UNIQUE CONSIDERATIONS FOR HUMAN-ROBOTIC INTERACTION IN HUMAN SPACEFLIGHT

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1.1 Robots for Space

The success of current and future human space exploration missions depends on effective integration of humans, automation, and robotic technology. Advancements in automation and robotics go hand-in-hand: better automation leads to more sophisticated and capable robots. NASA's Human Research Program (HRP) identifies inadequate design of human, automation, and robotic integration as one of the risks to human health and performance. It recognizes that failure to design and deploy effective systems and user interfaces, or to properly allocate automation and robotic resources, will compromise mission objectives and safety. The focus of this chapter section is to provide an overview of robots for space operations and the unique challenges posed by including robots in space operations, in order to characterize the relationship between safety and human performance when robots are involved.

In spaceflight, a generally accepted definition of a space telerobots is "a remotely operated robot that performs work in a rich space environment" (pg. 7, Fong et al 2013). Operators may be in space, experiencing either microgravity or partial-gravity, or on Earth. In general, there are two types of interactions people have with robots: remote interactions, where the robotic system is not co-located, and proximate interaction, where the robotic agent is co-located (Goodrich & Schultz, 2007). These two types of interactions bring about various issues regarding how robotic systems are used by or with people, termed human-robotic interaction (HRI). Robotic systems in the safety-critical domain of spaceflight are a driving function to carefully design and evaluate HRI.

Fundamentally, robotic systems are necessary in spaceflight because they significantly increase our capabilities to live, work, and explore space. Arguably, these ought to be the only reasons to introduce robotic systems into safety-critical domains. The benefits must outweigh the introduction of risk and safety concerns. These risks are robots inadvertently hurting astronauts and robotic operations unintentionally preventing mission success. Robotic systems need to do tasks that humans alone cannot complete, such as moving large space assets or scanning large areas of planetary surfaces. Robotic systems should also be leveraged to improve upon one of the most precious resources in space: people's time. Space telerobots could be deployed to complete mundane tasks for astronauts, freeing up time for them to do other critical work. While intermingling robots and people has the potential of increasing safety risks, on the other hand, space telerobots can improve overall crew and mission safety. Spacewalks (or extravehicular activities, EVAs) outside the ISS are considered one of the riskiest activities for astronauts due to the limited time humans can spend in a fragile, pressurized spacesuit, exposed to additional radiation. Robotic systems that complete exterior tasks without EVA astronauts improve International Space Station (ISS) crew safety as it reduces the overall number of EVA hours. Similarly, planetary missions should leverage space telerobots to minimize Lunar or Mars radiation exposure or perhaps, exploring terrain treacherous terrain, protecting astronaut crew health in the long term.

NASA currently leverages space telerobots to conduct critical space operations and is limited to two areas: large, robotic arms and planetary surface rovers. Building upon Shuttle's heritage, the ISS regularly uses the Space Station Remote Manipulator System (SSRMS) to complete EVAs, capturing free-flying vehicles and complete maintenance tasks. It was used extensively during ISS construction; as recently as 2015, the SSRMS was utilized to relocate a module (the large Permanent Multipurpose Module), allowing the installation of another docking port. The second robotic arm on ISS is the Special Purpose Dexterous Manipulator (SPDM), or Dextre, which plays a role in many of the exterior maintenance tasks required, such as inspection and relocation of Orbital Replacement Units (ORUs).

These dexterous robotic arms enable astronauts to safely live and work aboard ISS. Ground teams use Dextre to complete many tasks while crew completes other interior activities. They enable critical tasks that could not have been accomplished otherwise. For instance, in late 2007, Astronaut Scott Parazynski repaired an ISS solar array, which could only be reached while propped by the Shuttle's RMS (Cupples & Smith, 2011). SSRMS is essential for capturing visiting vehicles, including Space-X's Dragon and Orbital's Cygnus, and berthing them into one of the ISS docking ports. These spacecraft regularly resupply ISS with spare parts, science payloads, as well as food and medicine for astronauts.

