Space 2006
19 - 21 September 2006, San Jose, California

AIAA 2006-7388

Toward Human-Robot Interface Standards II: An Examination of Common Elements in Human-Robot Interaction Across the Space Enterprise

Jeffrey Ferketic*, Loel Goldblatt, Edward Hodgson, Sean Murray and Robert Wichowski
Hamilton Sundstrand Space Systems International, Inc., Windsor Locks, CT, 06096 USA

Arthur Bradley
NASA Langely Research Center, Hampton, VA 23681 USA

Terrence Fong
NASA Ames Research Center, Moffett Field, CA 94035 USA

John Evans
Aeolean, Inc., Ridgefield, CT 06877 USA

Wendell Chun and Randy Stiles
Lockheed Martin, Denver, CO 80126 and Sunnyvale, CA 94089

Michael A. Goodrich
Brigham Young University, Provo, UT 84602

Aaron Steinfeld
Carnegie Mellon University, Pittsburgh, PA 15213 USA

Dan King and Catherine Erkorkmaz
MacDonald, Dettwiler and Associates, Ltd., Brampton, Ontario Canada L6S 4J3

We previously discussed the need for enterprise-level human-robot interface standards (data, communication, etc.) to enable effective use of robotic systems in space exploration[1]. In that paper, an early commitment to standards development was recommended and a tentative path outlined. This paper examines in greater depth some of the underlying assumptions of our prior work and attempts to establish part of the foundation on which the recommended standards may be built. Specifically, we examine the premise that the broad range of human-robot interaction (HRI) needed for space exploration will present sufficient commonality to make interface standards feasible and useful. To ground our work, we explore one specific area of HRI and provide an initial roadmap for standardization.

I. Introduction

Since January 2004, NASA has been pursuing the “Vision for Space Exploration” (VSE), the primary goal of which is to establish a “sustained and affordable human and robotic program to explore the solar system and beyond”[2]. In contrast to previous exploration efforts, the VSE places significant emphasis on the development of joint human-robot systems. Robot systems have the potential to significantly enhance exploration capabilities, increase overall mission safety and success, and enable more robust handling of failures and anomalies. This is especially true for long-duration and deep space missions, both of which are complex and will require crew to intermittently operate independently (i.e., without communications) of ground control.

Planetary surface exploration, construction, and mobility operations will be highly dependent on robots and piloted surface vehicles with varying levels of autonomy and functionality. Similar expectations are present for space-based construction, assembly, maintenance, and science missions. A key consequence of this dependency is that human-robot interfaces will have a significant influence on mission architecture and execution. In particular, the

*Corresponding Author: jeff.ferketic@hs.utc.com

need for crew to be familiar with, and to employ, multiple robot user interfaces will directly impact training requirements, workload, risk, and numerous other factors.

The specification and use of standards is a well-known and accepted method to reduce risk and complexity in large systems. By providing a basis for commonality and interoperability, standardization can improve design and use throughout the system lifecycle. Most importantly, standards can: (1) encapsulate experience and lessons learned from sub-optimal prior designs, (2) provide design guidelines, and (3) reduce the time, cost, and process required to integrate diverse products and subsystems into a functioning whole.

At present, there are no formal standards (*de facto* or otherwise) for human-robot interaction (HRI). Although there are component standards (e.g., human engineering) that are highly relevant to the design of human-robot space systems, the interactive nature of HRI demands that we consider system-level issues as well. In the following sections, therefore, we present a notional description of the types and modes of human-robot interactions that we expect will be required for space exploration, as well as the operational and physical contexts in which they may occur. While HRI standards may ultimately include a wide range of features (including power, communication, mechanical, thermal and fluid), this paper will focus primarily on interaction interfaces for surface exploration.

II. HRI Scenarios Across the Space Enterprise

In this section, we explore the types of interactions that occur in anticipated scenarios for human-robot surface exploration[3-6]. Three different categories emerge from these scenarios: proximate (side-by-side) interactions, remote interactions without significant time delays, and remote interactions with significant time delays. To do this, we follow a timeline beginning at precursor missions, moving to early lunar missions, and concluding with outpost exploration including joint human-robot exploration of Mars. We then present a sample of anticipated robot uses for intravehicular activity (IVA) to illustrate possible human-robot interactions in that domain.

