National Aeronautics and Space Administration

CTSD-ADV-1788
Rev A
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Joint Augmented Reality Visual Informatics System

Concept of Operations

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REVISION HISTORY PAGE

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A		Major re-write of Baseline Con-Ops document	2023-11-14
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Contents

List of Figures

List of Tables

1 Introduction

The National Aeronautics and Space Administration (NASA) is embarking on a 21st century space exploration initiative via the Moon to Mars and Artemis programs.[1] These programs aim to establish a sustained lunar presence and explore the moon's surface using innovative technologies. One primary goal of these initiatives is to enable crew autonomy. The existing human spaceflight work domain must undergo a substantial transformation to redistribute and create work capabilities among future flight teams, which includes both crew and Earth based mission support personnel. For example, crew will be given greater access to a variety of information to make locally informed decisions. The broader flight team will need to simultaneously interact with this data and provide new means of support throughout the mission as crew take on more responsibility and authority. Achieving increased crew autonomy will require new technologies and operational concepts to facilitate information exchange among the flight team and crew in future planetary exploration work demands.

To meet these demands, NASA proposed requirements for a digital display for an EVA spacesuit to provide relevant information to the crew member. The Joint Augmented Reality Visual Informatics System (Joint AR) project pursued four years of research and development towards a suit-display system in a near-eye, AR form factor. The project was responsible for developing software (custom graphics engine and core flight software), physical hardware prototyping (controls, projection display optics, suited display platform), virtual prototyping platform (a virtual reality testbed), and human-in-the-loop (HITL) operational testing informed by EVA flight controllers, crew members, and human factors engineers for con-ops definition.

This document contains substantial updates to CTSD-ADV-1788 Rev. Basic. This revision was produced by the project to summarize the use-cases and and user experiences developed throughout the project, and refine the Basic revision originally drafted at the beginning of the project life cycle.

1.1 Purpose

The primary purpose of this document is to summarize and make available the scenario development efforts that have been pursued and explored within the Joint AR project. This includes descriptions of the scenarios themselves as well as corresponding potential of advanced informatics displays to support those specified scenarios. In doing so, this document provides a variety of approaches to deconstruct and hypothesize how future technological capabilities so that with future EVA work demands can be satisfied within future human planetary spaceflight missions.

1.2 Scope

The scope of this document is intended to support two audiences: 1) on-going NASA and vendor efforts to enable advanced informatics for EVA operations and 2) researchers and technology developers in the broader academic and commercial sector. This document extends the spacesuit informatics concepts found within published NASA documentation by exploring a variety of possible envisioned futures to help imagine and describe what future EVA operations could look like with crew having decision support capabilities via an advanced informatics display. The contents of this document are applicable to any advanced informatics development efforts.

[1] For more information: https://www.nasa.gov/MoonToMarsArchitecture

This document is neither prescriptive, nor definitive in offering solutions. Instead, this document offers a deliberate attempt to articulate the simultaneous creation of both the situated work demands of future EVA operations and the corresponding value propositions of Joint AR capabilities. In doing so, a shared vision of future EVA operations can be distilled to inform subsequent work domain development efforts in conjunction with technological development.

1.3 Change Authority and Responsibility

Proposed changes to this document shall be submitted to JSC-EV3 for consideration and disposition.

2 On the Path to Enabling Earth-Independence

In 2023, NASA released its Moon-to-Mars Architecture Definition Document. This architecture document serves to set the baseline goals to create a systems engineering framework for the necessary program contributions to return to the Moon and journey on to Mars. Furthermore, this architecture has established high level objectives in a variety of domains including science, infrastructure, transportation and habitation, and operations. Meeting these objectives will provide the scientific and technical capabilities for sustained lunar and eventual Martian presence.

“The implementation of Earth-independent missions will be one of the biggest challenges facing a sustained space presence. As of 2023, all aspects of space missions have been monitored and coordinated with reliance on Earth-based Mission Control Center (MCC). However, anticipated delays in radio communications and blackouts require future missions to be independent from Earth in a way not yet seen in space flight. Crew on these long duration missions will need technologies that promote autonomy across all phases of flight. Objective OP-2 from the architecture document reads *Optimize operations, training and interaction between the team on Earth, crew members on orbit, and a Martian surface team considering communication delays, autonomy level, and time required for an early return to the Earth.* In other words, technologies and new ways of working need to be developed to ensure mission goals are accomplished within the environmental constraints that will be present in future missions (e.g. limited communication bandwidth between all members of the flight team). Imagining how to support all phases of a future mission in new ways, with novel technology is no easy feat. This challenge broadly aligns with the *envisioned world problem* [16, 8] and is an active area of study within the fields of human factors and cognitive systems engineering [4, 3, 12].

For the purposes of this document, a subset of human spaceflight operations, known as EVA [7, 15, 9], is offered as a case study for how to begin the process of enabling Earth-independence. The methods employed in this document are inspired by the deliberate discussion of user context [14, 13, 1], function allocation [2], and work domain construction [8]. Collectively, these approaches attempt to help imagine the work domain that might one day exist and grapple with the practical realities of working in that hypothetical future.

3 Advanced Informatics Display System and EVA Concept of Operations Definition

The contents of this document aim to explore hypothetical future moments during EVA execution to establish more specific account of the contextually relevant details of existing concept of operations documents. Specifically, Section 5 explores moments within Phase 7 "EVA Operations" as shown in Figure 3.1. Section 6 describes potential solutions within the context of those hypothesized moments to help show how a spacesuit-compatible informatics system could help the user in that particular situation. Section 4 provides an overview of the methods involved in this detailed concept of operations process.

The remainder of this section describes how this document builds upon details found in parent concept of operations documents (Section 3.1). Additionally, Section 3.2 provides rationale on why a spacesuit-compatible *augmented reality informatics system* is the highest value proposition solution regarding an EVA informatics display system.

3.1 Con-Ops Traceability

Below is a list of the governing documents that were used to prioritize the scope of content in this document.

- EVA-EXP-0042 - Exploration EVA System Concept of Operations
- xEVAS System Requirement Document, specifically RQMT-065

Figure 3.1 outlines the over-arching phases of operation that are anticipated to be involved in future EVA operations. Section 7.2.8 and APPENDIX F of EVA-EXP-0042 also adds details regarding the variety of potential engineering and science tasks crew might perform. APPENDIX H INFORMATICS outlines a list of potentially desirable advanced digital content capabilities.