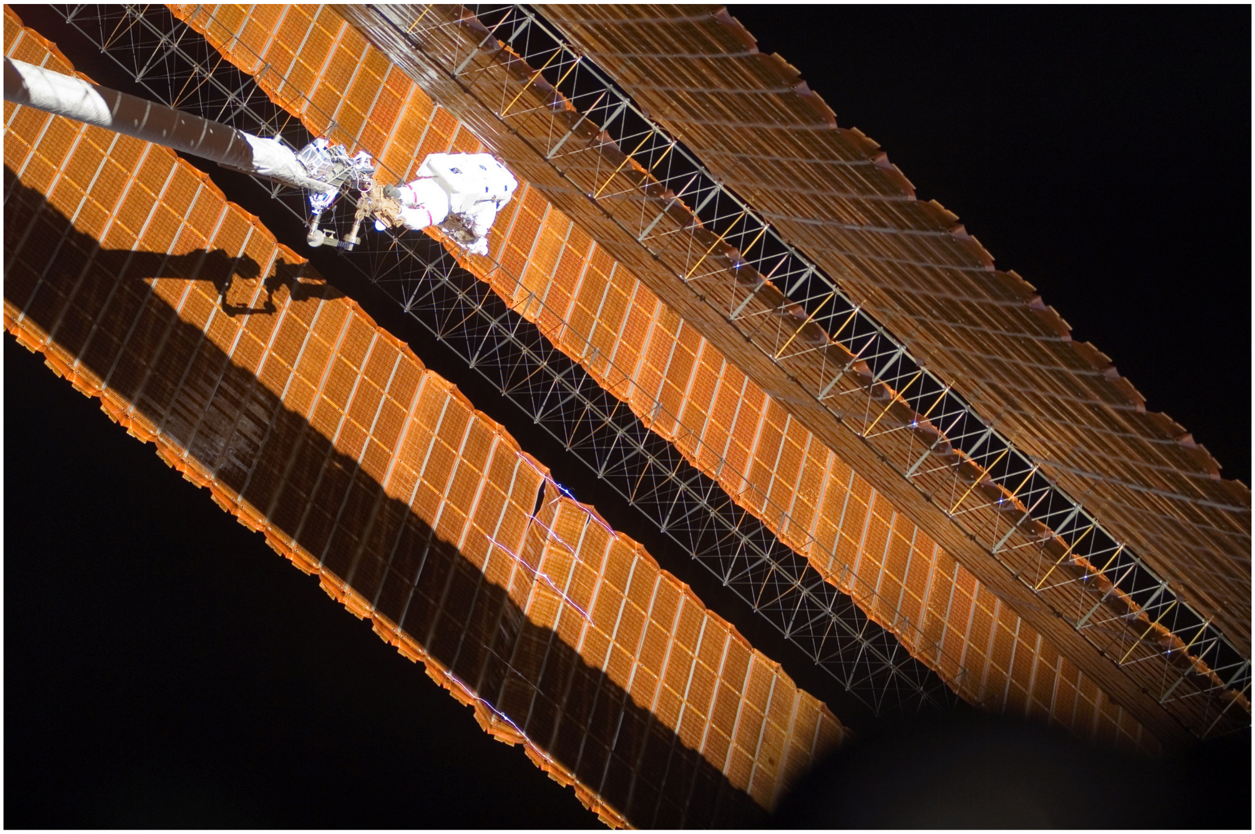
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Figure 1: Astronaut Scott Parazynski (STS-120) attached at the end of Remote Manipulator System. Credit: NASA, ISS016E009207.

Beyond low Earth orbit, NASA has deployed several rovers and landers on the Mars surface since 1976. Currently, there are two operational Mars rovers: Mars Exploration Rover, Opportunity, and Mars Science Laboratory, Curiosity. Each are equipped with a variety of scientific instruments and their own manipulator arm. The rovers traverse Mars, collecting data and analyzing samples for teams of scientists back on Earth. These rovers, far exceeding their planned lifetime, have increased our exploration capabilities, gathering scientific evidence to answer the question if Mars is or was habitable. Robotic missions, at first glance, may not appear to have an impact on space safety and human performance, but there are safety considerations for the human operators back on Earth. For example, the Curiosity mission purposefully determined to only operate on Mars time for the first 90 days. Unfortunately, Mars and Earth do not share the 24-hour day cycle. This meant that all the operators and scientists had to shift their work and sleep schedule 40 minutes every day. Such changes in circadian rhythm and sleep cycle have shown to have detrimental fatigue effects on people back on Earth, as experienced during Opportunity mission (Barger et al., 2012).

While there is no imminent safety risk on the operators, there are mission safety considerations. Maintaining mission safety is still important and must be balanced against exploration objectives. For the rover missions, engineers and operators want to mitigate any risk that might damage the valuable spacecraft asset. For that reason, the mission control team carefully plans out every command sent to the space telerobot, operating the rover well within its capabilities. Even under such risk-adverse operating constraints, unexpected circumstances still challenge mission operators to act safely. Notably, the Opportunity rover got stuck in a sand dune 446 sols into its surface mission (Helmick, Angelova, and Matthies, 2009). After a month, the engineers were able to maneuver it out. Such illustrative cases inform NASA of the indispensable value of good human-robotic interaction for crew and mission safety.