A. Precursor Missions

Prior to establishing permanent human outposts (on either the Moon or Mars), NASA plans to conduct precursor robotic missions to reduce risk and build surface infrastructure. The first of the missions, the Lunar Reconnaissance Orbiter, is designed to conduct detailed orbital mapping of the Moon and is scheduled for launch in 2008. Subsequent missions will include both landers and rovers, which will perform a variety of surface tasks in three areas: science, i*n-situ* resource utilization (ISRU), and testbeds.

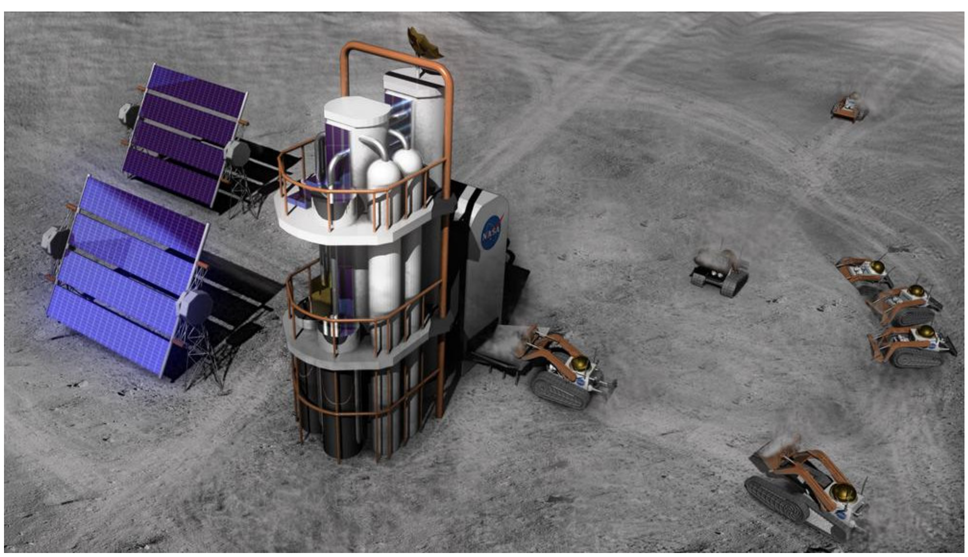

Figure 1. Firestarter concept for robotic regolith collection (courtesy iRobot Corp)

Candidate tasks for science include characterizing the lunar surface, emplacing science instruments, performing *in-situ* analysis, and returning material samples to Earth. As prior missions (e.g., Mars Exploration Rovers) have shown, these types of tasks can be performed by robots, teleoperated or supervised at various levels of autonomy. ISRU tasks will focus on mapping resources (including obtaining ground-truth of resources detected from orbit), material handling, and production (see Figure 1). This will require a combination of robotic vehicles and automated processes. Testbed tasks are primarily demonstration in nature, such as evaluating operational capabilities in cold or permanently shadowed locations (e.g., the lunar South pole) and developing advanced technology operations (precision landing, power production, etc.). Teleoperated or autonomous robot can provide support in numerous ways, including clearing sites and emplacing infrastructure (e.g., landing beacons).

Precursor missions will require significant remote human-robot coordination. Importantly, most of these missions require remote interaction in the presence of time delays. Unmanned rovers will explore multiple sites, under direct control or supervision from Earth. Similar to the current Mars rover missions, humans will operate the rovers and analyze the results from ground control. On-board sample pre-processing and data triage could be used to reduce communication resource needs, but would require humans to specify process constraints and priorities. In the Apollo missions, six flights (Apollo 11 to 17) were used to visit six sites. In a global explorer approach, three rovers could be deployed at three different, distant starting points and commanded to drive to a central location over a period of time, perhaps as long as two-years. Such a journey would collectively encompass sixty sites, a ten-fold increase in science productivity over the Apollo missions.

B. Telerobotics in Early Human Lunar Missions

When humans return to the Moon, lessons from using robotic systems in precursor missions will be applied to support human surface activities. Anticipated missions include all three categories of interaction: proximate, remote, and remote with time delays.

