

Interaction Challenges in Human-Robot Space Exploration

Terrence Fong
terry.fong@nasa.gov

Illah Nourbakhsh
illah@cs.cmu.edu

Artist conception of humans
and robotic assistants
building a space telescope.

IN JANUARY 2004, NASA established a new, long-term exploration program to support the President's "Vision for U.S. Space Exploration." The primary goal of this program is to establish a sustained human presence in space, beginning with robotic missions to the moon in 2008, followed by extended human expeditions to the moon as early as 2015. Moreover, the program places significant emphasis on the development of joint human-robot systems:

NASA will send human and robotic explorers as partners, leveraging the capabilities of each where most useful. Robotic explorers will visit new worlds first, to obtain scientific data, assess risks to our astronauts, demonstrate breakthrough technologies...Human explorers will follow to conduct in-depth research, direct and upgrade advanced robotic explorers, etc.

— NASA Vision for Space Exploration

A key difference from previous exploration efforts is that future space exploration activities must be sustainable over the long term. Experience with the space station has shown that cost pressures will keep astronaut teams small, and that care must be taken to extend the effectiveness of these teams well beyond their individual human capacity. Thus, in order to reduce human workload, costs, and fatigue-driven error and risk, intelligent robots will have to be an integral part of mission design.

Space Robotics. Although robots have previously been used for scientific purposes (e.g., geology) in space, robots will now also be called upon to perform non-scientific work. In particular, robots will be used for a wide range of tasks (under human control and autonomously) ranging from on-orbit assembly and maintenance of spacecraft to construction and maintenance of surface habitats to prospecting and processing of raw materials. The intricate nature of these tasks may require teams of robots capable of monitoring their own progress with a high level of autonomy.

Considerable research has already focused on developing human and robot systems for planetary surfaces. Scant attention, however, has been paid to joint human-robot teams. Such teams, however, are attractive for numerous applications. Robots could support long-duration manned excursions by scouting, surveying, and carrying equipment. Robots could assist in site preparation, sample collection, and transport. Finally, robots could be used for field labor, inspection and maintenance, and servicing of equipment and structures.



Construction. Construction, both in-space (on-orbit) and on planetary surfaces, is fundamental to exploration. Because structures are expected to be large and heavy, robots will be needed for a range of construction tasks including material transport, equipment positioning, and assembly. For example, planetary outpost construction will involve the transport, positioning

and assembly of habitat modules that have been deposited (landed) in a scattered manner around the construction site.

Infrastructure Support. Long-duration exploration will require significant robot support to maintain and service infrastructure. Robots could be used to search for, identify, and repair loose fixtures on interior structures (e.g., inside crewed spacecraft) and outdoor structures (solar array, communication structure, etc). A key challenge will be enabling the robot to perform these tasks as autonomously as possible, requesting human assistance and expertise only when necessary.

Contingency Life Support. Lunar pioneers will encounter hazards and crises requiring new emergency procedures. Given that crew sizes will be small, responding to medical emergencies will require robotic support. For example, robots could provide contingency life support or medical transport.

Science Exploration. Robots have long been identified as potentially useful assistants for science exploration. Since the 1990s, numerous researchers have studied how mobile robots can support the field activities of biologists and geologists. Robots can perform a wide variety of functions: scout, equipment transport, caretaker (monitor scientist during EVA), and co-worker (deploy sensor, survey region, etc.).

In-situ Resource Utilization. In-Situ Resource Utilization (ISRU) is a critical need for sustained exploration. Launching and deploying all the materials (consumables) that are needed for a permanent outpost is so cost-prohibitive, that in-situ resources will have to be used. At the same time, in order for ISRU to be cost effective, humans cannot perform this task unaided. Instead, groups of robots could be used to mine, transport, and even process materials such as regolith, water, etc.

HRI CHALLENGES. The interactions between humans and robots will be unlike anything that NASA has designed and implemented before. The operation of robot teams will at times be directed from ground control. For example, a lunar rover team may be assigned tactical assignments (e.g. "inspect solar array alpha"). Surface astronauts will also communicate with in-situ robots using voice-based commands, gestures, and wireless digital communication. Rovers, in turn, will communicate with one-another for team-based collabora-



Artist conception of human-robot lunar operations



Artist conception of robot medical transport



Artist conception of robot medical transport



Firestarter concept for robotic regolith collection

tion and must also develop sufficient self-diagnostic introspection to request human help when appropriate.

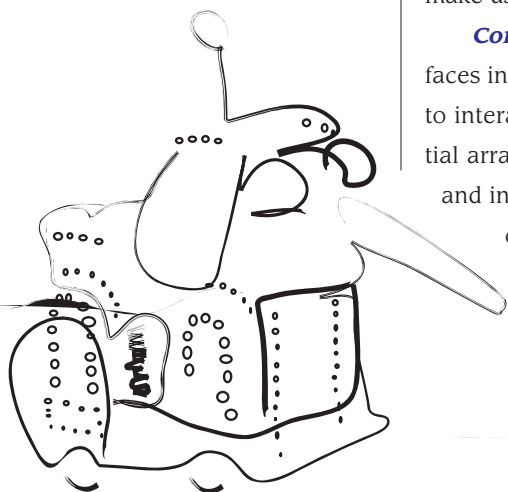
Making human-robot interaction (HRI) effective, efficient, and natural is crucial to future space exploration. In particular, we contend that humans and robots must be able to: communicate clearly about their goals, abilities, plans, and achievements; collaborate to solve problems, especially when situations exceed autonomous capabilities; and interact via multiple modalities (dialogue, gestures, etc), both locally and remotely. To achieve these goals, a number of HRI challenges must be addressed.