2.1 Space Human-Robotic Interaction Design Challenges

NASA’s Human Research Program (HRP) succinctly summarizes the interaction challenges (NASA, 2017): Given that automation and robotics must seamlessly integrate with crew, and given the greater dependence on automation and robotics in the context of long-duration spaceflight operations, there is a risk that systems will be inadequately designed, resulting in flight and ground crew errors and inefficiencies, failed mission and program objectives, and an increase in crew injuries. Furthermore, it identifies four gaps or research areas for the Risk of Inadequate Design of Human and Automation/Robotic Integration (HARI):

- We need to identify and scope the critical human-automation/robotic mission activities and tasks that are required for future long duration, long distance space missions.
- We need to evaluate, develop, and validate methods and guidelines for identifying human-automation/robot task information needs, function allocation, and team composition for future long duration, long distance space missions.
- We need to develop design guidelines for effective human-automation-robotic systems in operational environments that may include distributed, non-colocated adaptive mixed-agent teams with variable transmission latencies.
- We do not know how to quantify overall human-automation-robotic system performance to inform and evaluate system designs to ensure safe and efficient space mission operations.

In many ways, the fact that NASA can relate automation and robotic integration concerns together speaks to the tight relationship between these technologies. We should be able to infer, or at the very least, anticipate potential pitfalls in HRI from what we know about HAI. For instance, it is likely that higher degree of automation *in robotic systems* should result in decrements in situation awareness, though it was only concluded from a meta-analysis by Onnasch, Wickens, Li, and Manzey (2014) for automated systems. Challenges with operators maintaining mode awareness or overreliance in automation have been recognized in the past (Parasuraman & Riley, 1997). Arguably, we may have already evidenced this in space operations when Opportunity accidently drove into non-navigable terrain. Operators may have assumed incorrectly the capabilities of the robotic systems or may have over-relied on the existing capabilities of the rover.

Fundamentally, HRI challenges deal with the interaction between humans and robots. Goodrich & Schultz (2007) outline five attributes that affect HRI (pg. 216):

- Level and behavior of autonomy,
- Nature of information exchange,
- Structure of the team,
- Adaptation, learning, and training of people and robot,
- Shape of the task.

HRI design solutions for spaceflight are further constrained by the inherent nature of spaceflight. First, the space environment notably affects both robots and humans. Space-bound hardware systems need to be robust to survive environmental factors such as radiation, temperature extremes, illumination variations, and micrometeoroids (Fong et al., 2013). As a result, they usually are not as capable as their modern, Earth counterparts. Analogously, astronauts must live and work in microgravity (and partial gravity for exploration-class mission), exposed to high cumulative dosages of space radiation. Extended exposure to this extreme environment affects people's physiology, and in turn, their performance duration space operations (for overview, see Jones, 2010; for more details, see Churchill, 1997). Furthermore, astronauts must perform in less-than-ideal habitats and workspaces, exposed to long-duration isolation, space-efficient work-areas, and minimalist sleeping quarters. In turn, crews are at risk of experiencing chronic ergonomics-related disorders, prolonged sleep loss and corresponding fatigue, and other behavioral health issues (Jones, 2010).

Second, the distance, spatially and temporally, between space telerobots and their operators further limits HRI designs. Long-distance space exploration has equivalent transmission latencies, and current deep space communication infrastructure prevents continuous, large bandwidth transmissions. Even if the bandwidth is mitigated with future improvements to NASA's Deep Space Network, intermittent asynchronous communications result in unique space HRI designs. For Earth-Mars communication, one-way transmission latencies range from four to twenty-four minutes, and about every two years, Mars solar conjunction prevents transmissions between the two planets.

Considering future exploration-class missions, NASA's Design Reference Missions, like NASA (2009) describe a particular team structure. Crew teams will be small, likely four astronauts, with various diverse backgrounds and expertise. On their way to Mars, there will not be opportunities to "bring in" a robotics expert or rotate in any specialty operator during the three-year long mission. This small team will bear the responsibility of learning and using all robotic systems required of the mission. The robotic systems available to them will also be assorted. Future capabilities for space telerobots range from partnering with astronauts to explore to maintaining habitats while in quiescence (Weisbin, Lavery, & Rodriguez, 1997; Marquez et al. 2016). Some robots will be co-located, others may be operated from long distances at first, and then while in line-of-sight. Along with the previously mentioned constraints, the diversity in robotic systems accompanied by a small crew team necessitates space HRI to include interfaces for the support heterogeneity, multiple control modes, and varying degrees of autonomy (Fong et al., 2013).