The NASA Exploration Systems Architecture Study (ESAS)[7] defines the typical early human lunar mission consisting of four astronauts (all simultaneously performing extra-vehicular activity, EVA), two un-pressurized manned rovers, and one or more robotic systems. Since all astronauts are performing EVA, interactions between humans and robots fall into the category of proximate interaction. The robots in these missions may be mobile rovers or stationary systems, performing tasks such as science activities, providing situational awareness, collecting environment and mapping information, deploying and maintaining infrastructure, and providing mobility support to the astronauts. Robots may travel with the human party, or be pre-positioned on the lunar surface from previous (precursor) missions or human sorties.

Most of these robotic systems will have some level of autonomy, even if only simple scripted command execution. In all cases, however, there will be a human operator involved, whether manually controlling the robot, or monitoring the autonomous operation. Moreover, the closer a robot works with the EVA crew, the more likely (at least in terms of current lunar mission architecture) that robot will be manually controlled to ensure astronaut safety. To perform teleoperation or monitoring, the operator could be located in an terrestrial command center, or could be an astronaut performing intra-vehicular activity (IVA) inside the Lunar Surface Access Module (LSAM), or could be an EVA astronaut (using a suit-mounted control device or robot-mounted control panel).

Local telerobotic control performed by an IVA astronaut in the LSAM is the most effective, and the most likely, form of telerobotics that will be used in early human missions. The IVA operator will still be limited by situational awareness because the interaction is remote, but the human will not have to adapt to a time delay nor deal with frequent communication loss. Past experiences with the Shuttle Remote Manipulator System (SRMS) and Space Station Remote Manipulator System (SSRMS) have demonstrated that EVA astronauts can work safely in close proximity to a robotic system controlled by a local IVA operator. Thus, robots will be able to perform tasks jointly with the EVA crew that would not be safe with Earth-based teleoperation. Manual control by an IVA operator would also allow the robot to perform some tasks (e.g., avoidance of difficult to sense obstacles) more quickly than a fully autonomous system. For ESAS scenarios, where all four crew perform simultaneous EVA, lunar IVA telerobotics could be used to perform tasks both before and after EVA.

Local telerobotic control performed by an EVA astronaut may be necessary when an astronaut is working very closely with a robot. In these situations, full awareness of the robot and its environment are important, such as when an astronaut is riding on a manned rover. In such cases, the EVA astronaut will have significantly better situational than ground operators. However, designing effective controllers and display systems for EVA crew is a significant challenge, given the dexterity and space limitations of current space suits and Extravehicular Mobility Units (EMU's). As a result, precise EVA control in proximate missions may be difficult to implement for many tasks.

Earth-based supervision will most likely be used for scenarios where the robot is operating far away from the EVA astronauts, i.e., where a high level of autonomy can be employed without impacting crew safety. The primary constraints on such teleoperation are the lack of good situational awareness by the operator (due to the reliance on computer and video mediated interfaces) and communications link limitations such as time delays, bandwidth and intermittent transmission[8]. Moreover, the human-robot interface for an Earth-based operator will have to allow the human to adapt to an Earth-Moon transmission latency of approximately 3 seconds, plus any additional delays incurred by communications processing (e.g., relay through the Deep Space Network). Such adaptation will require robot autonomy designed to support this type of remote interaction in the presence of time delays. For example, an Earth-based operator could effectively monitor a semi-autonomous robot and provide necessary high-level commands. As long as the robot does not pose a danger, teleoperation from Earth can potentially increase mission productivity, as the astronauts on the lunar surface would be free to perform other tasks. For example, an Earth-based operator could use a robot to perform ISRU extraction while astronauts monitor ISRU plant production.

The number of robotic systems used in early human missions, and the multiple methods of teleoperation that may be required, support the need for HRI standards. First, there are benefits to standardizing command structures and data/situational awareness displays between robots such that an operator can easily adapt to operating multiple robots in sequence. Second, there are additional benefits to extending this standardization to similar control schemes for Earth-based, local teleoperation, and proximate EVA operators. The areas of standardization between the categories are more limited given differences in time delays, situational awareness requirements, and autonomy levels. However, basic standards should be considered, such as the use of similar command interfaces for an EVA astronaut to drive a manned rover forward as for an IVA astronaut to teleoperate a science rover.