The exploration EVA system found in EVA-EXP-0042 is shown in Figure 3.2 with annotations of the anticipated interconnections that will be required if an advanced informatics display such as an augmented reality display is to ever be realized [10]. A central point of this annotated diagram is that an advanced informatics device must not only service the needs of the suited crew member, but it must also support the broader team of remote support personnel and accommodate interfaces with a variety of other EVA assets. In other words, the advanced informatics device cannot simply be designed for a single user when EVA operations requires a team of people and a variety of assets.

Most recently, the xEVAS System Requirements Document (SRD) outlines the expected advanced informatics capabilities of future spacesuits within RQMT-065. This content is summarized alongside the desired features outlined in EVA-EXP-0042 in Figure 3.3 to help bound the capabilities discussed in the remainder of this document. Seven of the ten requirement statements align with concept of operations expectations. However, current xEVAS vendors are not required to implement an AR form factor as the necessary display for their spacesuits, which is the hypothesized ideal solution for future operations. EXP-EVA-0042 and subsequently this document continues to hypothesize that an augmented reality experience for the crew member will yield the most desired crew informatics interface possible to conduct an EVA. See Section 3.2 for more discussion on the value proposition of an augmented reality system.

In summary, there exists a variety of higher level descriptions of how future EVA operations might be performed. However, these existing concept of operations descriptions do not provide the amount

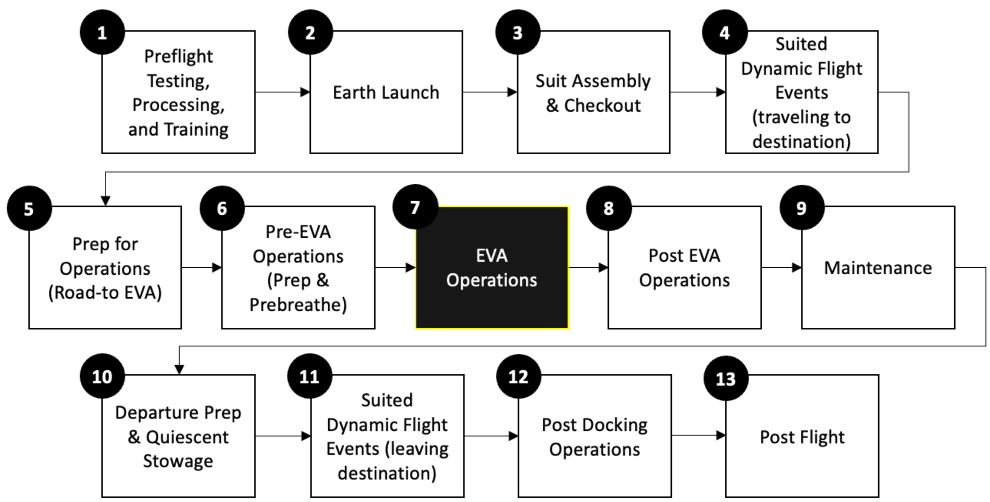

Figure 3.1: Phases of Operations for the xEVA System as defined in Section 4.1.3 of EXP-EVA-0042.

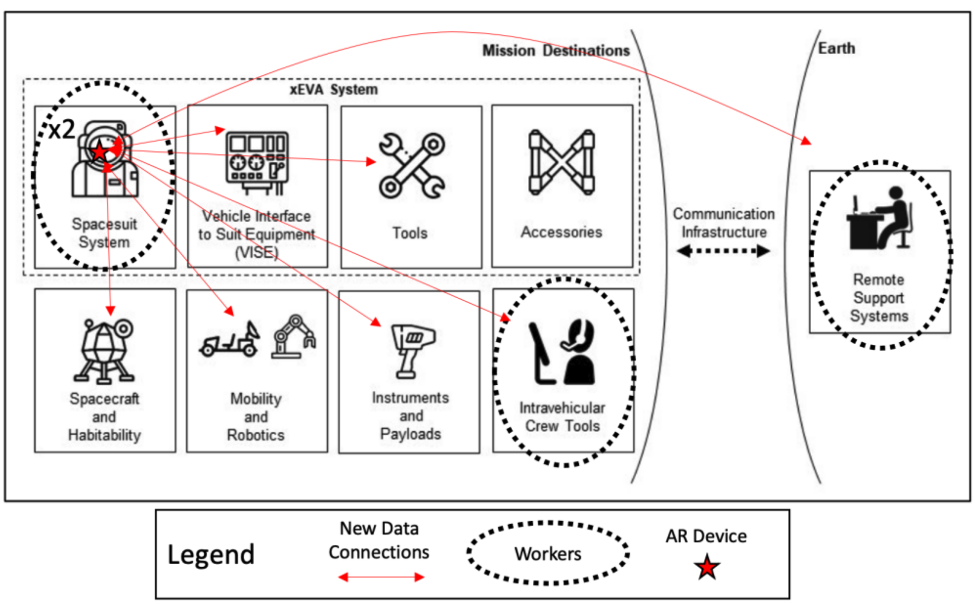

Figure 3.2: Annotated example from EXP-0042 Figure 5.2 that highlights how an AR Device must be integrated with the surrounding assets that encompass the broader EVA system which includes electronic systems and other human agents upon which the suited crew members must dependent to perform EVA work.

of detail required to actually situate how an advanced informatics system might support future user work demands during an EVA. The contents found in Section 5 below focus on expanding Phase 7

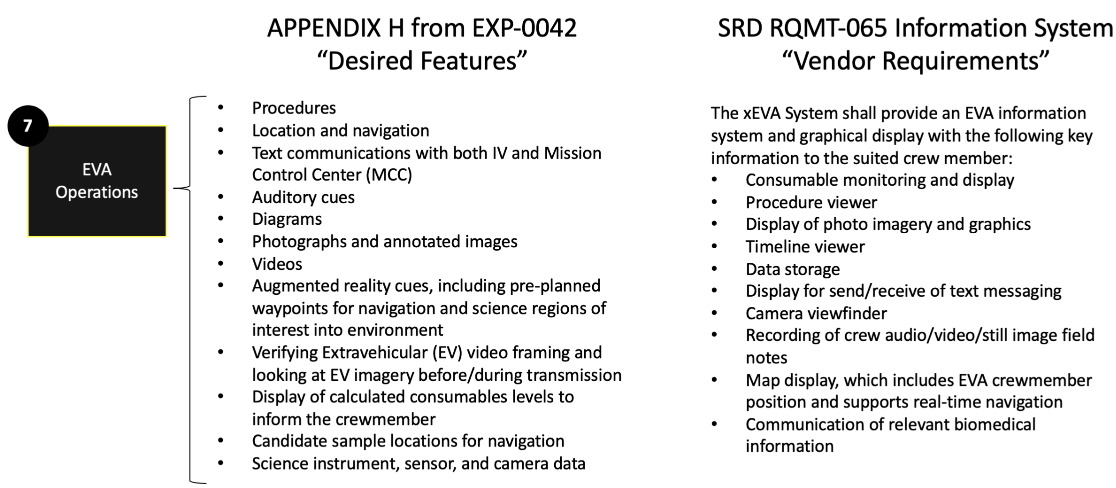

Figure 3.3: Summary of desired features and vendor requirements for an advanced informatics display for EVA operations.

