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Deriving Human-Centered Engineering Design Requirements for Exploration Extravehicular Activity Work Aids through Narrative-Rich Use Case Scenarios

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Abstract
Upcoming exploration extravehicular activity (EVA) will require crew to perform field geology to accomplish mission science goals. To support crew during science operations, technological work aids are being developed. However, deploying novel technologies inherently changes the characteristics of a work domain, which may introduce undesired work demands on operators. In this study, terrestrial field geologists were interviewed to derive human-centered engineering design requirements that help guide ongoing system development efforts to mitigate the human spaceflight risks of adverse mission outcomes due to Earth-independent human-systems operations and risk of injury and compromised performance during EVA operations. Engineering design requirements were synthesized from geologist feedback on narrative-rich use cases. These cases presented contextual scenarios of proposed exploration EVA work aids and function allocations between human and robotic agents to elicit decision-making influences. Engineering design requirements synthesized from this study can be adopted to improve human health and performance for planetary science operations.

Keywords
cognition, space systems, user-centered design, decision (aids, making, support, principles), automation

Introduction

Future Lunar and Martian exploration extravehicular activity (EVA) will require crew to perform field geology to accomplish overarching mission science goals (Banfield et al., 2020; Coan, 2020). However, planetary field geology will be constrained by the EVA environment and may conflict with how field geology has evolved to be executed on Earth (Hodges & Schmitt, 2011). Work aids are currently being developed to support future planetary EVA operations as crews will need increased independence from ground support teams due to communication delays. However, it is unclear how well these tools align with the underlying geological work crew will be conducting. In this study, terrestrial field geologists were interviewed to derive human-centered engineering design requirements that help guide ongoing system development efforts in order to mitigate the human spaceflight risks of (1) adverse mission outcomes due to Earth independent human-systems operations and (2) risk of injury and compromised performance during exploration EVA operations. Novel engineering design requirements were synthesized from geologist feedback on narrative-rich use cases. These cases presented different contextual scenarios of proposed technological work aids and function allocations between human and robotic agents within the exploration EVA environment to elicit different decision-making influences.

Background

Future missions beyond low-Earth orbit will require crews to operate more autonomously than any prior human spaceflight missions due to ground support teams being constrained by communication delay (Buckland et al., 2022). The development of systems and supporting technology required to enable mission success under increased crew autonomy has been identified as being one of the most severe human spaceflight risks for future Lunar surface and Martian

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missions (Antonsen et al., 2023). However, crew capabilities to independently make operational decisions during geological operations do not align with our current technological capabilities to support autonomous operations within the constraints of the EVA environment. Unlike technological capabilities, crew's capabilities to make independent operational decisions during exploration activities has increased through the emphasis placed on flexibility in modern geological training. While the ISS is a human-made structure, natural surfaces contain environmental information (scientific and terrain) that can only be obtained once on site. Having the capability to respond to unanticipated findings with on-the-fly replanning is essential for the execution of terrestrial field geology that returns maximum scientific yield (Hurtado et al., 2013). Thus, the United States Geological Survey training program and the European Space Agency's Planetary ANalogue Geological and Astrobiological Exercise for Astronauts (PANGAEA) training program have placed an increased emphasis on training crew to be flexible to strengthen their independent geologic capabilities (Graff et al., 2020; Sauro et al., 2023).

Deploying novel technologies inherently changes the characteristics of a work domain, which may introduce undesired work demands on operators, or lead to a difference between the envisioned and final work domain (Miller & Feigh, 2019). However, the human spaceflight risk of injury and compromised performance due to EVA operations is also a high risk for both Lunar and Martian surface missions (Dunn et al., 2022). During future exploration EVAs, the risk of adverse mission outcomes due to Earth independent human-systems operations and the risk of injury and compromised performance during EVA operations will intersect to influence crew health and performance during science operations. EVA support technologies that address the risk of adverse mission outcomes due to Earth independent human-systems operations, if not carefully designed, may inadvertently increase the risk of injury or compromised performance.

To inform the creation of supporting technologies, previous work has characterized the EVA work domain using cognitive work analysis (Miller et al., 2017). Work domain characterization allows for system development to follow a "work-driven pathway," leading to the benefits of identifying deficiencies in existing technologies and more readily identifying potential desirable technological enhancements to reach the envisioned work domain (Miller & Feigh, 2019). However, science-driven tasks are not captured in recent EVA work domain analyses because ISS EVAs do not pursue exploration objectives (Miller et al., 2017). While prior work on characterizing the EVA work domain will be pertinent to informing the design of systems for exploration EVAs, an opportunity exists to expand prior analyses by identifying how systems can be aligned to the geological work that will be introduced into the EVA work domain on planetary surfaces.