C. EVA Interactions in Outpost Exploration

Once the early missions are accomplished, the focus will move to long-duration surface exploration and exploitation. These missions will include sorties of longer distance and time, and will depend on joint teams of humans and robots. Some humans will perform EVA and leave the habitat accompanied by robots, while other humans will interact with the EVA humans and robots from a pressurized surface vehicle, from a surface habitat, or from earth. Robots will serve various roles on these EVA teams: they can include intelligent rovers that transport humans to a remote site on the surface, "mules" that carry tools and supplies, advanced robots that conduct initial explorations and prepare a site, and assistants that support activities by providing specialized sensors or by performing difficult or dangerous activities. These advanced missions will include periods of supervisory or waypoint-based interaction (such as when the robots navigate to a site) as well as periods of teleoperated interaction (e.g., for preliminary site assessment).

Figure 2. Human-robot crew on EVA sortie from a lunar outpost (NASA)

One possible workflow might begin with Earth-based scientists defining a work plan, which is then transmitted to a surface habitat. At the habitat, astronauts would deploy robots to gather preliminary information and prepare the remote site. On the moon, these robots would be ground vehicles, but on Mars they might include aerial vehicles that provide survey information. Using data acquired by the robots, the plan outline would then be refined and communicated to the EVA team. The EVA team would egress from the habitat and use a robotic rover that supports safe and reliable navigation to the remote site. As the team travels to the remote site, additional mobile or stationary robots might be deployed as relays to ensure that reliable communications are maintained to the habitat, ground control, or both.

Once the team arrives at the remote site, the EVA crew would exit the rover and proceed on foot (see Figure 2). The crew could be accompanied by a "mule" robot, which would carry tools and supplies and could autonomously return scientific samples or resources to the habitat. The crew could also be accompanied by robot equipped with special sensors; some might sense signs of dangerous conditions, others might provide multi-spectral imagery, still others might monitor activities. Other robots might carry specialized tools that allow them to, for example, excavate a portion of the surface or drill a sample.

The humans on the EVA will interact with their robot companions using voice or dedicated devices (tablet-like interfaces, wearable computers, etc.), but these communications may not allow sufficiently precise control that is required for some activities unless, for example, an astronaut uses a teleoperation interface available on the rover. Thus, it may be necessary for habitat crew, or perhaps ground controllers, to provide additional support. IVA crew, for example, could manage the robots using a rich set of interfaces, which display and interpret sensor information returned from the remote team (humans and robots alike) through high bandwidth communication channels.

Interestingly, the types of interactions in outpost exploration are very similar to those used in early lunar missions. Thus, standardization efforts that aim for precursor missions and early lunar missions will likely have significant benefits for outpost exploration.

D. IVA Robots

Before turning attention to identifying elements of a roadmap for standardizing HRI, we briefly discuss a subset of possible missions involving IVA robots. IVA robots are designed to work inside space structures, such as the International Space Station (ISS) and other future space structures including habitats or pressurized vehicles. IVA tasks are normally designed for shirtsleeve environments (i.e. wearing a space suit is not required). At present, there are no IVA robots in operation in space. However, IVA robots are envisioned to have a role in future space operations, especially for inventory control, science experiment automation, and crew assistance. To better understand the types of interactions that occur in IVA, we examine three past IVA robot prototypes.

1. SPHERES

The MIT Space Systems Laboratory developed the Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) system to provide researchers with a long-term, replenishable, and upgradeable testbed to validate technologies for use in formation flight and autonomous docking[9] (see Figure 3). Such technologies can be used in IVA to, for example, support laboratory automation and precise inspection.

Figure 3. SPHERES test on a KC-135 flight (NASA)

SPHERES are being used to examine how a constellation of free-flying autonomous robots in a microgravity environment can interactively communicate, maintain position, run diagnostics, regroup after disturbances, and move to commanded locations. Three SPHERES satellites are to be launched to the ISS in 2006 for a series of navigation tests.

Interaction with SPHERES may include proximate interaction in joint human-robot maintenance and science applications, and it may involve some local teleoperation from within, for example, the ISS. Thus, designing for standardized proximate and remote interaction should transfer to this type of IVA operation, albeit with extension to the zero gravity environment and to team-level control.

2. The Personal Satellite Assistant (PSA)

PSA (Figure 4) is a small, spherical robot designed to assist astronauts with their chores in the microgravity environment of space-based vehicles[10]. In particular, PSA was developed to perform a variety of tasks including: patrolling astronaut living quarters and laboratories, monitoring gas levels, temperature, and atmospheric pressure, and serving as a mobile data display terminal.