"EVA Operations" via a series of use-cases.

3.2 Value Proposition for Augmented Reality

This document does not attempt to document all possible informatics display form factors and their corresponding value propositions. Both the narratives and user interface solutions in this document are directly applicable to a multitude of display form factors. However, we make a deliberate attempt to propose that an augmented reality system as an informatics display technology offers the most desired end result of capabilities to support future EVA operations.

The value proposition discussed in this section that motivates the Joint AR solution [11] was driven by the design philosophies outlined below:

An advanced informatics display and control system for suited crew operations should:

- Maximize EV crew productivity without compromising their safety.
- Minimize the number of discrete physical acts required by the EV crew to operate.
- Minimize the amount of time required to change from the current state to a desired state.
- Minimize the interference with other means of communication among the work system (e.g., audio, visual).
- Provide redundant means of control for EV crew.

Simply put, EVA is the most expensive, demanding, and arguably the riskiest phase of human spaceflight. Crew time during EVA is precious and *any* time spent not achieving EVA goals is time wasted. AR as technology theoretically offers the fastest mode of information access by simply having the data immediately in view and contextualized within crew surroundings for consumption. In other words, crew would not be required to physically handle a piece of separate display hardware like a portable display (e.g. tablet) which requires time and attention of the crew member.

Additionally, AR that is integrated with the helmet bubble offers the potential to align digital content within the real-world view from the crew member's first person perspective. This capability is known as registered AR and could further reduce the necessary time for the crew member to view and understand digital content while performing EVA. For example, the crew could simply see the destination they need to reach in their real-world by looking at the horizon without ever having to look at a 2-dimensional map and perform the orienting work required to transform 2-D map data into their 3-D surroundings to identify where to travel.

In addition to the display form factor, numerous different control schemes should be considered for feasibility, ease of use, and overall functionality compatible with a suit-compatible AR system. The Joint AR advocates that a multi-modal control scheme that includes both direct EV control (e.g. physical crew control and hands free control), in tandem with remote control offers the most flexibility to support EVA work dynamics. EVA work ebbs and flows through a series of possible situations that necessitate a fluid control scheme among the broader flight team. A particular control method might be momentarily infeasible due to the work situation the crew are facing. For example, crew might experience a brief communication outage with their remote teammates, physical hand control might be prevented when crew hands are occupied with task work, or existing audio conversations among the team might preclude or interrupt the activation of voice control commands. Ultimately, if an advanced informatics display is to be used and found useful by crew, the display and control system must be capable of coping with the complexities of the jobs that crew will face in future operational scenarios.

For more detail on the Joint AR project, please see Refs: [10, 11].

4 Framing the Scenarios

This document prioritizes the deliberate articulation of future work domain attributes and potential corresponding solutions to demands faced by users in those hypothetical situations. In doing so, aspects of the envisioned world problem challenges summarized below can begin to be addressed [16].

- **plurality**: there are multiple versions of how the proposed changes will effect the character of the field of practice in the future.
- **underspecification**: each envisioned concept is vague on many aspects of what it would mean to function in that field of practice in the future; in other words, each is a simplification, or partial representation of what it will mean to practice when that envisioned world becomes concrete.
- **ungrounded**: envisioned concepts can easily be disconnected or even contradict, from the research base, the actual consequences of the changes on people, technology and work.
- **overconfident**: advocates are miscalibrated and overconfident that, if the systems envisioned can be realized, the predicted consequences and only the predicted consequence will occur.

These challenges all stem from many people having internalized assumptions about what a future system is and what it could and should do. In an attempt to help build a common vision for what the future work could look like, this document implements the approach shown Figure 4.1. We acknowledge that there is a boundless set of options that might exist one day. To cope with the limitless possibilities, we encourage the deliberate construction of a finite set of imagined futures to help narrow the discussion. As discussed in Section 4.1, this method is an attempt to overcome some of the initial challenges of the envisioned world problem. use case narratives and momentary demands provide a deliberate set of specific instances that address plurality, underspecification, and ungrounded concerns. Providing interface prototypes that trace directly to momentary demands provide a mechanism to help address being overconfident by calibrating user expectations to meet the moment in question. These efforts should be coupled with iterative prototype testing of a real-world solution help build alignment with system expectations and capabilities within the work domain being built.

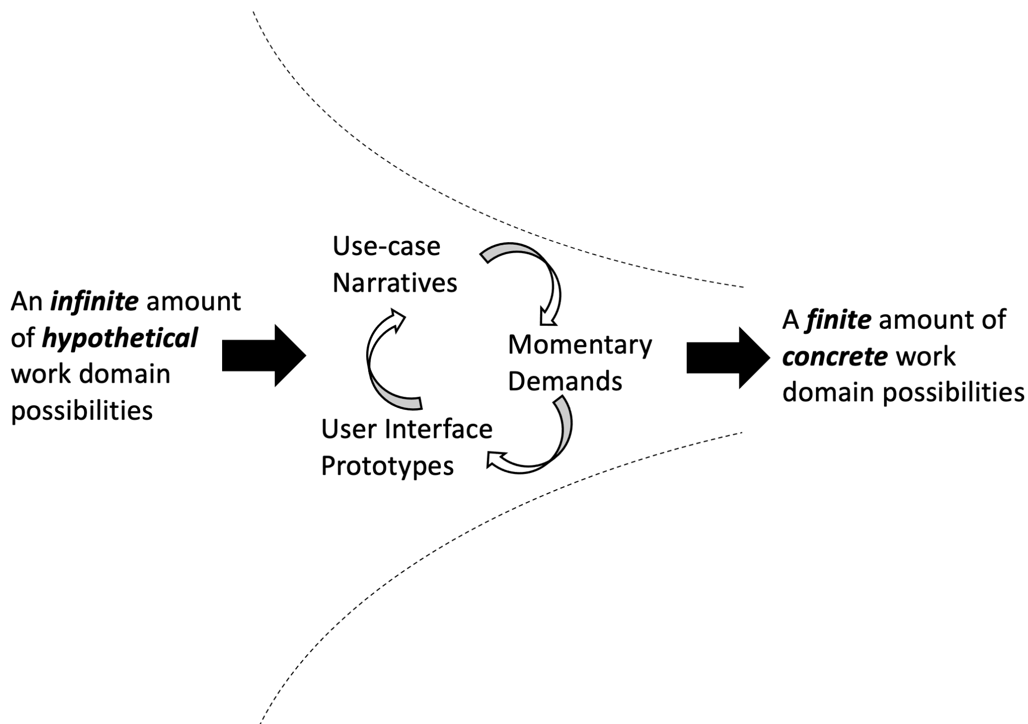

Figure 4.1: Visual description of the translation of an infinite amount of hypothetical work domain possibilities to a more concrete set of concrete work domain possibilities

