Perspectives on Level of Autonomy Decisions in Space Robotics

Cailyn Smith
Colorado School of Mines
Golden, CO, USA
ccsmith1@mines.edu

Terran Mott
Colorado School of Mines
Golden, CO, USA
terranmott@mines.edu

Tom Williams
Colorado School of Mines
Golden, CO, USA
twilliams@mines.edu

ABSTRACT

The use of robotics in space exploration and space sustainability has become increasingly more prevalent in recent years. Aerospace contexts pose unique challenges to both robotic capabilities as well as human operator control as these robots often operate in safety-critical situations, unknown environments, and with significant communication latency to Earth. There exist both advantages and potential risks to increased levels of autonomy in these contexts. Therefore, this paper aims to elucidate perspectives on the future role of human operators and the trade-offs when deciding on the level of autonomy for a system. To investigate these perspectives, we conducted qualitative interviews with five professionals in the space robotics industry. Our findings show that—in addition to straightforward technical considerations—financial concerns, operators' willingness to accept new technology, and even humans' emotional experiences during missions will likely play a role in the future of shared control in space robotics.

CCS CONCEPTS

• **Human-centered computing** → *Human computer interaction (HCI)*; • **Applied computing** → **Aerospace**; • **Computer systems organization** → **Robotic autonomy**.

KEYWORDS

space robotics, aerospace, level of autonomy

ACM Reference Format:
Cailyn Smith, Terran Mott, and Tom Williams. 2024. Perspectives on Level of Autonomy Decisions in Space Robotics. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction (HRI '24 Companion), March 11–14, 2024, Boulder, CO, USA.* ACM, New York, NY, USA, 4 pages. https://doi.org/10.1145/3610978.3640697

1 MOTIVATION

In the past few decades, autonomous capabilities in space exploration systems have increased, including in satellite systems [35], planetary rovers [19], and robots on the International Space Station [6]. These systems rely on human operator control for some functionality, often for evaluating the system's environment and deciding on future actions or goals [35, 46]. While these current space robots rely on human-in-the-loop control, reports conducted by the National Aeronautics and Space Administration (NASA) show that increased autonomous capabilities for space exploration systems will be needed, especially as unknown environments are explored and the delay between spacecraft and human operators increases as missions travel further from Earth [1, 35].

Although increased autonomy can enable robots to accomplish new objectives, implementing high levels of autonomy is accompanied by complex trade-offs. Situation Awareness is a critical human factor during high risk or high time pressure tasks [29]. It is a three-level concept [13], referring to the perception of stimulus in the environment, the comprehension of those stimuli in the task context, and the ability to predict the state of the environment in the near-future. High levels of autonomy can negatively impact a human's Situation Awareness and task accuracy during a collaborative task with a robot [24, 43]. Additionally, autonomous capabilities can impact an operator's trust in the system, depending on the operator's beliefs, the robot's competency, and the situation that the robot is operating in [34]. The interplay of autonomy and human factors that affect the success of robotic missions informs how a robot should convey its decisions to a human collaborator [40, 43]. These dynamics are particularly important to evaluate in a space exploration context, as space robotics missions have significant uncertainty and have recently seen a dramatic increase in the amount and type of autonomous systems [35]. In this way, space robotics missions bring unique challenges to designing shared control, including high latency, high risk, and collaborative decision-making between engineers and operators [30].

Therefore, it is essential for HRI researchers to understand how potential trade-offs between human-in-the-loop control and fully autonomous systems lead to decisions about the design of shared control in space robotics. Specifically, researchers should consider the perspectives of aerospace industry professionals who may be affected by the advantages and potential limitations of shared control. In this way, we can understand how space robotics professionals view shared autonomy in space robotics and in what ways they may feel optimism or concern about autonomy in space. Therefore, we ask the research question: ***How do space robotics experts conceptualize the advantages, risks, and trade-offs relating to the future of semiautonomous space robots?*** To investigate this question, we conducted five interviews with space robotics professionals who are already grappling with the trade-offs of working with semiautonomous robots during missions. Our results show that professionals place importance on technical factors related to the robotic mission as well as how the level of autonomy affects humans' emotional experiences, trust, and acceptance of new tools.

2 RELATED WORK

2.1 Robotics in the Space Industry

In the space industry, robotics are used for planetary exploration [19], on-orbit servicing [32], and on the International Space Station [6]. On planetary surfaces, robotics are used for scientific purposes,

HRI '24 Companion, March 11–14, 2024, Boulder, CO, USA

ACM ISBN 979-8-4007-0323-2/24/03.
https://doi.org/10.1145/3610978.3640697

including for exploring the Moon and Mars [19]. Robotics on-orbit are often used for satellite servicing, inspection, and repair [32]. Proposed future robotic space missions plan to increase the prevalence of these technologies and their applications in space [19].