2.1.1 Illustrative Space HRI Example: Shape of Task

In the last few years, robotics operations have become a critical component to berthing visiting vehicles. Crew and ground teams work together through the SSRMS to grapple and berth visiting vehicles (Figure 2). Additionally, the visiting vehicle is undocked and moved with the SSRMS to a safe distance and trajectory from ISS for its return back to Earth. Berthing visiting vehicles is an adapted procedure from previously existing robotics tasks. For visiting vehicle operations, a robotics workstation is arranged by the crew within the Cupola to conduct the task and the task is coordinated between ground teams and onboard crewmembers. This new operation, which changed the shape of the previously vetted robotic tasks, require careful HRI evaluation, applying lessons learned regarding systems, procedures and operations collected over the life of ISS.

Figure 2: Astronaut Karen Nyberg (Expedition 36) at the robotics workstation in the ISS Cupola preparing for grappling and berthing of the Japanese H2 Transfer Vehicle-4 (HTV-4). Credit: NASA.

The SSRMS manipulation for EVA-related robotics and visiting vehicle operations share many similarities with respect to tasks, but diverge in two key manners. First, visiting vehicle operations requires the SSRMS to capture another spacecraft moving in space. Second, despite using functionally the same robotic workstation, visiting vehicle operations requires the astronaut to integrate more (or different) information. There are two robotic workstations aboard the ISS, one in the Cupola, surrounded by windows, and the other is in the U.S. Lab module. The Cupola affords crew a direct view of the spacecraft and the SSRMS; this visual input thus must be integrated as part of the task. Crew commented that, initially, limited guidance was provided on how best to set up the robotic workstation in the Cupola. Additionally, there are many crew comments regarding the out-the-window lighting conditions (i.e., too bright or too dark) and their potential effect on performance (e.g., ability to assess out-of-window views like relative size or changing rates of motion). It is important to note that ground teams immediately addressed these crew comments to better support visiting vehicle robotic operations aboard ISS (Marquez et al., TBD). The adaptation of space robotics operations, using a single robotic system with a rich operational history, for a comparable yet slightly different task illustrates how challenging space HRI is and will be for future exploration-class missions.

3.1 Developing Operationally-Valid Space HRI

Through various space analogous test environments, NASA has begun to investigate the complexity of the design space encompassed by space-bound HRI: different types of robotic systems, control modes (manual through supervisory control), and operational concepts (co-located/proximal teaming, 1:many vs. many:1, robot before/after human, etc.). For example, there are several studies that have been performed aboard ISS. Robonaut 2 (R2), a highly dexterous humanoid robot, is currently aboard the ISS (Diftler et al., 2011) and is being evaluated as a means to reduce crew time by completing routine and redundant tasks. Bualat and her team tested remote surface telerobotics from the ISS (Bualat et al., 2013), while the European Space Agency has several ISS experiments evaluating methods of human-robotic interaction, including haptic feedback (Schiele et al., 2016). On Earth, space robotic evaluations are difficult because it is hard 1) to have high fidelity simulations of all aspects of the space environment, 2) to acquire matching astronaut or ground controller populations, and 3) to mimic one-of-a-kind space telerobots (Fong et al., 2013). Nonetheless, in an effort to understand how to design human-robotic interaction for safe and efficient use, studies have examined rovers as scouts and as systems to follow-up after human exploration (e.g., Bualat et al., 2011; Deans et al., 2012).

While exercising future space telerobots in extreme environments is essential for operationally validating safe and efficient human-robotic systems, there is still fundamental research that can be studied in laboratory settings. The HARI gaps (previously mentioned) recommend areas of investigation. For instance, developing user interface designs that quickly help operators recover situation awareness when a system enters an off-nominal state will be important for both highly autonomous and robotic systems. Seamless integration of various control modes will be indispensible in future space telerobotics, yet we have not developed design standards to accommodate these types of interactions, or to assess their impacts on situation awareness, workload, and task performance. There is much to learn and understand with regards to the effects of trust in safety of these robotic systems, particularly with robots that will be in close proximity with astronauts. Inadequate training may also play a role in trust, leading to automation biases, over or under-reliance on automation, increased operator workload, safety hazards, and failure of mission objectives. For example, Olsen al. (2011) acknowledges the importance of training to reduce biases and educate the operator on how the robot functions. Lastly, while we an infer a relationship between robotic tasks and fatigue, there is limited evidence that directly maps the relationship between sleep deprivation and the performance of human-automation/robotic systems.

3.1.1 Concluding Remarks

Future exploration-class missions will require heterogeneous robots to enable mission objectives without sacrificing safety. Good design is foundational to reducing integration risks, both of safety and of failure to complete missions due to inefficiency or ineffectiveness. Continued work and research in human-automation and human-robotic interaction will improve and inform NASA Standards 3001 in order to set standards for human-automation-robotic safety.

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