Robot, Take the Joystick: Understanding Space Robotics Experts' Views on Autonomy

Cailyn Smith, Terran Mott, and Tom Williams

Abstract— **As robots become increasingly used in space exploration, it is important to ensure that space robots are developed with the appropriate level of autonomy. Semiautonomous robots operating in space contexts face unique challenges, as these robots often operate in situations that may be safety-critical, environments that are not fully known, and with communication delay to operators on Earth. Due to these challenges, there exist both advantages and risks to developing systems with high levels of autonomy to operate in space contexts. Therefore, we aim to investigate perspectives on the trade-offs of increased autonomy for space robotic systems and the human factors considerations that should be evaluated when designing these systems. We conducted qualitative interviews with five professionals in the space robotics industry to explore these perspectives. Our findings demonstrate that decisions regarding the level of autonomy of space robots is shaped not only by technical considerations, but also by operators' willingness to accept new technology, financial considerations, and even human operators' sense of control. Based on these results, we present design recommendations for roboticists and human factors engineers in the space robotics domain.**

I. INTRODUCTION

In the past few decades, autonomous capabilities in space exploration systems have increased, both in non-robotic systems like satellites [1], and on robots like planetary rovers [2] and those used on the International Space Station [3]. These systems rely on human operator control for some functionality, often for evaluating the current context and deciding on future actions or goals [1], [4]. While these current space robots rely on human-in-the-loop control, reports conducted by NASA show that increased autonomous capabilities for space exploration systems will be needed in the future, especially as unknown environments are explored and the communication delay to Earth increases as missions travel further [1], [5].

Although increased autonomy can enable robots to accomplish new objectives, implementing high levels of autonomy presents complex trade-offs. High levels of autonomy can negatively impact a human's Situational Awareness and task accuracy during a collaborative task with a robot [6], [7]. Additionally, autonomous capabilities can impact operator trust, depending on the operator's beliefs, the robot's competency, and the context into which the robot is deployed [8]. Level of autonomy thus interacts with human factors considerations to determine the success of robotic missions; a phenomenon that has been used to inform how robots adapt their level of autonomy and how they signal that level of autonomy to others [7], [9].

The authors are with the MIRRORLab at the Colorado School of Mines, Golden, CO, USA. {ccsmith1, terranmott, twilliams}@mines.edu

These dynamics are particularly important within space exploration contexts. Space robotics missions bring unique challenges relevant to level of autonomy selection, including high latency, high uncertainty, high risk, and frequent collaborative decision-making between engineers and operators [10]. Moreover, there has been a dramatic increase in the number and type of autonomous systems used in space contexts [1], increasing both the difficulty and importance of understanding when and how autonomy should be used.

Therefore, it is essential for human-robot interaction researchers to understand how potential trade-offs between human-in-the-loop control and fully autonomous systems will impact the future of 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 the future of 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 semiautonomous robots. Our results show that when considering the level of autonomy of space robotic systems, space industry professionals view the risk and cost associated with autonomous systems as especially important, but that these professionals' views are also shaped by their trust in technology, their willingness to accept new tools, and the expected emotional impacts of autonomous systems.

II. RELATED WORK

A. Robotics in the Space Industry

In the space industry, robots are used for planetary exploration [2], on-orbit servicing [11], and assistance on the International Space Station [3]. On planetary surfaces, robots are used for scientific purposes, including exploration of the Moon and Mars [2]. Meanwhile, robots on-orbit are often used for satellite servicing, inspection, and repair [11]. Future space missions have proposed to further increase the use of these technologies [2].

B. 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" [12]. Researchers have developed taxonomies for describing and selecting the ideal Level of Autonomy (LoA) for semiautonomous technologies [13], [14], [15]. Kim et al. [16] proposes six forms of autonomy, of which *operational autonomy* and *shared autonomy* are primarily considered in this work. Although level of autonomy frameworks are varied, the taxonomy proposed by Endsley and Kaber designates 10 levels of autonomy, ranging from manual control to full automation, based on whether the human or the computer system is responsible for monitoring the current status, generating options for potential actions, selecting an option, and implementing that choice [14]. In robotics, roboticists must determine who within a human-robot team is responsible for these tasks of observing the environment, generating possible actions, selecting a planned action, implementing the action, and detecting system-critical events [17], [18]. The distribution and monitoring of these tasks within the team directly impact mission performance [19], [20] and cause credit or blame to be allocated differently for task outcomes [21]. Thus, roboticists must make decisions regarding which aspects of a task to automate [13], [22] and must create interfaces that aid in these cognitive processes [23], [24], [25]. 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 [13].