The PSA is equipped with both communication input and output capabilities, including a microphone, speakers, camera, and flat display panel. These features allow for video and audio conferencing, as well as a wireless relay to link to hardwired communication systems. Ground controllers are able to communicate with the PSA and maneuver the device into the desired location. Once in position, the PSA can use its on-board sensors to autonomously monitor the status of experimental lab animals in holding bays, or to provide remote views of mission operations.

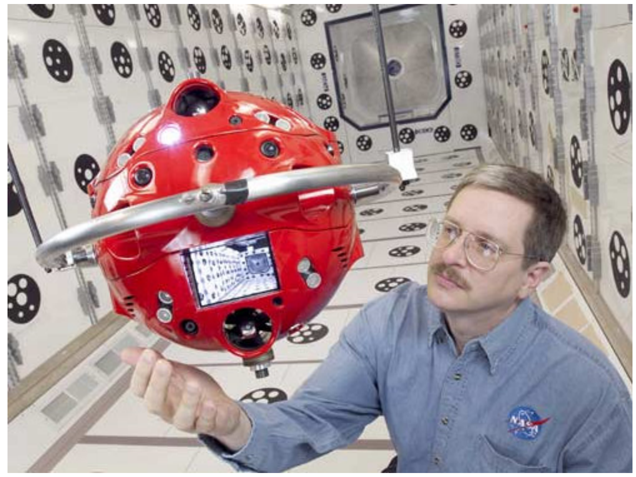

Figure 4. The Personal Satellite Assistant (NASA)

The PSA is envisioned to provide astronauts work site access to such information as vehicle status and health data, mission schedule, inventory tracking, location information, and just-in-time-training support. Interactions will potentially include both remote and proximate interactions, similar to SPHERES.

3. Charlotte

Charlotte (Figure 5) was a cable-direct-driven robot, a rectangular box driven in parallel by eight cables, with eight tensioning motors mounted on-board (one on each corner) developed by McDonnell Douglas Aerospace[11]. The robot moves along cables and was designed to perform many routine procedures similar to a gantry robot.

Charlotte found use in performing post-flight inspections of the Space Shuttle radiator bays. During Shuttle mission STS-60, Charlotte was flown to test six degree-of-freedom motion control. In such a role, the robot requires remote interaction.

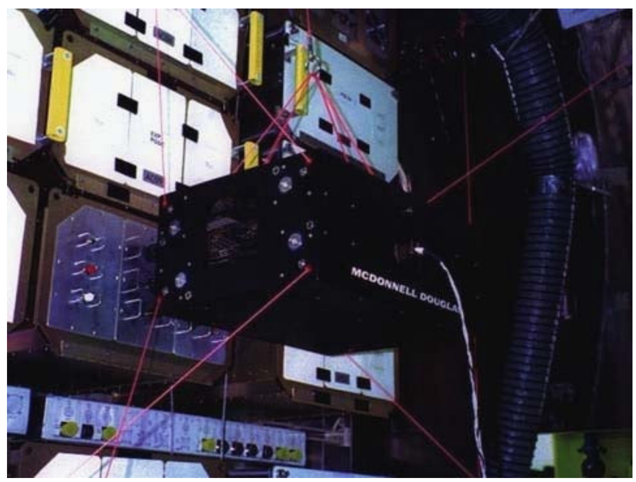

Figure 5. The Charlotte IVA robot (NASA)

III. Standardized Interactions: Towards a Roadmap for HRI

In the current state of the art, every robot has a custom-crafted user interface and custom-crafted interaction modes. This is undesirable for a multitude of reasons[12]. It means that a user needs to relearn control methods for each new robot. It means that two robots may parse the same command a different way. It means that software for robot control needs to be re-crafted for each robot. Most importantly, it means that it is very difficult to port new control modes from robot to robot.

A few emerging standards, such as JAUS[13], seek to standardize message sets and control architectures used for robot control. However, these standards only cover the lowest layer and do not address interface design, interaction modes, or mental models. There are also efforts underway to identify and develop general-purpose methodology for evaluating HRI[14]. Having common metrics and measures will be essential if we are to standardize HRI.