DISCLAIMER The framing described here depends on a highly iterative refinement and should serve as a means by which a group of people can imagine in a common direction. Agreement and discussion should be iteratively assessed on the use case narratives, momentary demands, and user interface prototypes. This approach is not meant to serve as a standalone method but rather demonstrate how to start the process of understanding envisioned user needs and iteratively discover potential solutions as documented in existing human-centered design processes [5, 6].

4.1 Methods and Approach for Eliciting Advanced Informatics Features

4.1.1 Use Case Definition Template

Figure 4.2 shows the components of the use cases defined in this document. The section header conveys the primary work goal illustrated within the hypothetical use case narrative. The agents involved in the use case narrative are represented with their respective icons. Icons representing all possible agents are derived from the elements outlined in the EXP-EVA-0042 document (see Figure 3.2). The body of the narrative is written in the third person perspective and showcases the sequence of interactions among appropriate agent(s) and their informatics display. The informatics display addresses pertinent momentary demands related to information needs for successful task completion. Each momentary demand (also referred to as "I want to..." statements) is indicated in superscript within the narrative. Some momentary demands may not be listed in the footnote for that use case because it was already referenced/defined in a previously stated narrative.

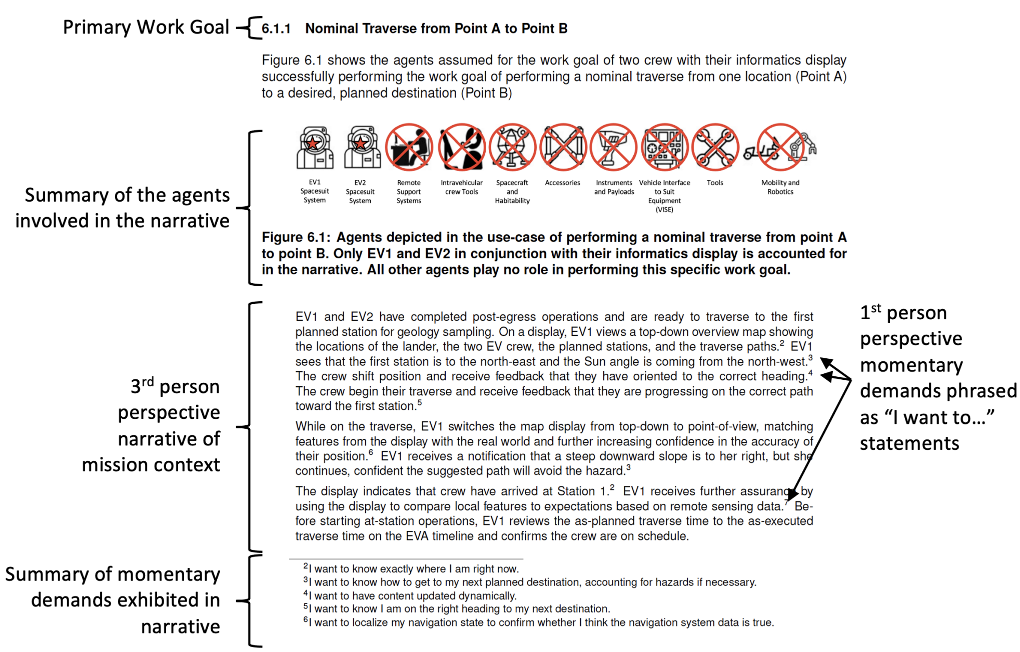

Figure 4.2: Use case definition depiction of key elements

4.1.2 Joint AR Proposed User Interface Template

Figure 4.3 shows the synthesized work demands identified in the use cases with corresponding feature elements. These feature elements were considered the minimum amount of necessary information a user could hypothetically require in order to answer that specific work demand.

Consolidated List of Work Demands and User Interface Features

Scenario	Momentary Demands	User Interface Feature
Navigation	I want to know exactly where I am right now	Current location Current heading
Navigation	I want to know how to get to my next planned destination	Current location Current heading Next location
Navigation	I want to have content updated dynamically	Display changeability
Navigation	I want to know I am on the right heading to my next destination	Current heading Next location
Navigation	I want to confirm the nav system data is true. I want to trust my nav system.	Current location Identifiable landmarks Scale
Navigation	I want to see	

Figure 4.3: Mapping of use case work demands to associated user interface features

Figure 4.4 shows the corresponding work demand and representative user interface. The user interface is annotated with the features represented on the screen to indicate how those features might be represented for user interpretation. Black components of the user interface are transparent to the user. Given the variable lighting conditions in a lunar surface setting, a monochrome green color was selected for early prototyping to increase the likelihood of fielding a visible and legible interface solution.

The Joint AR prototype optical placement is outlined approximately in Figure 4.5. The prototype user interface solutions assume a monocular, monochromatic transparent AR solution that is seamlessly integrated with the helmet bubble. The display is slightly offset to the right side of the user and slightly above the horizontal field of view. The depictions shown in Figure 4.5 are notional alignments to help situate the context of the user interface displays described in the subsequent section. See Ref: [11] for more details on the broader Joint AR solution.

Unless otherwise indicated, all user interface solutions described in this document are supported by a multi-modal control scheme that consists of a crew physical hand controller that consists of a two-button and dial configuration. Hands-free control includes voice control and remote control.

Each use case section is decomposed into specific features considered by the Joint AR team and prototype solutions are provided for a large portion of the work demands discussed in this document. Note, the solutions provided here offer a specific traceable method to connect use case demands to user interface and experience considerations. The solutions provided are neither comprehensive nor final. Instead, the prototype solutions offer a snapshot of potential solutions to critique, examine, and adjust via iterative prototype development and testing. The primary focus of providing potential system solution content in this concept of operations document is to help explicitly link use case assumptions and corresponding system design concepts.