When determining the LoA for a system, roboticists must also account for the potential drawbacks of increasing autonomy. Issues with higher autonomy include its perceived lack of reliability, mistrust of autonomous capabilities, complacency due to overtrust, and skill loss in operators [26] [27]. Highly autonomous systems can have negative effects on operators' Situation Awareness [28], which impacts failure and human error rates [29]. This can pose risks in critical tasks that have potential safety concerns [30], [31]. These risks may be particularly salient in challenging and dynamic environments that would necessitate greater sensing capabilities if they are designed to be highly autonomous [32]. However, even with greater capabilities, a high LoA might not be justifiable unless a complex environment is predictable. In unpredictable environments, a robot may need to be supervised or teleoperated [33]. Research has also been conducted on changing the level of autonomy based on the situation by employing adaptive autonomy, in which the system dynamically changes its autonomy, typically by increasing autonomy in response to high cognitive load; performance of autonomy, in which the system uses a lower level of autonomy than necessary in response to low Situation Awareness [7]; and adaptable autonomy, in which a human can dynamically assign the system's level of autonomy [34].

C. Human Factors in Mission-Critical Robotics

Designing semiautonomous systems to be sensitive to their operators' human factors needs and cognitive load is essential for those systems to harmonize with human capabilities [35]. Human factors such as Situation Awareness and trust are crucial for mission success and human safety [28], [35]. A multitude of factors, including level of autonomy, impact trust in human-robot teams [36], [37]. Moreover, both over-trust and under-trust of a system can reduce the effectiveness of human-robot teaming [38].

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 [39], [40]. These frameworks are relevant to semiautonomous robotics across domains such as search and rescue [41], [42], collaborative exploration [43], [23], automated vehicles [44], and the operation of multi-robot systems [45]. However, Situation Awareness has been shown to decrease as the autonomy of the robotic system increases [46]. Furthermore, research has shown that intentionally lowering a system's autonomy can increase situational awareness in space contexts [7] and other situations with high latency [47].

Selecting the appropriate level of autonomy for a robotic system thus presents challenging trade-offs to those working in space robotics. In this work, we aim to better understand how space robotics experts navigate those trade-offs.

III. Methods

We conducted semi-structured ethics-board approved 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 space robotics professionals. Participants were recruited through online professional channels and provided informed consent. Their combined experiences spanned on-orbit robotics, planetary rovers, and human spaceflight missions. Each participant worked at a different aerospace company, ranging from large entities to startups. The interviewees typically had previous experience in engineering but currently held roles in project management or executive leadership. Additionally, one participant worked as a spacecraft operator before moving into leadership roles. The interviewees' professional experience after completing their education ranged from approximately 5 to 25 years. Three of the participants had completed advanced degrees.

Interviews were conducted virtually in November 2023. Each interview lasted between 30 minutes and 1 hour with one interviewer present. During the interview, the participant was 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 high robot autonomy, and how adding autonomous capabilities impacts the risk and cost of a project.

At the beginning of each interview, the participant was provided with the definition of autonomy given in [12] to help ensure the concept of autonomy being discussed was consistent across participants. The following five questions are examples of interview questions asked to all participants, and additional questions were often tailored based on participants' responses to these:

1) Could you describe the main aerospace robotic technologies that [company] develops, what autonomous capabilities they have, and where they use humans to help control or monitor the robot?
2) When developing a new system, what drives how autonomous it will be and in what areas of the system it will have autonomy?
3) What do you see as the main advantages of having more autonomous space robotic systems and the main disadvantages?
4) Is the complex and uncertain nature of space environments something that drives more human involvement in robotic operation or more autonomy?
5) Do you believe that human-in-the-loop control of robotic space systems will remain necessary or useful even if autonomous capabilities are further developed? How might this change in the future?