We define *standardized interactions* as a core set of commands, actions, and interfaces that will produce predictable, uniform (or very similar) robot behaviors regardless of robot type and capability. For example, when a driver enters a current passenger car, they know that the steering wheel is used to turn the car, that the accelerator pedal is used to control speed, etc. Automobile control devices, therefore, are standardized interactions. The question, therefore, is: what interface designs and robot actions are suitable for standardization? We propose that such standardization efforts should begin within the categories of possible interactions: proximate, remote, and remote with time delays. These efforts should also support standardization across the categories, but not at the expense of the types of missions that can be performed.

The benefits of such standardization are manifold. If all space robots have the same set of mobility commands, then users would not inadvertently send erroneous commands when switching between different robots (e.g., those made by a different organizations or manufacturers). If all similar robots had the same set of user interface controls and modes, then users would be able to better habituate to the interface and dedicate fewer mental resources to interaction. As a consequence, operator efficiency would be greatly enhanced, training requirements would be reduced, and safety increased.

The first roadmap element, therefore, is to identify the capabilities and limitations of humans and robots. Consider, for example, the factors associated with vehicle teleoperation. For a human, there are three basic concerns: figuring out where the vehicle is and what state it is in, determining where it should go, and moving it there[15]. These problems can be difficult to solve, particularly if the vehicle operates in a hazardous environment with a limited communication link. With manual control, performance is limited by the operator's motor skills and his ability to maintain situational awareness. Fatigue, lack of concentration, and poor displays all contribute to reduced performance[12,16]. Distance estimation, obstacle detection and attitude judgment can also be difficult[17]. Developing a standard interface that addresses all these issues is extremely challenging. We believe, however, that it should be possible.

For robots, capabilities and limitations can be compiled into a taxonomy of robot competencies, commands, and behaviors that are understandable by humans and rapidly learned. Table 1, for example, presents a few examples of human-focused features, functions, and interactions. Such a taxonomy would then be used to build a human-robot system architecture. Another approach might be to make use of design guidelines, such as the set proposed by Goodrich and Olson[18].

Table 1. Examples of human-focused feature, function, and interaction.

	Feature	Function	Interaction
Robot	2D laser scanner mechanically panned to create 3D data	Object tracking and warning thresholds for collisions	2 DOF from an analog input
Human	3D laser scanner	Collision warning system	Joystick control
Automotive analogy:			
Robot	Goodyear XYZ-123 or Firestone ABC-789 tires	Speed sensor, algorithms, and engine control	4 SPST buttons and 2 LEDs
Human	Standard all-weather tires	Cruise control	Buttons with lights

The second element in the roadmap is identifying key challenges that must be addressed. Making HRI effective, efficient, and natural is crucial to the success of future space exploration[2]. In particular, 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. A number of long-term HRI challenges must be addressed.

First, an active program of exploration will require human-robot collaboration across multiple spatial ranges, from shoulder-to-shoulder (shared space) to line-of-sight interaction (human inside, robot outside) to over-the-horizon (human inside, robot far away) to interplanetary (human at ground control, robot on planetary surface). The challenge for space exploration, therefore, is to develop techniques that support human-robot collaboration over a wide range of distances.

Second, interaction architectures that support HRI must be developed. Interaction architectures are structured software frameworks that support human-computer interaction. These architectures typically provide a set of core services (e.g., data messaging), support a variety of displays, and facilitate human-centered interaction. Significant research effort has focused on interaction architectures during the past several years, particularly for ubiquitous and context-aware applications, but few are appropriate for robotics. Moreover, none support the range of interaction scenarios and data requirements we believe will be necessary for long-term exploration.

Third, human-robot teams will require appropriate user interfaces in order to effectively perform exploration "field labor". Because humans will need to interact with robots in a variety of ways (different levels of autonomy, different spatial arrangements, etc.), a wide range of interfaces will be needed, both inside habitats and in EVA. Moreover, to improve usability and interaction effectiveness, a significant challenge is to develop constrained, standardized user interfaces. Standardized methods must balance the competing pressures of supporting a wide range of robots and tasks, and supporting common interactions. An appropriate balance will reduce training time, increase reusability by allowing modular improvements, and still support a wide range of behaviors and robot designs.

Finally, accurate and affordable methods for prototyping and evaluating HRI must be developed. Prototyping methods may include model-based simulation and trade studies to analyze different HRI "dimensions" (spatial distribution, robot autonomy level, team makeup, task dependencies, etc). Evaluation, especially for assessing standard performance, will require quantitative metrics. Although metrics from other fields (human factors, psychology, etc.) can be applied to satisfy specific needs, HRI has characteristics (e.g., physical interaction by an embodied robot) that set it apart.