Momentary Demand

7.1.1 I want to know exactly where I am right now

Associated User Interface Features

Figure 7.2 describes the momentary demand that a user might face where they "want to know exactly where I am right now." Two features 1) Current Location and 2) Current Heading denotes possible user interface features that support the user addressing this momentary demand.

Prototype User Interface with Annotated Features

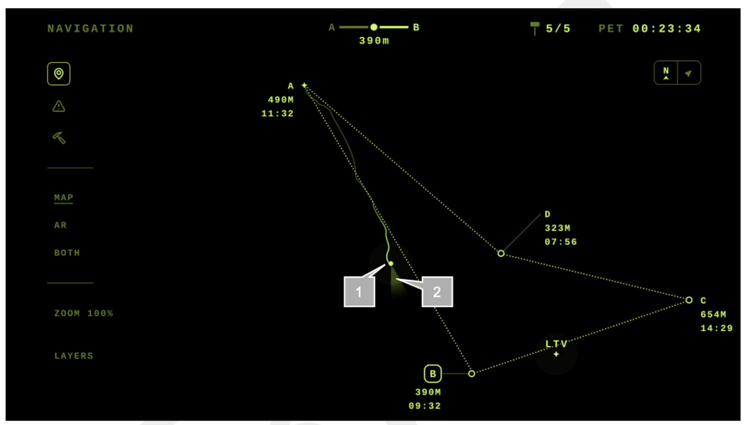

Figure 7.2: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know exactly where I am right now"

Figure 4.4: Mapping of work demands to associated user interface prototype with annotations

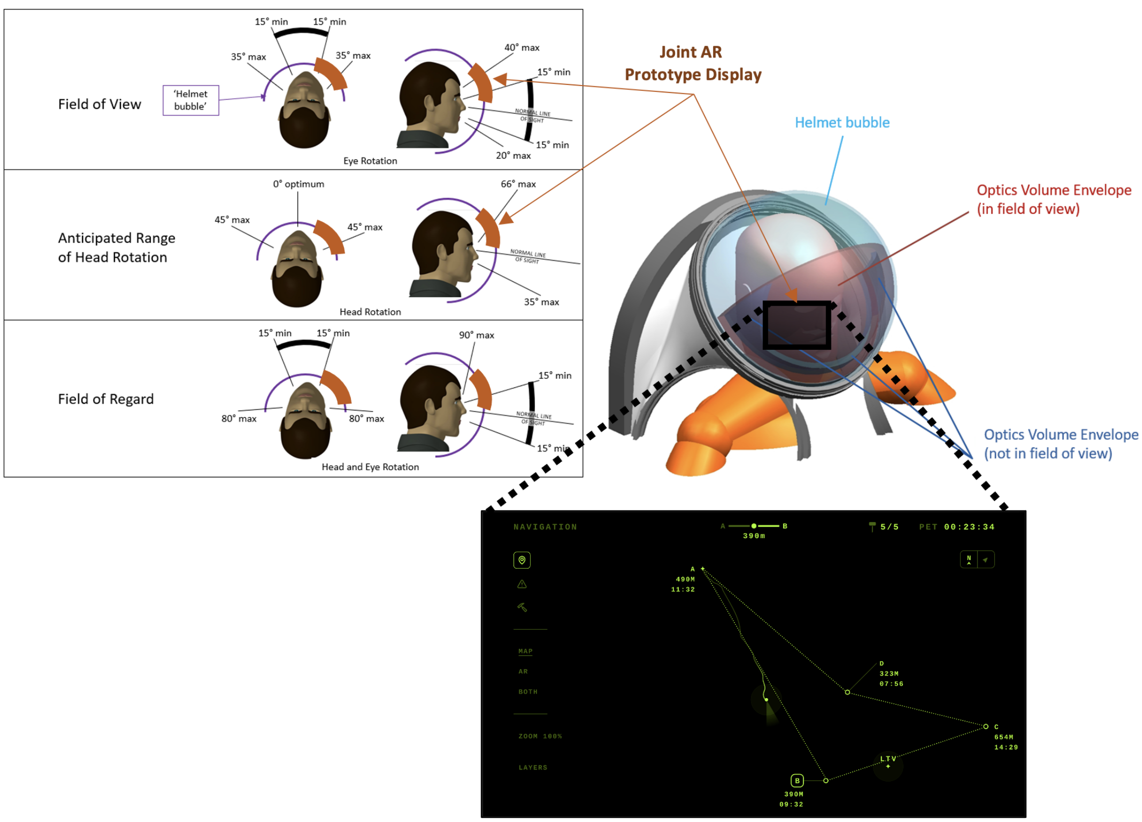

Figure 4.5: Approximate optical placement of the proposed Joint AR system

5 EVA Use Case Definition Utilizing Advanced Informatics

This section contains a variety of EVA operations tasks as summarized in parent documents found in Section 3.1. However, this section extends this content by elaborating on specific hypothetical moments that future crew members might face, particularly in the context of utilizing an advanced informatics display. The following moments summarized below:

- Navigation Use Cases (Section 5.1)
- Tool and Hardware Use Cases (Section 5.2)
- Science Exploration Use Cases (Section 5.3)

All categories of use cases are presented in the form as described in Section 4.1.1. The reader should approach this content with the expectation that the moments and corresponding work assumptions described in each use case should be a topic of specific debate and discussion. Each narrative offers a glimpse at what the future of EVA surface operations could look like. The content provided in the remainder of this section was built with integrated conversations with EVA domain experts in the flight operations community and a variety of integrated testing efforts. By writing these narratives, interested communities can deliberately discuss the anticipated work demands and the corresponding system capabilities intended to support that work.

5.1 Navigation Use Cases

This section describes a set of narratives that consist of crew attempting to navigate during a variety of situations while on the lunar surface during EVA. These sections are summarized below:

- Nominal Traverse from Point A to Point B (Section 5.1.1)
- Off-nominal Traverse from Point A to Point B (Section 5.1.2)
- Nominal at-Station Operations (Section 5.1.3)
- Opportunistic Traverse to Unplanned Destination (Section 5.1.4)
- Crew Separation (Section 5.1.5)
- Contingency Walk-Back (Section 5.1.6)

5.1.1 Nominal Traverse from Point A to Point B

Figure 5.1 shows the agents assumed for the work goal of two crew with their informatics display successfully performing the work goal of performing a nominal traverse from one location (Point A) to a desired, planned destination (Point B)

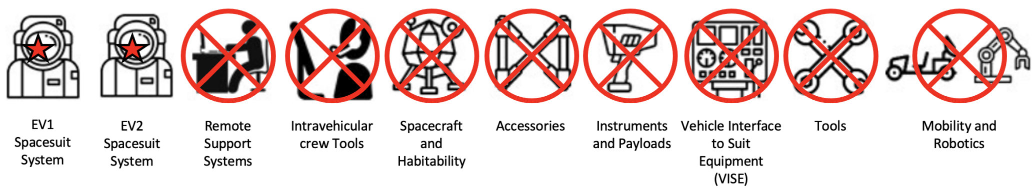

Figure 5.1: Agents depicted in the use case of performing a nominal traverse from point A to point B. Only EV1 and EV2 in conjunction with their informatics display is accounted for in the narrative. All other agents play no role in performing this specific work goal.