2.2 Semiautonomy in Mission-Critical Domains

While definitions of autonomy are varied, the definition of autonomy used by NASA is applicable to a wide range of systems, especially space robotics. It defines autonomy as "the ability of a system to achieve goals while operating independently of external control" [17]. *Human-in-the-loop* refers to robots that require a human command to perform an action while *human-on-the-loop* refers to robots that carry out actions independently while humans provide oversight and have the ability to veto an action [10].

Researchers have developed taxonomies for describing and selecting the ideal Level of Autonomy (LoA) for semiautonomous technologies [2, 15, 22]. In robotics, roboticists must determine who within a human-robot team is responsible for observing the environment, generating possible actions, selecting a planned action, implementing the action, and detecting system-critical events [23, 25]. The distribution and monitoring of these tasks within the team directly impact mission performance [16, 26] and cause credit or blame to be allocated differently for task outcomes [28]. Thus, technologists must choose which aspects of a task to automate without risking human safety [2, 21] and must design interfaces to support these cognitive processes [3, 11, 41]. While LoA design decisions are complex and case-specific, guidelines emphasize that task criticality, task accountability, and environmental complexity are key dimensions that must be considered when designing semiautonomous or human-in-the-loop systems [2].

When determining the LoA for a system, roboticists must also account for the potential drawbacks of increasing autonomy. Highly autonomous systems can negatively affect an operator's Situation Awareness [14], which impacts failure and human error rates [7]. This can introduce unique risks in highly critical tasks with potential safety concerns [37, 38]. These risks may be particularly salient in complex and dynamic environments that would require higher sensing capabilities if they are designed to be highly autonomous [45]. However, even with high sensing capabilities, a high LoA may only be justifiable when a complex environment is predictable. When an environment is unpredictable, a robot may need to be teleoperated or, at minimum, supervised [9].

2.3 Human Factors in Mission-Critical Robotics

Designing semiautonomous systems to be sensitive to their operators' human factors needs and cognitive load is essential to develop technology that can harmonize with human capabilities [13]. Human factors of Situation Awareness and trust are critical for both human safety and mission success [13, 14]. A multitude of factors—related to the human, robot, and environment—as well as the autonomy of a system impact trust in a human-robot team [27] [18]. Both a lack of trust and over-trust of a system can reduce the effectiveness of human-robot teaming [4].

In addition to trust, Situation Awareness impacts the effectiveness of a semiautonomous robotic system. Researchers have studied how operators direct their attention to build and maintain Situation Awareness in high-stakes or time-dominant mission environments [8, 12]. These frameworks are relevant to semiautonomous robotics across domains such as search and rescue [20, 33], collaborative exploration [31, 41], automated vehicles [39], and the operation of multi-robot systems [42]. However, Situation Awareness has been shown to decrease as the autonomy of the robotic system increases [36]. Furthermore, research has shown that intentionally lowering a system's autonomy can increase situational awareness in space contexts [43] and situations with latency [44].

3 METHODS

We conducted IRB-approved semi-structured interviews to investigate the research question: ***How do space robotics experts conceptualize the advantages, risks, and trade-offs relating to the future of semiautonomous space robots?*** We interviewed five professionals in the space robotics industry. Participants were recruited through online professional channels and signed a consent form for the interview. Their combined experiences spanned on-orbit robotics, planetary rovers, and human spaceflight missions. Participants were asked about their perspectives on level of autonomy decisions in space robotics, including how they make decisions about autonomy when they develop a new system, what they view as the main advantages and disadvantages of robots with higher autonomy, and how adding autonomous capabilities impacts the risk and cost of a project. Each interview recording was transcribed and anonymized. We then used the transcripts to conduct thematic analysis [5] and report preliminary results of this analysis here. These findings focus on how participants perceived the value of autonomy and human decision-making in space robotics, as well as the varied motives for decisions about autonomy in space missions.

4 RESULTS

4.1 Participants supported autonomy while valuing humans' decisions

Across interviews, participants expressed that the level of autonomy in space robotics would increase in the near future, but operations will continue to involve humans in some capacity. Technological factors and new developments, as well as considerations of human perception of autonomy, will fuel higher degrees of autonomy to be utilized in space robotics. From the technology standpoint, new developments in space-grade hardware and validated autonomous capabilities will remove many of the current limitations on incorporating higher levels of autonomy. In addition to technological developments enabling more autonomous capabilities, certain types of missions may become more prevalent in the future and require more autonomy—such as extremely high time pressure situations, situations that are critical to the system's safety, and situations that require the propagation of trajectories into the future in a way that a human cannot accurately determine. Participants also highlighted that large fleets of robotic systems and deep space missions with substantial latency will not be feasible for direct human control.