Audio was recorded during each interview. Each interview recording was then transcribed, anonymized, and analyzed through a thematic analysis [48]. One of the authors of this paper read the entirety of each interview transcript and generated initial codes from the transcripts. The same author then categorized and refined the 30 initial codes into 3 main themes with 17 sub-themes. The themes and sub-themes analyzed in Section IV were chosen due to their prevalence across interviews and relevance to the research question.

Preliminary analysis of our interview data demonstrated that both technical and non-technical factors are important when determining level of autonomy for space robots [49]. However, it is necessary to further explore the human factors that impact level of autonomy decisions and how these considerations may inform roboticists and human factors researchers in this domain. These findings focus on how participants perceived the value of autonomy and human decision-making in space robotics and present design recommendations for determining the appropriate level of autonomy for space robotic systems.

IV. Results

In this section, we present the main findings of our thematic analysis. Our results reveal key insights into how space industry professionals perceive the value of autonomy and human decision-making in space robotics, and the different motives for their decisions about autonomy.

A. Technical factors and human perceptions motivate LoA

We begin by discussing the role of both technical and non-technical factors when determining the level of autonomy for space robotics.

1) Technical factors motivate LoA choices: Often, technical factors, such as latency and computational power, influence the choice of level of autonomy for space robotic missions. Several of the participants who work on on-orbit robotics or deep-space missions described that functionality is performed on the robotic platform with human supervision due to communication latency. P5 described 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.*" Participants emphasized that even for missions with lower latency, such as Earth orbiting satellite servicing, time and safety critical decisions will need to be made autonomously. Participants also highlighted that large fleets of robotic systems will not be feasible for direct human control, as P5 described that unless these systems are automated "*you'd have thousands of people coordinating with each other, which would be ... impossible.*" Additionally, interviewees expressed that the inability to transmit substantial amounts of data to the ground often necessitates robot autonomy, particularly when 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. Participants expressed that the choice to provide more human involvement was often influenced by limited computational resources on space hardware. When discussing on-orbit robotics, P1 described that "*there's not a lot of compute hardware right now that is extremely high performance,*" which limits the ability to run complex autonomous algorithms on satellites. Until space-grade hardware improvements are made that allow for running computationally-intensive algorithms, complex decision-making must be deferred to humans instead.

Furthermore, due to the risk of operating robotics in space, several participants expressed plans to operate new robotic missions with lower levels of autonomy until the robot had been tested sufficiently in the space environment. P3 described that their initial mission for a new type of technology would rely heavily on human control, but that the data from those missions were expected 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.*"

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 amount of autonomy a robot will be provided, participants highlighted that human perceptions frequently drive decisions on level of autonomy. In many cases, participants expressed 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 continue its operations. Some participants expressed a lower level of trust in human operators than in autonomous systems due to their inability to predict how a human may make quick decisions under pressure. P4 said that they did not want human operators "*grabbing the stick and going haywire and burning all of the propellant.*" Similarly, P5 expressed a lack of trust in operators' decision making until they had developed an intuition for the unique dynamics characterizing space teleoperation.

However, participants also noted that the overvaluation of human capabilities and preferences could lead to choices about autonomy that were detrimental to their mission. To increase trust in their system, one company chose to allow humans to abort its operations 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, stating, "*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, space professionals expressed a need to consider both technical and sociotechnical factors when deciding on the level of autonomy for space robots.

B. Perspectives on future LoA of space robotics

1) Participants supported increased autonomy: Across interviews, participants articulated a belief that the level of autonomy used in space robotics would change substantially in the near future. P2 expressed that "*the long-term vision is ... building ever greater autonomy.*" New developments in technology for space computing, as well as considerations of human perception of autonomy, were expected to fuel increasingly higher degrees of autonomy. For example, P2 explained that progress in heterogeneous computing could allow them to "*run our autonomous systems on, where before it might have been infeasible.*" This demonstrates the expected future removal of some of the inhibiting technical factors discussed in Section IV-A.1. Space experts thus overall expect that these developments in space-grade hardware and data availability may ameliorate the current challenges associated with higher levels of autonomy.