Methods

Semi-structured interviews were conducted with field geology experts (n = 8) who specialize in domains that align with NASA's Artemis and Martian science goals (e.g., Sedimentology, Volcanology, Geologic Mapping, etc. (Banfield et al., 2020; Weber et al., 2021)). Terrestrial field geologist experts were chosen for this study because they were the best available analog operators identified to provide insight into planetary science operations. Experts were defined as geologists that hold a Ph.D. in a geological science discipline or have at least four years of applicable work experience (experience ranged from 5 to 29 years, $\bar{x} = 17.50$, $s = 7.76$). All experts interviewed additionally had experience supporting simulated Lunar or Martian analog missions.

Exploration EVAs are still an envisioned work domain, meaning that the type of work that this study is interested in currently does not exist. To overcome this challenge, narrative-rich use cases were leveraged to provide contextual scenarios for the envisioned planetary work domain. Before being presented with use cases, the known constraints of the EVA work domain were reviewed with the geologists. After reading a description of the EVA work domain constraints, geologists were prompted to verbalize ways in which their work may be made more difficult by the introduction of these new constraints. This exercise enabled geologists to better translate their work into a planetary context.

Each narrative-rich use case (Figure 1) was written in first-person from the perspective of a geologist-astronaut and were based on purposed technological work aids to support geologic operations during an EVA. The first two use case narratives were based on technologies from literature, and the last two use case narratives were created by the study team. Use case scenarios included (1) a teleoperated rover inspired by Panzirsch et al. (2022), (2) a "field book" type communication aid that is shared between an extravehicular (EV) and an intravehicular (IV) agent, with the goal of increasing team situational awareness around science operations, inspired by Pritchard et al. (2019), (3) a sample return drone inspired by the rise of drone technology in terrestrial field geology (Bateman et al., 2022), and (4) a pre-excursion and human exploration robotic assistant inspired by Hodges and Schmitt's original vision of advanced planetary field geology (Hodges & Schmitt, 2011). Geologists were prompted to provide their thoughts on the technologies and function allocations between human and robotic agents presented in a use case after they finished reading the contextual scenarios. During the discussion, questions specific to the use case content were asked to elicit different decision-making influences relevant to the proposed technology.

A thematic analysis was conducted on interview transcripts, and a grounded theory and constant comparative approach were used for data analysis (Charmaz, 2008; Glaser, 1965). Data collection ceased when no new themes from interviews were being identified. All interview

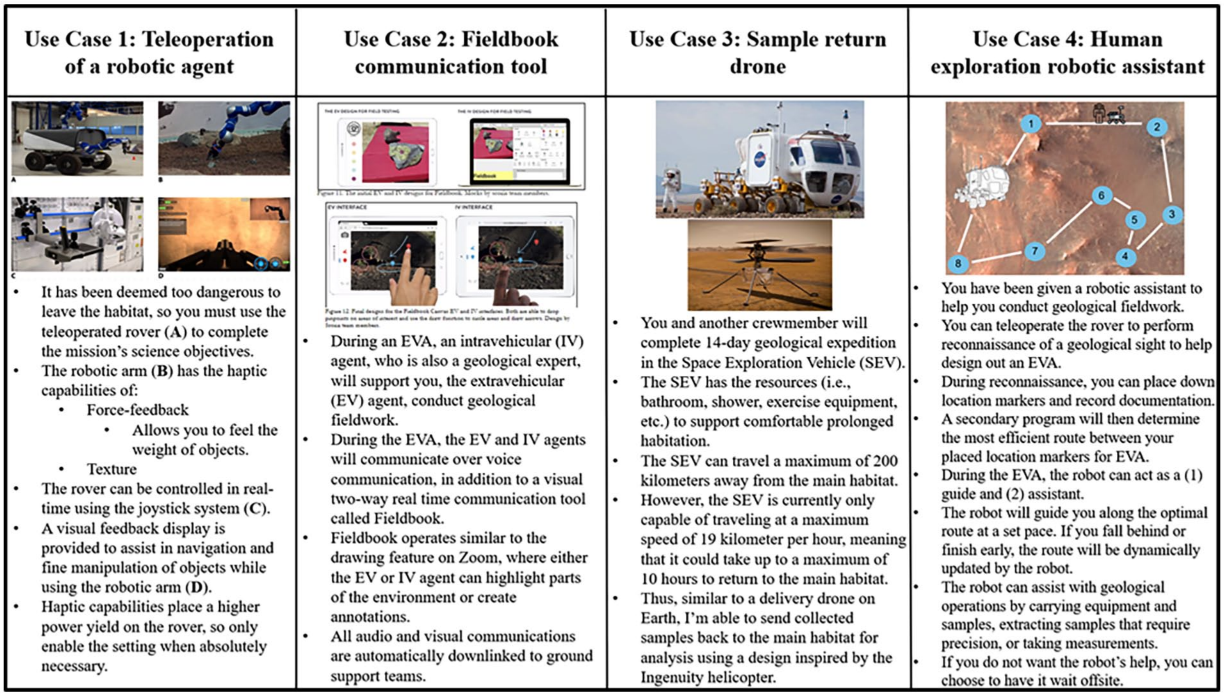

Figure 1. Use case scenario reference images and key points. Use Case 1 was sourced from Panzirsch et al. (2022), Use Case 2 was sourced from Pritchard et al. (2019), and reference images for Use Case 3 and 4 were sourced from images.nasa.gov.