> EV1 and EV2 have completed post-egress operations and are ready to traverse to the first planned station for geology sampling. On a display, EV1 views a top-down overview map showing the locations of the lander, the two EV crew, the planned stations, and the traverse paths.[2] EV1 sees that the first station is to the north-east and the Sun angle is coming from the north-west.[3] The crew shift position and receive feedback that they have oriented to the correct heading.[4] The crew begin their traverse and receive feedback that they are progressing on the correct path toward the first station.[5]
>
> While on the traverse, EV1 switches the map display from top-down to point-of-view, matching features from the display with the real world and further increasing confidence in the accuracy of their position.[6] EV1 receives a notification that a steep downward slope is to her right, but she continues, confident the suggested path will avoid the hazard.[3]
>
> The display indicates that crew have arrived at Station 1.[2] EV1 receives further assurance by using the display to compare local features to expectations based on remote sensing data.[7] Before starting at-station operations, EV1 reviews the as-planned traverse time to the as-executed traverse time on the EVA timeline and confirms the crew are on schedule.

[2] I want to know exactly where I am right now.
[3] I want to know how to get to my next planned destination, accounting for hazards if necessary.
[4] I want to have content updated dynamically.
[5] I want to know I am on the right heading to my next destination.
[6] I want to localize my navigation state to confirm whether I think the navigation system data is true.

5.1.2 Off-nominal Traverse from Point A to Point B

Figure 5.2 shows the agents assumed for the work goal of two crew with their informatics display successfully performing the work goal of performing an off-nominal traverse from one location (Point A) to a desired, planned destination (Point B).

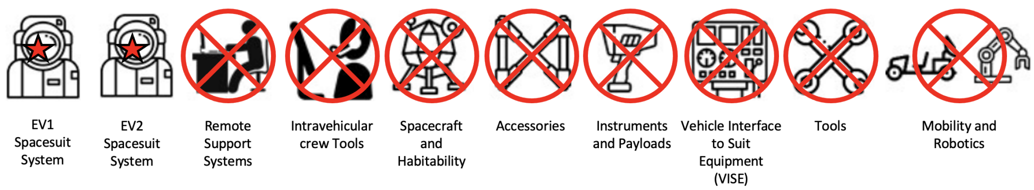

Figure 5.2: Agents depicted in the use case of performing an off-nominal traverse from point A to point B. Only EV1 and EV2, in conjunction with their informatics displays, is accounted for in the narrative. All other agents play no role in performing this specific work goal.

> While on the traverse, EV1 switches the map display from top-down to point-of-view, matching features from the display with the real world and further increasing confidence in the accuracy of their position.[7] EV1 receives a notification that a steep downward slope is to her right, but she continues, confident the suggested path will avoid the hazard.[3]
>
> The display indicates that crew have arrived at Station 1.[2] EV1 receives further assurance by using the display to compare local features to expectations based on remote sensing data.[7] Before starting at-station operations, EV1 reviews the as-planned traverse time to the as-executed traverse time on the EVA timeline and discovers the traverse took 12 minutes longer than planned. The display reflects changes to the EVA plan, including updated traverse time blocks based on actual traverse rates being longer than anticipated, as well as suggestions to reduce time or drop subsequent stations as to not exceed overall EVA duration constraints.[4,8]

[7] I want to localize my navigation state to confirm whether I think the navigation system data is true.

[8] I want to see an indication that content was dynamically updated.

5.1.3 Nominal at-Station Operations

Figure 5.3 shows the agents assumed for the work goal of two crew with their informatics displays using a handheld camera and sample marker to perform successful nominal at-station operations.

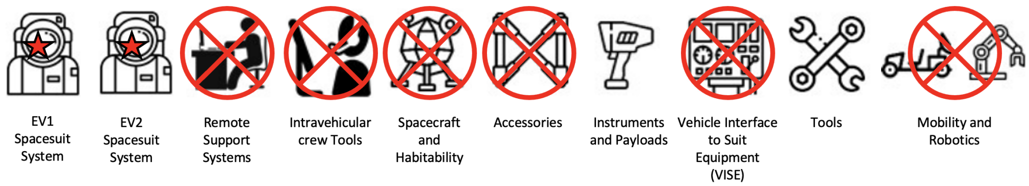

Figure 5.3: Agents depicted in the use case of performing nominal at-station operations. EV1, EV2, in conjunction with their informatics displays, instruments and payloads, and tools are accounted for in this narrative. All other agents play no role in performing this specific work goal.

> After performing some initial broad-scale observations and taking panoramic imagery, EV1 and EV2 split up to identify candidate samples and deploy sample markers. EV2 finds a boulder with interesting features and decides to place a sample marker near it. He vocalizes "deploying sample marker 5" to establish this boulder as a candidate sample with marker number 5. Using EV2's coordinates, a pin appears on the map display with the label "Station 1, Sample Marker 5". [4,8] MCC and IV also see this pin appear on their support displays. EV2 distances himself a few meters from the marker to take handheld camera photos. His map display updates and he now sees two other pins, labeled "S1 M1" and "S1 M2", corresponding to markers he heard EV1 had deployed.[4,8] He sees these pins are about 100 meters to his west, as indicated by registered AR beacons.[9]

[9] I want to know where object(s) are relative to my current position.

5.1.4 Opportunistic Traverse to Unplanned Destination

Figure 5.4 shows the agents assumed for the work goal of two crew with their informatics displays and ground support successfully performing an opportunistic traverse to an unplanned destination.

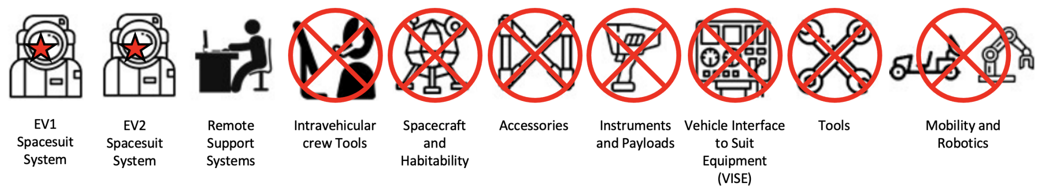

Figure 5.4: Agents depicted in the use case of performing an opportunistic traverse to an unplanned destination. Only EV1 and EV2, in conjunction with their informatics displays, and remote support systems are accounted for in this narrative. All other agents play no role in performing this specific work goal.