A second prediction interviewees made about the future pertained to the types of missions that would become prevalent in the future, and the levels of autonomy needed for those missions. Participants anticipated more missions with extremely high time pressure, high potential for harm, and high degrees of unpredictability[1]. For example, P2 explained that when using electric propulsion, which has very low thrust, an autonomous system is able to "*project out into the future*" and "*make the fine-grain corrections before a human operator can even understand necessarily what's happening.*" Participants also highlighted that large fleets of robotic systems and deep space missions with substantial latency will not be feasible for direct human control. Increasing autonomy can also benefit human operators, as P4 explained that doing so "*takes a lot of that burden off of the operator.*"

[1]Interestingly, these factors are known to shape requirements for robot interaction dynamics [50], [51]

2) Participants valued humans' decisions: Although participants supported increasing autonomy in many systems, they also 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 understanding situations holistically as reasons for their continued 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 predicted that the future role of operators would include defining high-level objectives for the space robot to carry out autonomously, barring unforeseen failures. In such failure cases, participants expressed the need for systems that could alert human operators and allow them to take over. P2 explained that human-in-the-loop control may be needed if unexpected situations arise, describing that "*if it needed to abort for a reason, then a human can get in the loop.*"

Additionally, participants foresaw human oversight remaining prevalent in aerospace. Describing the drawbacks of autonomous systems, P5 stated that the biggest challenge with autonomy is that "*the implications of failures in our industry ... can be very high.*" P1 expressed that this high 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.*" Yet, determining the appropriate level of autonomy in a given scenario is very context-dependent. P4 stated that some of the most important questions they consider when developing a semiautonomous system are understanding the situations in which the human or the system will have more information, and whether human intervention at certain times would cause the system to fail to continue on its own.

C. Business-oriented considerations for LoA

In addition to the technical and sociotechnical considerations described above, participants' comments also signaled the significant extent to which economic and attitudinal factors served as key motivators.

1) Financial perspectives determine when autonomy is worthwhile: Despite trends towards autonomy in space robotics, participants demonstrated an aversion to autonomy when its adoption would lead to increased mission costs. For example, some participants argued that developing autonomous capabilities for a one-off technology would not be "worth the cost", and that autonomy development was only worthwhile if the autonomous capability would be used across missions or at a large scale. P5 articulated this as, "*the problem with autonomy is you're spending $100 to save a nickel.*" P5 asserted that more autonomy for very high-cost missions increased the possibility of exceeding the projected cost and time of development to such an extent that there was pressure to "*minimize autonomy to what is strictly necessary.*" Participants also explicitly weighed the cost of autonomy relative to the cost of hiring human operators. P5, for example, argued that "*there will always be a role for* *humans because humans are the cheapest computers that we have*" – a sentiment that (de)values human workers only to the extent that they can provide cheap and efficient labor. On the other hand, P5 highlighted that the value of autonomy came from more than just its potential cost-effectiveness, arguing that developing autonomy "*is more cost typically than it saves, but you sometimes have to do it.*"

Other participants signaled similar values, while interpreting the financial tradeoffs differently. Several participants thought that increasing autonomy adds to short-term costs but reduces cost in the long-term. For satellite servicing robotics, P1 expressed that "*building that autonomy in (the system) now is gonna pay off heavily in spades later.*" Some participants also were motivated in terms of *time costs*, viewing autonomy as decreasing the risk of the program timeline since it could reduce development time for later missions. P4 stated that for satellite technology, "*it is a huge benefit in the risk and cost because now we have the technology to cut down all the time that we were spending manually trying to figure it out.*" Similarly, P1 emphasized the *cost of human labor*, expressing that "*without extensive training, humans don't provide necessarily that much advantage and provide a huge cost.*" P1 also described how increasing human involvement leads to higher overhead cost as it requires a trained staff that are infrequently used. They explained that involving humans for operations or monitoring of robotic capabilities requires "*hiring and training dedicated staff for something that's fairly rare.*"

Overall, participants tended to agree that autonomy made sense fiscally on projects with more risk tolerance, large-scale systems, and tasks that necessitate autonomy. And, in doing so, participants demonstrated the extent to which economics motivated their decisions surrounding autonomy.