transcripts were used to develop the emergent themes that informed engineering design requirement creation. To derive engineering design requirements, the methods of Miller et al. (2023) created for the Joint Augmented Reality Visual Informatics System concept of operations were used. Response themes for each use case were organized into "I want. . ." statements. The "I want. . ." statements were then expanded into proposed engineering design requirements to capture user needs.

Results and Discussion

Use Case 1: Teleoperation of Robotic Agent

Geologists overall responded positively towards the inclusion of force-feedback capabilities, as it has the potential to improve observational capabilities and decision-making for collecting samples. As one geologist said about the inclusion of force-feedback, "*If I pick up a rock and it is heavier than I'm expecting, I'm going to be like, what are you doing? Or if it's lighter, the same response. So, I think there's things that you can't get visually by hefting a rock.*"

However, geologists were more concerned with the rover's potential visual capabilities and the ability to rove. For visual capabilities, there were concerns about the use case narrative missing a description of the rover's ability to zoom in on fine details with its camera, as this capability is often necessary for obtaining information to inform observations related to the microstructure of rocks. Some geologists also indicated they would want a subsystem added to the rover that could obtain compositional information outside of the visible light spectrum, such as the Alpha Particle X-ray Spectrometer system used on previous Martian rovers. Compositional information can inform geological decision-making by improving the geologist's geochemical understanding of the environment. Feedback on the ability to rove primarily revolved around the rover's technical capabilities to traverse slopes and the rover's movement speed. Rover speed was a major concern given the infamously slow pace of Martian rovers. As one geologist who has worked on multiple Martian rover science teams said when reflecting on exploration pace, "*We just spent three months on this outcrop, had we had a human there we could have done this in like an afternoon*."

Use Case 2: Fieldbook

Responses around the "field book" communication aid were largely positive as the geologists believed that the technology would promote collaboration and could lower the cognitive workload of the EV agent. Geologists identified potential collaboration enhancements through this technology such as receiving assistance on operational decision making and geologic interpretations through the IV agent, and the standardization of mental models between extravehicular EV and IV agents. An example of standardizing mental models one geologist gave is, "*Oh, when [geologist's last name] says something that looks like whatever is medium green and angular, that's what he's talking about. In my mind, I was thinking something that was a little more green, less angular. So, it allows you to converge on a lexicon pretty quickly*." Geologists were enthusiastic about the function allocation presented in the use case potentially lowering the EV agent's cognitive workload. As one geologist stated, "*So, I think that this allows the crew to focus on what is mission relevant, and by having somebody be in the [habitat] versus being out in the field, allows that mental load we were talking about earlier, somebody is not dealing with that. So [the EV agent] can be more aware of focusing on geology*."

However, geologists were concerned about the potential failure modes of the technology, such as latency issues or poor image resolution in the camera-feed. Communication is critical to EVA operations, so if supporting technologies around communication fail, there may be drastic impacts on EVA operations and crew safety.

Use Case 3: Sample Return Drone

The sample return drone was the most polarizing use case as geologists liked the presence of a drone but did not like how it was being utilized within the use case. Responses to this use case revealed alternate function allocations for drones or other robotic agents that may assist crew during EVA operations, such as for sampling in inaccessible areas or for extending visual capabilities. One geologist detailed how, "*we've been building drones that can then land and retrieve sample tubes, or rocks that they can scoop, or claw, or dig, or even drill and return those materials. So essentially [the drone is] a very disciplined team member*." In the terrestrial context, the most common use of drones is to extend visual capabilities, offering a layer of observation between orbital imagery and the boots-on-the-ground perspective. This additional in-between visual perspective can be used to inform geologist's working hypotheses and inform operational decision-making related to traverse replanning.

