers in space robotics could also draw lessons from the development of methods and metrics of HRI in USAR and EOD, who have taken the forefront for developing objective measures of human-robot task performance for cross-system comparisons. In particular the development of testbeds in these two disciplines should be noted. A testbed, in which human-robot systems perform identical tasks and are evaluated in identical ways, can provide an objective means for collecting comparing human-robot task performance. When a testbed involves realistic task components, then it can also be used for defining criteria for acceptable performance and validating systems. Developing a testbed involves an iterative process of steps including: understanding the operational challenges of the tasks and environments, selecting a subset of representative tasks, identifying appropriate metrics and criteria for performance, and validating the testbed [18-19]. A testbed needs to addresses the characteristics of the task sufficiently, be used in a timely manner, and use meaningful metrics that can affect design decisions.

Although there have been testbeds created for space robotic applications, particularly for space robotic arms, these have been largely focused on developing simulations to validate specific technology or behavioral algorithms of robotic systems [20-22] Unlike the testbeds developed for USAR or EOD robots, these testbeds are designed to simulate existing robots rather than provide a set of representative tasks and human-robot task performance metrics that can be used to compare different robot systems or interfaces. There is a need to develop these types of testbeds embedded with unique space-related characteristics as well as developing testbeds for dexterous robots, such as Robonaut 2, that work in close proximity to crewmembers. These testbeds for dexterous robots may need to have metrics associated with teamwork, communication, and decision making.

C. Research Gaps

The literature review on methods and metrics reveals some HRI interface gaps in space-robotics research critical to system usability. Although not inclusive, the match between input device (e.g., gesture, voice, physical control) and task, compensations for poor or ambiguous video feedback, and communication issues (i.e., loss of signal, communication delay, natural communication) appear to have significant effects on HRI across a number of space applications. Additionally, non-intrusive measures of situation awareness and workload, such as behavioral or psycho-physiological measures, need to be validated for use in HRI across space domains.

Methodological considerations that were identified included robot fidelity for research. Experimental control in HRI research can be a challenge with physical robots, as these robots need to act reliably over time and be easy to manipulate within the variables of interest. Thus alternative methods to study HRI for space applications need to be developed and validated. These methods may included concurrent and retroactive field studies, studies in analog environments, “Wizard-of-Oz” techniques, studies with virtual robots, and video trial methods.

III. KNOWLEDGE CAPTURE OF SPDM OPERATIONS

Concurrent to the literature review, a survey of current and future space robotics work was completed, along with knowledge capture on SPDM operations. During knowledge capture of SPDM, the team reviewed operator manuals, training materials, operational procedures, and lesson-learned presentations. The review of these documents provided the team with system and operational knowledge that complemented observations of SPDM operations and discussions with SPDM operators and trainers.

The approach uncovered some discrepancies between research in space robotic operations and real operations, as well as areas of applicable research. For example, the majority of research on teleoperated space robotic arms investigated human control of the arm with continuous input devices, usually a rotational hand controller (RHC) and a translational hand controller (THC) [14-16, 23-24]. These studies assumed that a single human operator performs real-time decision making for controlling a robot arm. The knowledge capture process, however, revealed that operators on the ground control SPDM through discrete inputs (i.e., uplinked commands) that are governed by detailed procedures created weeks in advance. Additionally, multiple individuals – the ISS Robotics Officer, System Officer, and Task Officer – are involved in the operations, each with specific roles. Teamwork and appropriate communication between these individuals is essential to operations and decision-making. For example, two officers are required to verify a command before it is sent (i.e., call-and-verify). There are also constraints in operations due operational safety requirements, such as all commands need an initial "arm" (select the command), and second "arm" (confirm the command), and a "fire" (send the command). Hand controllers would not comply with current operational requirements. Within the current operational paradigm, it would be difficult to verify the status of hand controller inputs during a loss of signal situation. Our discussions with operators also revealed that, in general, sequences of commands or scripts are avoided due to the long verification process required and inability to change the script without additional verification. Thus, there is clear need to address HRI issues related to current operations that can make control more efficient within the historical constraints of NASA activities.

Observations of SPDM operations (December 2010) also revealed several concerns about interface adequacy. One observation was that non-optimal lighting conditions from camera views tended to "wash-out" camera overlays. Overlays on end-effector camera views for grappling were also highly dependent on calibration, which could be offset by small vehicle vibrations and changes due to mechanical tolerances that are not represented in the modeling program. There were no overlays for guiding operator inputs when the target was not in the camera field of view. Camera views, in our opinion, appeared ambiguous as to distance between objects and robot speed. The loss of high-gain antenna signals (i.e., camera feedback) was another observed issue that affected operations. No motions commands were allowed during these periods or immediately preceding these periods, which could last upwards of 20 minutes. In terms of information, operators were presented with a large amount of telemetry that was not task-specific. These, and other observations presented themselves as research opportunities for future work.