> On the traverse from Station 1 toward Station 2, EV1 spots something interesting in the distance. The features she sees do not appear in the orbital imagery map so she estimates the location relative to her position.[10] The feature is beyond a shadowed area, approximately 300-400 meters away from the planned traverse path. EV1 does not see any evidence of craters indicated by map topography of the shadowed region.[3] After conferring with the ground team on remaining timeline and consumables, EV1 and EV2 decide to traverse to this new area of interest.[11] As EV crew arrive at the interesting feature, the display indicates they are 510 meters from the point of deviation.[12] The ground team uses this as-measured distance and time spent traversing to adjust the forward plan. The crew begins pre-sampling. The ground team annotates their map to mark this new station and the locations for sample marker deployed by the crew. EV1 and EV2 view and confirm the annotations appearing on their map[8] display match what they see[9].

[10] I want to know the location of an area I see in the real world as portrayed on a map.
[11] I want to consider whether I could deviate from the next planned destination to visit an unplanned destination.
[12] I want to know how far I've gone and how far I have still to go.

5.1.5 Crew Separation

Figure 5.5 shows the agents assumed for the work goal of two crew successfully performing sampling operations while separated, using their informatics displays, a helmet camera, and ground support.

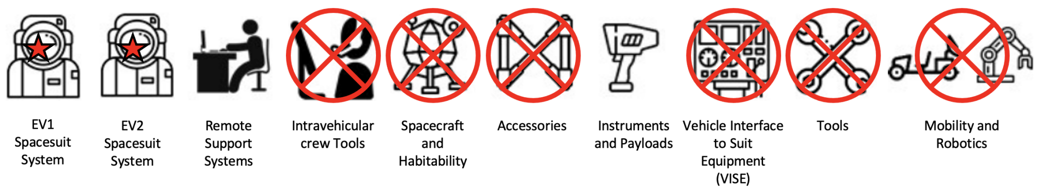

Figure 5.5: Agents depicted in the use case of performing sampling operations while separated. Only EV1 and EV2, in conjunction with their informatics displays, instruments and payloads, and remote support systems are accounted for in this narrative. All other agents play no role in performing this specific work goal.

> During pre-sampling at a station, EV2 walks to a local high spot at the north edge of the station for panoramic imagery. He notices a large boulder in the distance that seems different than the material at this station. EV1 is south of EV2 in the lower area of the station, surveying for sample candidates. EV2 uses his current location and the orbital imagery map to estimate the boulder is approximately 200 meters away but is not within sight of EV1. The EV crew discuss and agree EV2 should investigate the boulder while EV1 performs sampling at the station. MCC concurs with the plan after checking for hazards and communications coverage.
>
> As EV2 walks to the boulder, EV1 monitors EV2's relative position.[9] As EV2 arrives at the boulder, he describes the boulder and how it differs from the material at the station. EV1 sees that EV2 is 230 meters away from her.[9] EV1 displays EV2's helmet camera and compares it to what she sees in front of her. She confirms to EV2 that these are different materials.

5.1.6 Contingency Walk-Back

Figure 5.6 shows the agents assumed for the work goal of two crew successfully performing a contingency walk-back to the lander, using their informatics displays, cuff checklist, and ground support.

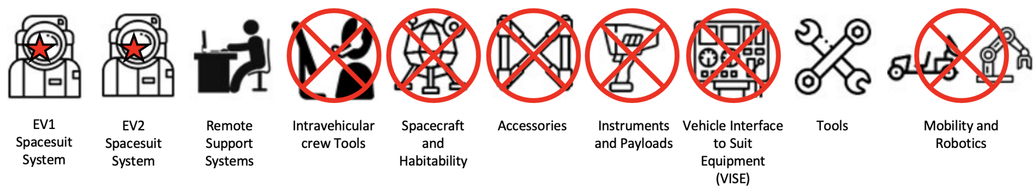

Figure 5.6: Agents depicted in the use case of performing a contingency walk-back. Only EV1 and EV2, in conjunction with their informatics displays, tools, and remote support systems are accounted for in this narrative. All other agents play no role in performing this specific work goal.

As the EV crew are traversing from Station 2 to Station 3, EV2 receives an alert from his suit. Based on suit telemetry and the cuff checklist, EV2 determines he is in an abort scenario and must immediately return to the lander. Based on their current location[2] and the location of the lander, EV1 determines the distance of a direct path to the lander is approximately 1.6 kilometers[13] across unplanned terrain.

EV crew use their displays to gather more information to help them decide which path to take back to the lander. EV1 views the top-down map, including topography and an illumination map layer,[14] while EV2 views the top-down map and line-of-sight communication coverage layer.[14] EV1 voices that the direct path includes some shadowed regions and the topography indicates a high likelihood of craters. EV2 voices that, on the direct path, they should expect to lose communications for approximately 10 minutes. EV1 then views and compares the direct path to other path time estimates based on distance, slope, and terrain classification.[12] The direct path is estimated to be faster than the planned path and backtracking along the previously followed path. Crew decide to take the direct path back[13] but to deviate from this path as required to circumnavigate the crater shadows using the topography and illumination map layers.[14] MCC is able to view this same information on their ground displays and, after evaluating the situation, they respond that they concur with the EV crew's plan. The EV crew begin walking in the heading indicated on their displays for the direct path toward the lander.[5]

[13] I want to know how to get to my lander and how long it is estimated to take.
[14] I want to analyze different map layers to evaluate my situation.

5.2 Tool and Hardware Use Cases

Another potential use case for an AR informatics display is to integrate support while utilizing powered tool and hardware. These devices create their own digital data that could become a component of the procedures required by the crew incorporate. Consider an electronically driven bolt driver. The sections outlined below provide a glimpse of how a crew member might interact with device data in the context of performing engineering tasks.

- Pre-Traverse Equipment Preparations (Section 5.2.1)
- Nominal instance of driving bolts to torque (Section 5.2.2)
- Off-nominal instance of driving bolts to torque (Section 5.2.3)
- Handheld photography documentation (Section 5.2.4)

5.2.1 Pre-Traverse Equipment Preparations

Figure 5.7 shows the agents assumed for the work goal of pre–traverse equipment preparations using their informatics display.