Although participants supported increasing autonomy in many systems, all participants valued the role of human decision-making in the future of space robotics. Participants pointed to the advantages of humans in high-level decision-making and to fully understand a situation as reasons why they will continue to have a role in the operation of space robotics. P4 stated, "*humans will always be needed in the loop because we're able to understand a situation at times comprehensively better than a computer.*" Participants viewed the future of space robotics involving humans creating high-level objectives for the system, which the system can carry out autonomously unless there are unforeseen failures that the system cannot resolve by itself. Additionally, participants foresee human-on-the-loop control remaining prevalent in aerospace. P1 expressed that the consequence of failure in a space environment leads to the desire for human monitoring: "*It is worth that human check-in in order to validate that what the satellite sees out of its sensors and feels comfortable with is in fact what we can verify on the ground.*"

4.2 Technical factors and human perceptions motivate LoA decisions

4.2.1 Technical factors motivate LoA choices. Often, technical factors, such as latency and computational power, influence the choice of the level of autonomy for space robotic missions. Several of the participants who work on on-orbit robotic missions or deep-space missions describe that functionality is performed on the robotic platform with human supervision due to the communication latency present in these situations. P5 describes that a particular mission has "*[an] hour or more of lag time and everything has to be done autonomously because the operations are just a few minutes long.*" Additionally, interviewees expressed that the inability to transmit substantial amounts of data to the ground often necessitates providing autonomous capabilities on the robotic system itself, particularly in situations where decisions must be made rapidly.

While some technical factors of space missions increased the desired autonomy of robotic behaviors, other technical factors drove the need for human control of the system. Participants expressed that the choice to provide more human involvement was often influenced by limited computational resources on space hardware.

Furthermore, several participants expressed plans to operate new robotic missions with lower levels of autonomy until the system had been sufficiently tested in the space environment to be comfortable with increasing its autonomy. P3 described that their initial mission for a new type of technology would rely heavily on human control. Then they would use the data from the mission to allow for high levels of autonomy in future missions, explaining that "*we start gathering data and we'll be able to build some of the algorithms for some level of autonomy.*" P2 explains what this monitoring and potential involvement can look like for the spacecraft they work on as, "*if it needed to do abort for a reason, then a human can get in the loop, can analyze some of that data.*"

4.2.2 Nontechnical factors also impact LoA choices. Although the technical parameters of a robotic mission, including latency, ability to communicate consistently with ground stations, and computational limitations, impact the decision about the amount of autonomy a robot will be provided, participants highlighted how human perceptions drive decisions on level of autonomy. In many cases, there was a concern that humans would make worse decisions than an autonomous system, either by using more propellant for a maneuver, executing a command that would introduce more risk to the spacecraft, or causing the autonomous system to be unable to resume its operations. Some participants expressed a lower level of trust in human operators than in an autonomous system due to the inability to predict how a human may react under pressure to make quick decisions. P4 pronounced that they do not want human operators "*grabbing the stick and going haywire and burning all of the propellant.*"

However, participants also valued humans' perception of the system to such a high degree that they made choices about autonomy that may even detriment the mission. In order to increase trust in the system, one company chose to allow humans to abort the system even though P1 stated that "*if executed at the wrong time could actually put the whole scenario at higher risk.*" In another case of prioritizing human perceptions over technical risk, P4 explained that they chose to include more human involvement in the system because it gave the astronauts a task during a long mission, describing, "*we didn't really need humans there, but it was the right thing to allow them to do things while they were out there so that they felt involved in the mission.*" Thus, participants expressed a need to consider both technical factors and mission requirements as well as human factors and perceptions when deciding on the level of autonomy for a space robotics mission.

5 DISCUSSION

While this paper includes preliminary results that do not attempt to cover the full scope of the research question, our initial findings show that space industry professionals believe that many space robotic domains will require robotics with a higher LoA; however, the role of human decision-making will likely remain important.

Interviewees described that both technical and nontechnical factors contribute to how space robotics professionals make design decisions about shared control in space domains. In many cases, straightforward technical considerations motivate these design decisions—such as latency or lack of computing power. However, interviewees also highlighted that perceptions of operators, engineers, and astronauts involved in space robotics missions contribute to LoA decisions. In order for these stakeholders to feel that they are involved in missions and can trust their robotic tools, it can be important for humans to retain control over semiautonomous robots, even if this increases the risk of human error.

6 CONCLUSION

Interviews conducted with professionals in the space robotics industry illuminate the role that humans may take in the operation of shared autonomy systems. These interviews demonstrate the need for systems that allow human monitoring of space robotic technology and take into consideration the unique aspects of space, including latency and high time pressure situations. This paper demonstrates that researchers in space robotic contexts must consider both technical and human factors specific to the context of the robotic system's deployment when determining the level of autonomy for a system in space.

ACKNOWLEDGMENTS

This work was funded in part by NASA Early Career Faculty award 80NSSC20K0070.

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