Multiple Spatial Ranges. Exploration will require human-robot collaboration across multiple spatial ranges, from shoulder-to-shoulder (e.g., human and robot in a shared space) to line-of-sight interaction (human in habitat, robot outside) to over-the-horizon (human in habitat, robot far away) to interplanetary (human at ground control, robot on planetary surface). Although a great many telerobotic systems have been developed during the past 50 years, none currently support multiple spatial ranges (i.e., all existing systems have been optimized for a particular spatial range). The challenge, therefore, is to develop HRI techniques for supporting multiple spatial ranges.

Interaction Architecture. Interaction architectures are structured software frameworks that support human-computer interaction. These architectures typically provide a set of core services (messaging, event/data distribution, etc.), support a variety of interfaces and displays, and facilitate human-centered interaction (as opposed to device-centered). Significant research effort has focused on developing interaction architectures during the past several years, particularly for supporting ubiquitous and context-aware applications, but few are designed for robotics. Moreover, none support the range of interaction scenarios and data requirements we believe will be necessary for exploration.

Peer-to-Peer Dialogue. Human-robot dialogue is an emerging sub-domain of HRI research. At present, most HRI systems rely on explicit dialogue (i.e. task commands), which is directed from a human to one, or more, robots. A few systems, such as NRL's multi-modal dialogue system, use multiple interaction modes (gesturing, natural language, etc.) to improve usability and for disambiguation. In all these systems, however, the dialogue model is essentially the same: the human "speaks;" the robot "listens" and perhaps asks for clarification. What we need for exploration, however, is dialogue that works both ways. We need to enable robots to ask questions of the human (so that they can obtain assistance with cognition and perception) and to develop techniques so that robots will be able to make use of "implicit" language and gesturing.

Constrained Interfaces. 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 will reduce training time and will increase reusability by allowing modular improvements.



CONCLUSION. The goal of effective, diverse collaboration between human/robot teams demands broad collaboration between members of disparate fields, including human factors researchers, human-computer interaction experts, roboticists and artificial intelligence researchers. Enabling fruitful collaboration across the philosophical and scientific divides of disparate fields of inquiry can be a daunting task, and overcoming these divides may prove to be the biggest challenge of all.

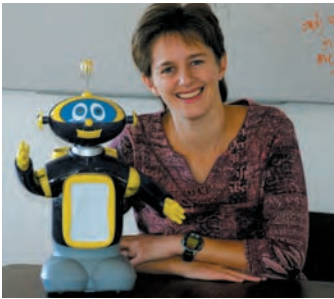


ABOUT THE AUTHORS *Terrence Fong is the deputy leader of the Intelligent Robotics Group at the NASA Ames Research Center (ARC). From 2001 to 2004, he was a joint post-doctoral fellow at Carnegie Mellon University (CMU) and the Swiss Federal Institute of Technology (EPFL). At EPFL, he served as deputy group leader of the Virtual Reality and Active Interfaces Group was co-investigator for virtual environment telerobotic field experiments at NASA ARC from 1990 to 1994. He received his B.S. and M.S. in Aeronautics and Astronautics from MIT and his Ph.D. in Robotics from CMU.*



Illah Nourbakhsh is an associate professor of Robotics in The Robotics Institute at Carnegie Mellon University. He received his Ph.D. in computer science from Stanford University in 1996. He is co-founder of the Toy Robots Initiative at The Robotics Institute. He is a founder and chief scientist of Blue Pumpkin Software, Inc. Illah recently authored the MIT Press textbook, Introduction to Autonomous Mobile Robots.

© ACM 1072-5220/05/0300 \$5.00



DR. CORINNA LATHAN is the president and CEO of AnthroTronix, a human factors engineering firm located in Silver Spring, Maryland. Before founding AnthroTronix, Dr. Lathan was an associate professor of Biomedical Engineering at The Catholic University of America (CUA). She holds advanced degrees in Neuroscience and Aeronautics and Astronautics from MIT. In 2002, she was named one of the world's top young innovators by MIT's *Technology Review*. In that same year, the AnthroTronix product, CosmoBot was named the innovation of the year by Maryland's *The Daily Record*. AnthroTronix does R&D in human-technology interaction products in the healthcare rehabilitation, defense, space, and entertainment areas.

Tell me about your interest in robotics. When did you start working in this area?

My interest in robotics is focused on the human-technology interaction. In graduate school, I was interested in biomedical aspects of space flight. One of the interesting questions posed at this time was the operation of a robot in space. When I was a professor in the Biomedical Engineering department at CUA, I was interested in robots applied to surgical procedures. I worked with faculty at Georgetown Radiology on surgical robots. I came to CUA partially because of their relationship with the National Rehabilitation Hospital. I saw the same key question with astronauts in space, a marine in the trench, and children with disabilities: how to manipulate and explore an environment that is remote, dangerous,

An Interview with Dr. Corinna Lathan of AnthroTronix

Jean Scholtz
jean.scholtz@nist.gov