2) Space industry professionals may resist change: Participants stressed the importance of evaluating how autonomy may be impacted by viewpoints held by the developers or operators. Many participants highlighted that space professionals' perception of autonomy would "need to shift" if robot autonomy were to increase. Participants expressed that professionals in the aerospace industry are accustomed to more human involvement in space systems and often distrust increasing the autonomy of a new system. P1 articulated, "*they're used to humans in the loop. They wanna see humans in the loop ... they're gonna wanna feel like they can take that control back, even though from a safety perspective, it doesn't really offer anything.*"

Participants asserted that attitudes on human involvement would "have to" change as autonomy becomes more prevalent in space technology. P3 described that one of the greatest challenges in increasing autonomy is convincing others that it is advantageous, stating "*technology will not be necessarily (an) impediment but having humans considering that as an opportunity (is an impediment).*" Similarly, P1 expressed a need to prioritize increasing trust to overcome the hesitancy of using autonomy, explaining: "*it's a perception problem, not a technology one, and that will have to be proven by proving that technology side out.*" However, participants also indicated the importance of being aware that operators are likely to place too much trust in a system; for example, P4 believed that many individuals in the space community have "*a false sense of security*" surrounding autonomy.

V. Overarching Takeaways

In this section, we use our interview findings to formulate high-level takeaways and guidelines for selecting the level of autonomy for space robotic systems.

A. Account for Technical Restrictions on LoA

The deployment of robotic systems in space introduces unique technical concerns that must first be taken into consideration when determining the appropriate LoA for a system. Primary to these decisions are the expected communication delay between the system and humans, computational hardware limitations, and the ability to transmit data to the ground. Additionally, the feasibility of human control is influenced by the number of systems being operated – especially if swarms or constellations of spacecraft are used – and the speed with which decisions must be made. These technical aspects of a space robotic mission place restrictions on the degree of autonomy that is possible (e.g., high latency making quick human intervention infeasible), and as such, these factors are vital in deciding on an appropriate LoA.

B. Allow Humans to Remain As Supervisors

Our results demonstrate the importance of allowing humans to remain as supervisors during the use of semi-autonomous space robotic systems, even as autonomous capabilities in space increase. Roboticists should prioritize designing systems in which human operators monitor robotic technology, as this can leverage human capabilities to enable better decision validation. However, this choice must be made carefully as research has shown that monitors of autonomous systems have a decreased Situation Awareness compared to those manually operating the system [26], [52]. Despite this, semiautonomous systems designed with this consideration in mind may be able to maintain operators' awareness by allowing them to focus on crucial information or delegating to them some control over the system [53].

Furthermore, due to hesitancy surrounding the adoption of novel technology, especially in a domain as high-risk as space, it is important to design systems with humans as supervisors in order to help bridge the gap between full human control and full autonomy while enabling better calibrated human-robot trust. However, the ability for human operators to intervene once in-the-loop should be made carefully as direct human intervention can pose a higher risk to system performance than autonomous operations. As such, engineers should look for opportunities to bring humans into the loop to vet autonomous decisions while limiting direct human intervention to situations where it is necessary.

C. Validate Human Decisions

On the other hand, due to the high risk and high time pressure that can arise in the space domain, human factors engineers should recognize that human operators are not guaranteed to make better decisions than autonomous systems. They should be particularly cognizant of this in situations where the human is put under significant stress, has limited time to make a decision, or is less aware of the current situation than the autonomous system. In these scenarios, designers should look for opportunities to bring autonomous systems onto the human loop as decision support systems. By allowing humans to monitor autonomous systems and vice versa, the unique advantages of both human and autonomous decision making can be leveraged, as neither will perform optimally in all situations.

D. Design Explainable Systems to Support Trust

Human factors engineers should be aware that human operators may develop miscalibrated trust in space robots, either by placing too much trust in a semiautonomous system or by dangerously attempting to take control back from a system that is capable of accomplishing its task. The issues that arise from miscalibrated trust have previously been explored in the literature [38]. Due to the unfamiliarity for many space system operators of monitoring rather than controlling systems, designers of space robotic systems should strive for transparency and explainability in the design of semiautonomous systems.