IV. FORWARD WORK

Building upon the foundational work of the past few months, the HRI team at NASA's Johnson Space Center is working towards a series of studies and activities to address some of the critical issues identified as gaps in research. One of these near-term activities will be to bring together a diverse group of experts in HRI in a workshop later this year. Topics planned for discussion include identification and effects of variables of interest across three classes of space robotics – Arm/Heavy Lift, Mobility, and Dexterous. Numerous near- and long-term studies are also planned. One set of studies will focus on overlay guidance for operators. An area of interest is the effects of command-guidance versus situation-guidance (i.e., providing command input information and errors versus providing natural guidance cues) on human-robot task performance across input types and tasks. Input types will include discrete commanding similar to current SPDM operations. Other overlay studies may look at superimposed versus integrated heads-up information on displays across information type (e.g., information that needs to be continuously monitored versus intermittently monitored). A set of studies will be carried out to investigate variables associated with camera configurations and display layouts to identify ways to improve operator awareness of a robots status relative to its environment during various tasks. Other studies are planned that will focus on developing gesture and voice vocabulary for rover-type robots. The ability of individuals to learn and recall traditional and novel control inputs will be assessed. Finally, the team plans to conduct studies related to ways operators could regain awareness of robot status after a loss of signal event. Throughout these studies, the team plans to apply and refine tools, methods, and metrics for measuring HRI.

REFERENCES

[1] R. Ambrose, *et al.*, "DRAFT Robotics, Tele-Robotics and Autonomous Systems Roadmap," N. A. a. S. Administration, Ed., ed, 2010.

[2] M. A. Goodrich and A. C. Schultz, "Human-robot interaction: A survey," *Foundations and Trends in Human-Computer Interaction,* vol. 1, pp. 203-275, 2007.

[3] L. Pedersen, *et al.*, "A survey of space robotics," 2003, pp. 19-23.

[4] W. Bluethmann, *et al.*, "Robonaut: A robot designed to work with humans in space," *Autonomous Robots,* vol. 14, pp. 179-197, 2003.

[5] M. Diftler, *et al.*, "Robonaut 2 the first humanoid robot in space."

[6] J. J. Biesiadecki, *et al.*, "Tradeoffs between directed and autonomous driving on the mars exploration rovers," *The International Journal of Robotics Research,* vol. 26, p. 91, 2007.

[7] R. Mukherji, *et al.*, "Special Purpose Dexterous Manipulator (SPDM) Advanced Control Features and Development Test Results," 2001.

[8] A. Steinfeld, *et al.*, "Common metrics for human-robot interaction," 2006, pp. 33-40.

[9] K. Dautenhahn, "Methodology and themes of human-robot interaction: a growing research field," *International Journal of Advanced Robotic Systems,* vol. 4, pp. 103-108, 2007.

[10] J. Burke, *et al.*, "Task performance metrics in human-robot interaction: Taking a systems approach," *Performance Metrics for Intelligent Systems,* 2004.

[11] A. Weiss, *et al.*, "The USUS evaluation framework for human-robot interaction," in *AISB2009: Symposium on New Frontiers in Human-Robot Interaction*, 2009.

[12] J. Burke, *et al.*, "Final report for the DARPA/NSF interdisciplinary study on human-robot interaction," *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on,* vol. 34, pp. 103-112, 2004.

[13] P. De Barros and R. Lindeman, "A Survey of User Interfaces for Robot Teleoperation," 2008.

[14] M. A. Menchaca-Brandan, *et al.*, "Influence of perspective-taking and mental rotation abilities in space teleoperation," 2007, pp. 271-278.

[15] T. M. Bray, *et al.*, "Effectiveness of 2-D Views for 6-D Robotics Simulation Maneuvers," 2003, pp. 975-979.

[16] P. Lamb and D. Owen, "Human performance in space telerobotic manipulation," 2005, pp. 31-37.

[17] T. M. Akagi, *et al.*, "Toward the construction of an efficient set of robot arm operator performance metrics," 2004, pp. 1194-1198.

[18] J. Scholtz, *et al.*, "Development of a test bed for evaluating human-robot performance for explosive ordnance disposal robots," 2006, pp. 10-17.

[19] R. Murphy, *et al.*, "Assessment of the NIST standard test bed for urban search and rescue," *NIST SPECIAL PUBLICATION SP,* pp. 260-266, 2001.

[20] J. Artigas, *et al.*, "Testbed for Telepresent On-Orbit Satellite Servicing," 2006.

[21] S. Hayati, *et al.*, "A testbed for a unified teleoperated-autonomous dual-arm robotic system," 2002, pp. 1090-1095.

[22] M. Uchiyama, *et al.*, "Development of a flexible dual-arm manipulator testbed for space robotics," 2002, pp. 375-381.

[23] R. L. Smith and M. A. Stuart, "The effects of spatially displaced visual feedback on remote manipulator performance," 1989, pp. 1430-1434.

[24] J. Maida, *et al.*, "Enhanced lighting techniques and augmented reality to improve human task performance," *NASA Tech Paper TP-2006-213724 July,* 2006.