Use Case 4: Human Exploration Robotic Assistant

The human exploration robotic assistant overall received the most positive feedback out of all the use cases. The features that received the most praise were the pre-excursion exploration capabilities, and storage space for equipment and samples. For pre-excursion exploration, one geologist described that "*It would help me prioritize my time in the field. . . if I start with 20 [points-of-interest] and I can take the robot out and eliminate 5 of those, then I just don't have to waste my time*." Initial robotic reconnaissance of sites has the potential to reduce the amount of replanning needed during the EVA, as the geologist would have an increased initial understanding of the environment. One geologist further compared this to terrestrial practices, "*I mean, that's what you do as a field geologist, the first time at a place, you just sort of meander around and check everything out. . . so having that recon component of exploring ahead of time, I think makes your EVA so much more efficient.*" For storage of equipment and samples, having a robot perform this task would reduce an EV agent's physical workload and eliminate the need to push a tool cart between stations. This function allocation could have major performance benefits as pushing tool carts has been observed to be the most metabolically demanding task during simulated planetary analog EVAs (Coan & Miller, 2023). Allocating this task to a robotic agent would likely reduce crewmember fatigue, potentially improving decision-making capabilities later in an EVA.

Geologists did raise concerns about potential inefficient function allocations between human and robotic agents. As one geologist described about function allocations, "*It kind of comes down to efficiency. If the robot is doing something for me and it's monotonous, that's great. If I have to wait for the robot to be done before I can do my work and the robot's taking a lot of time, I would be unhappy*." One function allocation that geologists were concerned over was the robotic agent controlling path replanning. As one geologist described about that function allocation, "*The part that I'm slightly concerned about maybe is the human not necessarily having all of the control over that decision making, or feeling like you have to do this thing, and so it maybe takes away a little bit of the way we do geologic exploration of responding to things that maybe the robot didn't see*."

Engineering Design Requirements

Preliminary engineering design requirements were derived from feedback themes and highlight the mapping from "I want. . ." statements to their corresponding engineering design requirements (Table 1). Table 1 provides an example of an engineering design requirement created from each use case scenario. While highlighted examples do not explicitly assert injury risk, they implicitly create opportunities for reducing risk. For example, in use case three, introducing strong visual imagery capabilities on a drone can enable crew to safely access information-rich areas that may be too dangerous for human exploration or inform traverse replanning efforts.

Future Work and Limitations

Future work should use geologist feedback collected from this study to further enhance use case narratives to enrich the contextual scenarios. Doing so will increase the ecological validity of the contextual scenarios enabling continued identification

Table 1. Example Engineering Design Requirements.

Use case	Geologist insight ("I want. . .")	Proposed engineering design requirement(s)
Case 1: Teleoperation	I want to avoid damaging the rover from striking an obstacle.	The rover shall assist the operator with emergency braking when a possible obstacle collision is detected.
Case 2: Fieldbook	I want to be able to access prior documentation of the geological site I am at if it exists.	Fieldbook shall be capable of displaying past documentation to the extravehicular agent based on their proximity to previously documented geological sites.
Case 3: Sample return drone	I want to use the drone in order to view the environment from a different perspective.	The drone shall be capable of transmitting real time visual feed data from its camera system to a display accessible by the extravehicular agent.
Case 4: Human exploration robotic assistant	I want the robot to help carry equipment and samples.	The robot's sample storage volume shall be greater than or equal to twice the volume of the Sample Collection Bag (SCB) created for the Artemis missions.
		The robot's tool storage volume shall be greater than or equal to the volume of the tool carrier created for the Artemis missions.

of engineering design requirements. Additionally, there is an opportunity for these design requirements to be further assessed in the context of current geological training efforts to determine alignment with current practices and identification of gaps that did not emerge from the interviews.

One limitation of this study was the sample size. However, we selected participants with research interests that intersect applications in both planetary geology and field geology, increasing the relevance of the findings. Yet due to the sample size, frequency of themes was not analyzed. Requirement derivation from emerging themes is ongoing and future work will validate requirements with follow-up interviews with subject matter experts. Additionally, there are limitations to geologists' perspectives on work in planetary environments as they are not EVA specialists. This limitation will be mitigated by continuing to build on these use cases with EVA experts to capture complementary perspectives.

Conclusion

This study used narrative-rich use cases to inform human-centered engineering design requirements for technological aids that can help mitigate the (1) risk of adverse mission outcomes due to Earth independent human-systems operations and (2) the risk of injury and compromised performance during EVAs. Across all use cases, geologists were primarily interested in leveraging technology in a way that extends human capabilities during EVA. The strength of a geologist compared to a robotic agent is the geologist's decision-making capabilities. This decision-making is informed by environmental information that will be more challenging to obtain during planetary EVAs compared to terrestrial fieldwork. The majority of the environmental information pertinent for decision-making is observational; thus, technologies such as robotic agents that extended visual capabilities to areas humans cannot safely access, have the opportunity to improve human health and performance. Additionally, function allocations between human-human and human-robot teams that improve overall EVA efficiency are also likely to be successful as they can enable EV agents to spend more time exploring the environment and to direct more of their limited cognitive resources to their science. By integrating the human-centered engineering design requirements synthesized from this study, support systems can be better aligned to the underlying constraints and goals of the exploration EVA work domain, leading to human health and performance benefits.

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