E. Use Cost to Inform LoA Decisions

Finally, however, designers must remain cognizant that despite the reported benefits of allowing humans to remain on the robotic loop when possible, allowing autonomous decision support systems to remain on the human loop when possible, and designing systems to be explainable to better calibrate trust, the final selection of candidate designs may ultimately be made on the basis of cost.

Level of autonomy decisions come with complex economic trade-offs – and those working in space robotics elevate these trade-offs in their decision-making. Thus, designers must be aware of the ways that higher levels of autonomy may save cost in the long-term, depending on scale and context – but also the ways that cost saving may be used to wield autonomy in order to cut costs of hiring and training human workers – and how these economic factors will ultimately weigh on managers' decisions in adopting or arbitrating between candidate designs.

VI. Conclusion

The space robotics professionals interviewed in this work demonstrate the need for systems that allow human monitoring of space robotic technology and take into consideration the unique aspects of space contexts, including latency, high time pressure situations, and non-intuitive environments. This paper demonstrates that researchers in space robotics contexts must consider technical factors specific to the robotic system's deployment, prioritize humans' adjustment to novel technologies, and use cost to inform decisions on the level of autonomy for a system in space.

Overall, our interviews showcased the importance of considering socio-technical factors such as cost, risk-to-mission, and human factors. These considerations should take precedence even when human involvement is unnecessary or poses additional risk to the mission. While beliefs about the impact of autonomy on cost were varied, this study clearly demonstrated that it was a key factor in guiding space industry professionals' autonomy choices.

Building on these interviews, we see several key directions for future work. First, although our participants possessed a wide variety of experience in different types of space robotics missions, the majority of interviewees were engineers and managers in charge of making decisions about the robotic systems. Future work should consider a wider variety of stakeholders' perspectives, especially from operators of these technologies. Second, while this work explored the high-level considerations important across space robotics in selecting level of autonomy, future work should also consider the trade-offs associated with levels of autonomy for specific mission profiles. Finally, researchers should explore how the proposed design recommendations can be practically implemented into space robotic systems, and be used to inform user interfaces designed to support human operators, especially as the level of autonomy used for space robotic missions changes due to new technology developments.

Acknowledgment

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

References

[1] I. A. Nesnas, L. M. Fesq, and R. A. Volpe, "Autonomy for space robots: Past, present, and future," *Current Robotics Reports*, 2021.
[2] Y. Gao and S. Chien, "Review on space robotics: Toward top-level science through space exploration," *Science Robotics*, 2017.
[3] M. G. Bualat, T. Smith, E. E. Smith, T. Fong, and D. Wheeler, "Astrobee: A new tool for ISS operations," in *SpaceOps Conf.*, 2018.
[4] V. Verma, M. W. Maimone, D. M. Gaines, R. Francis, T. A. Estlin, S. R. Kuhn, G. R. Rabideau, S. A. Chien, M. M. McHenry, E. J. Graser, A. L. Rankin, and E. R. Thiel, "Autonomous robotics is driving perseverance rover's progress on mars," *Science Robotics*, 2023.
[5] National Aeronautics and Space Administration Goddard Space Flight Center, *On-Orbit Satellite Servicing Study*, 2010.
[6] D. B. Kaber and M. R. Endsley, "The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task," *Theoretical Issues in Ergonomics Science*, 2004.
[7] S. Roy, T. Smith, B. Coltin, and T. Williams, "I need your help... or do i?: Maintaining situation awareness through performative autonomy," in *Proc. of the 2023 ACM/IEEE Int'l Conf. on Human-Robot Interaction*, 2023.
[8] S. Nahavandi, "Trusted autonomy between humans and robots: Toward human-on-the-loop in robotics and autonomous systems," *IEEE Systems, Man, and Cybernetics Magazine*, 2017.
[9] K. Petersen and O. von Stryk, "Towards a general communication concept for human supervision of autonomous robot teams," in *Int'l Conf. on Advances in Computer-Human Interaction*, 2011.
[10] M. B. Luebbers, C. T. Chang, A. Tabrez, J. Dixon, and B. Hayes, "Emerging autonomy solutions for human and robotic deep space exploration," *Proc. of Space CHI: Human-Computer Interaction for Space Exploration (SpaceCHI)*, 2021.
[11] B. Ma, Z. Jiang, Y. Liu, and Z. Xie, "Advances in space robots for on-orbit servicing: A comprehensive review," *Advanced Intelligent Systems*, 2023.
[12] T. W. Fong, J. D. Frank, J. M. Badger, I. A. Nesnas, and M. S. Feary, "Autonomous systems taxonomy," NASA Ames Research Center, Tech. Rep., 2018.