As HRI evolves to meet each of these challenges, HRI standards will also have to evolve. In particular, as robots become more competent, more human aware, and better able to communicate on human terms, standard specifications will need to be adapted accordingly. Moreover, improved HRI tools and techniques will enable human-robot teams to jointly perform an increasing range of tasks. Future HRI standards may, therefore, need to encompass aspects of coordination and teamwork.

IV. Conclusion

As NASA continues to develop systems to support future space exploration, we believe there is a clear and pressing need for strong enterprise-level HRI standards. Effective standards will benefit mission architects, system designers, developers, and end-users (ground controllers, flight crew, etc.) in myriad ways. For the engineer, standards will result in reduced development and integration complexity, lower cost, and greater deployment efficiency. For operators, standards will reduce training requirements and time, decrease workload, and enable increased mission flexibility. To achieve this, key stakeholders within NASA, the academic community and the space industry will need to engage in a coordinated effort to define, scope, and promote human-robot standards as soon as possible.

References

[1] Ferketic, J., Goldblatt, L., Hodgson, E., et al. "Toward Human-Robot Interface Standards (I): Use of Standardization and Intelligent Subsystems for Advancing Human-Robotic Competency in Space Exploration". SAE 2006-01-2019. *Proc. SAE 36th International Conference on Environmental Systems*, 2006.

[2] NASA, "The Vision for Space Exploration", NP-2004-01-334-HQ, 2004.

[3] Fong, T. and Nourbakhsh, I., "Interaction challenges in human-robot space exploration", *ACM Interactions* 12(2), 2005.

[4] Duke, M., Hoffman, S., and Snook, K., "Lunar Surface Reference Missions: A description of Human and Robotic Surface Activities", NASA TP-2003-210793, 2003.

[5] Huntsberger, T., Rodriguez, G., and Schenker, P. "Robotics Challenges for Robotic and Human Mars Exploration". *Proc. Robotics*, 2000.

[6] Culbert, C., Rochlis, J., et al. "Activities of the NASA Exploration Team Human-Robotics Working Group", *Proc. AIAA Space*, 2003.

[7] NASA, "NASA's Exploration Systems Architecture Study", Final Report, NASA-TM-2005-214062, 2005.

[8] Dupuis, E., and Gillett, R. "Validation of Ground Control Technology for International Space Station Robot Systems", *6th International Symposium on Artificial Intelligence,. Robotics and Automation in Space*, 2001.

[9] Chen, A., Saenz-Otero, A., Hilstad, M., and Miller, D., "Development of Formation Flight and Docking Algorithms Using the SPHERES Testbed", 15th Annual USU Conference on Small Satellites, 2001.

[10] Dorais, Gregory A., and Gawdiak, Yuri, "The Personal Satellite Assistant: An internal spacecraft mobile monitor", *Proc. of the IEEE Aerospace Conference*, 2003.

[11] Campbell, P., Swaim, P., and Thompson, C. "*Charlotte Robot Technology for Space and Terrestrial Applications"*, 25th International Conference on Environmental Systems, SAE Paper 951520, 1995.

[12] Steinfeld, A., "Interface lessons for fully and semi-autonomous mobile robots", *Proc. IEEE International Conference on Robotics and Automation*, 2004

[13] JAUS Working Group, "Joint Architecture for Unmanned Systems (JAUS)", 2004.

[14] Steinfeld, A., Fong, T., et al., "Common metrics for human-robot interaction", *Proc. ACM Conference on Human-Robot Interaction*, 2006.

[15] Fong, T. and Thorpe, C., "Vehicle teleoperation interfaces," *Autonomous Robots* 11(1), 2001.

[16] Kaber, D.B., et al., "Effects of visual interface design, control interface type, and control latency on performance, telepresence, and workload in a teleoperation task", *Proc. Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society*, 2000.

[17] McGovern, D., "Experiences and Results in Teleoperation of Land Vehicles", Technical Report SAND 90-0299, Sandia National Laboratories, 1990.

[18] Goodrich, M. and D. Olsen, "Seven principles of efficient human robot interaction", *Proc. IEEE International Conference on Systems, Man and Cybernetics*, 2003.