[13] J. M. Beer, A. D. Fisk, and W. A. Rogers, "Toward a framework for levels of robot autonomy in human-robot interaction," *Journal of Human-Robot Interaction*, 2014.

[14] M. R. Endsley and D. B. Kaber, "Level of automation effects on performance, situation awareness and workload in a dynamic control task," *Ergonomics*, vol. 42, no. 3, pp. 462–492, 1999.

[15] C. D. Johnson, M. E. Miller, C. F. Rusnock, and D. R. Jacques, "A framework for understanding automation in terms of levels of human control abstraction," in *2017 IEEE Int'l Conf. on Systems, Man, and Cybernetics (SMC)*, 2017.

[16] S. Kim, J. R. Anthis, and S. Sebo, "A taxonomy of robot autonomy for human-robot interaction," in *Proc. of the 2024 ACM/IEEE Int'l Conf. on Human-Robot Interaction*, 2024, pp. 381–393.

[17] D. B. Kaber and M. R. Endsley, "Out-of-the-loop performance problems and the use of intermediate levels of automation for improved control system functioning and safety," *Process Safety Progress*, 1997.

[18] C. Kardos, Z. Kemény, A. Kovács, B. Pataki, and J. Váncza, "Context-Dependent Multimodal Communication in Human-Robot Collaboration," *CIRP Conf. on Manufacturing Systems*, 2018.

[19] A. Khasawneh, H. Rogers, J. Bertrand, K. C. Madathil, and A. Gramopadhye, "Human adaptation to latency in teleoperated multi-robot human-agent search and rescue teams," *Automation in Construction*, 2019.

[20] L. Feng, C. Wiltsche, L. Humphrey, and U. Topcu, "Synthesis of Human-in-the-Loop Control Protocols for Autonomous Systems," *IEEE Transactions on Automation Science and Engineering*, 2016.

[21] T. Kim and P. Hinds, "Who should I blame? Effects of autonomy and transparency on attributions in human-robot interaction," in *IEEE Int'l Symp. on Robot and Human Interactive Communication*, 2006.

[22] V. Govindarajan, S. Bhattacharya, and V. Kumar, "Human-robot collaborative topological exploration for search and rescue applications," *Springer Tracts in Advanced Robotics*, 2016.

[23] C. Reardon, K. Lee, and J. Fink, "Come see this! Augmented reality to enable human-robot cooperative search," *IEEE Int'l Symp. on Safety, Security, and Rescue Robotics*, 2018.

[24] A. Bock, A. Kleiner, J. Lundberg, and T. Ropinski, "Supporting urban search and rescue mission planning through visualization-based analysis," *Int'l Workshop on Vision, Modeling and Visualization*, 2014.

[25] V. Domova, E. Gärtner, F. Präntare, M. Pallin, J. Källström, and N. Korzhitskii, "Improving Usability of Search and Rescue Decision Support Systems: WARA-PS Case Study," *IEEE Symp. on Emerging Technologies and Factory Automation*, 2020.

[26] L. Bainbridge, "Ironies of automation," *Automatica*, 1983.

[27] C. D. Wickens, S. E. Gordon, and Y. Liu, *An introduction to human factors engineering*, 1998.

[28] M. R. Endsley, "Situation awareness in future autonomous vehicles: Beware of the unexpected," in *Congress of the Int'l Ergonomics Association*, 2018.

[29] J. Carlson, R. R. Murphy, and A. Nelson, "Follow-up analysis of mobile robot failures," in *Proc. of the IEEE Int'l Conf. on Robotics and Automation*, 2004.

[30] R. Parasuraman, T. B. Sheridan, and C. D. Wickens, "A model for types and levels of human interaction with automation," *IEEE Trans. on systems, man, and cybernetics*, 2000.

[31] R. Parasuraman and C. D. Wickens, "Humans: Still vital after all these years of automation," *Human Factors*, 2008.

[32] S. Thrun, "Toward a framework for human-robot interaction," *Human-Computer Interaction*, 2004.

[33] M. Desai, K. Stubbs, A. Steinfeld, and H. Yanco, "Creating trustworthy robots: Lessons and inspirations from automated systems," in *Proc. of AISB Convention: New Frontiers in Human-Robot Interaction*, 2009.

[34] G. Calhoun, "Adaptable (not adaptive) automation: Forefront of human–automation teaming," *Human Factors*, 2022.

[35] M. R. Endsley, "Toward a theory of situation awareness in dynamic systems," *Human Factors*, 1995.

[36] Z. R. Khavas, R. Ahmadzadeh, and P. Robinette, "Modeling trust in human-robot interaction: A survey," *Int'l Conf. on Soc. Robotics*, 2020.

[37] C. Furlough, T. Stokes, and D. J. Gillan, "Attributing blame to robots: I. the influence of robot autonomy," *Human Factors*, 2021.

[38] J. M. Bradshaw, R. R. Hoffman, D. D. Woods, and M. Johnson, "The seven deadly myths of "autonomous systems"," *IEEE Intelligent Systems*, 2013.

[39] M. R. Endsley, "Measurement of situation awareness in dynamic systems," *Human Factors*, 1995.

[40] J. Y. C. Chen, K. Procci, M. Boyce, J. Wright, A. Garcia, and M. J. Barnes, "Situation Awareness-Based Agent Transparency," *US Army Research Laboratory*, 2014.

[41] Y. Gatsoulis, G. S. Virk, and A. A. Dehghani-Sanij, "On the Measurement of Situation Awareness for Effective Human-Robot Interaction in Teleoperated Systems," *Journal of Cognitive Engineering and Decision Making*, 2010.

[42] T. Mott and T. Williams, "How can dog handlers help us understand the future of wilderness search & rescue robots?" in *IEEE Int'l Symp. on Robot and Human Interactive Communication (RO-MAN)*, 2023.

[43] S. Lukosch, H. Lukosch, D. Datcu, and M. Cidota, "Providing information on the spot: Using augmented reality for situational awareness in the security domain," *Computer Supported Cooperative Work*, 2015.

[44] B. J. Park, C. Yoon, J. W. Lee, and K. H. Kim, "Augmented reality based on driving situation awareness in vehicle," *Int'l Conf. on Advanced Communication Technology*, 2015.

[45] J. J. Roldán, E. Peña-Tapia, A. Martín-Barrio, M. A. Olivares-Méndez, J. del Cerro, and A. Barrientos, "Multi-robot interfaces and operator situational awareness: Study of the impact of immersion and prediction," *Sensors*, 2017.

[46] L. Onnasch, C. D. Wickens, H. Li, and D. Manzey, "Human performance consequences of stages and levels of automation: An integrated meta-analysis," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 2014.

[47] R. S. Silva, M. Lieng, E. Muly, and T. Williams, "Worth the wait: Understanding how the benefits of performative autonomy depend on communication latency," in *IEEE Int'l Conf. on Robot and Human Interactive Communication*, 2023.

[48] V. Braun and V. Clarke, *Thematic analysis.* American Psychological Association, 2012.

[49] C. Smith, T. Mott, and T. Williams, "Perspectives on level of autonomy decisions in space robotics," in *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*, 2024.

[50] C. Smith, C. Gorgemans, R. Wen, S. Elbeleidy, S. Roy, and T. Williams, "Leveraging intentional factors and task context to predict linguistic norm adherence," in *Proc. CogSci*, 2022.

[51] J. Lockshin and T. Williams, "'We need to start thinking ahead': The impact of social context on linguistic norm adherence," in *Proc. CogSci*, 2020.

[52] C. E. Billings, "Human-centered aircraft automation: A concept and guidelines," *NASA Technical Memorandum 103885*, 1991.

[53] M. R. Endsley and E. O. Kiris, "The out-of-the-loop performance problem and level of control in automation," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 1995.