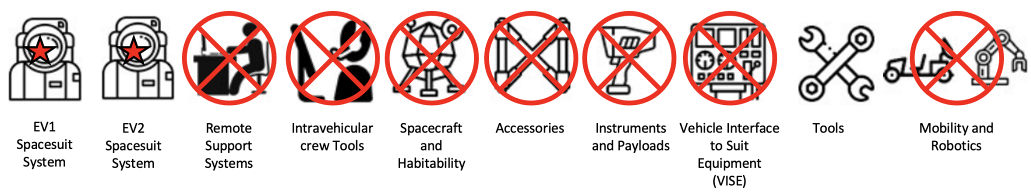

Figure 5.7: Agents depicted in the use case of performing pre-traverse equipment preparation. All other agents play no role in performing this specific work goal.

> EV1 and EV2 work together to retrieve tools and other sample collection equipment from the lander. Some tools are stowed on the suits and the rest are stowed in the tool carrier. As the crew work together to transfer and configure this hardware, they refer to a checklist to confirm they have the expected hardware and stow it in the planned configuration for EVA traverse[15]. For example, there are 10 sample markers each with a unique ID on the label. EV1 puts five in her collection pack and EV2 puts five in his collection pack. The display indicates the location of each item changing during the transition from "lander" to "tool cart[16]."

[15] I want to verify I have all items stowed and accounted for

[16] I want to have content updated dynamically

5.2.2 Nominal instance of driving bolts to torque

Figure 5.8 shows the agents assumed for the work goal of a nominal bolt driving scenario.

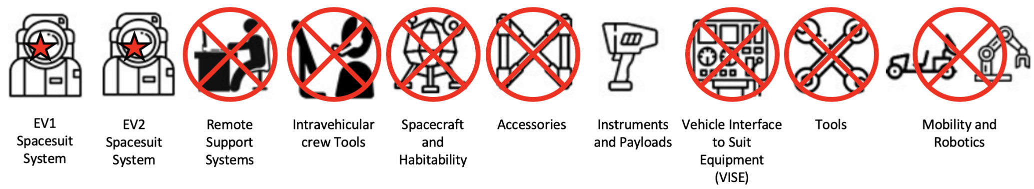

Figure 5.8: Agents depicted in the use case of performing a nominal bolt driving operation. All other agents play no role in performing this specific work goal.

EV1 begins the portion of the timeline to drive bolts on some hardware, as part of an installation. They access their display procedure content necessary to complete the bolt operations[17]. Before setting up at the worksite, they review cautions and warnings[18]. They review the task content to be performed on the 3 bolts and determine the center bolt is to be driven first[19], that only one socket configuration is required for all bolts[20], and that all three bolts can be accessed from one position[21]. They configure themselves and their equipment to the correct position for driving the first bolt[22]. They locate the center bolt[23] and verify no Foreign Objects or Debris (FOD) are present[24]. They compare the required power tool hardware configuration against the procedures and verify the correct socket is installed[25].

From the procedure details they determine they will drive this bolt to torque (12.0 ft-lb) and expect 7-10 turns[24]. They are reminded that they are expected to count turns manually and to verbally report turns and torque achieved once complete[26]. They configure their power tool settings to B1 CW2[27]. With the settings configured, they drive the bolt. Once the power tool stops turning, they vocalize that they achieved 8 turns and a torque of 11.7 ft-lb. The informatics system detects these words, interprets them, and determines the results were within success critical[24]. The display provides visual indication the step was completed successfully[28]. Based on the results of the completed step, the display updates the next step based on a decision tree portion of the procedures[29]. With visual confirmation that the next step has been updated[30], they determine they will drive this bolt back out exactly 1.5 turns[24] and that they are expected to report turns[26]. They configure their power tool to B5 CCW2[27], drive the bolt, and vocalize 1.5 turns completed as expected[24].

[17] I want to know exactly what procedures are needed for the current task at hand.

[18] I want to receive caution or warning notifications related to sensitive/hazardous environments/equipment that could be inadvertently disturbed while completing the current task

[19] I want to know if a specific order of bolt driving is necessary

[20] I want to know how many tasks will be completed before changing/altering the equipment configuration (socket, TM, etc.)

[21] I want to know how many bolts I need to drive/release before repositioning/translating elsewhere

[22] I want to know how to get to the correct location to perform power tool operations (wayfinding/map)

[23] I want to know what the bolt/equipment/hardware looks like (visual aid)

[24] I want to know the range or characteristics of acceptable "success criteria" for each specific task (e.g., verify no FOD, drive turns or torque, desired turns and/or torque

[25] I want to know the required equipment configuration (socket, TM, etc.)

[26] I want to receive prompts for specific information that must be delivered to remote operators

[27] I want to know exact device setting(s) for torque and speed

[28] I want to see that a step was completed successfully

[29] I want to have content updated dynamically

[30] I want to see that content was dynamically updated

5.2.3 Off-nominal instance of driving bolts to torque

Figure 5.9 shows the agents assumed for the work goal of dealing with an off-nominal instance of driving bolts.

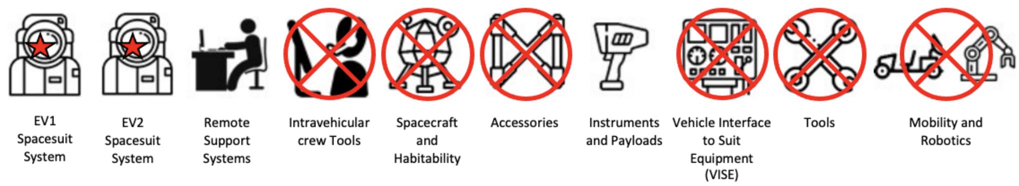

Figure 5.9: Agents depicted in the use case of performing an off-nominal bold driving operation. All other agents play no role in performing this specific work goal.

EV1 has completed bolt driving operations on the first of three bolts at a worksite[31]. They review the procedure to confirm the second bolt operation will be on the left bolt[19]. They locate the left bolt[23] and verify no Foreign Objects or Debris (FOD) are present[24].

They determine they will drive this bolt to torque (12.0 ft-lb) and expect 7-10 turns[24]. They are reminded that they are expected to count turns manually and to verbally report turns and torque achieved once complete [26]. They configure the power tool to B1 CW2[27], drive, and report 3 turns and torque of 12.1 ft-lb. The informatics system detects the vocal feedback, interprets it, and provides a visual indication that the step did not meet success criteria[32]. They realize they did not achieve the required turn count[24] and report to their remote support about the issue[33]. The display has already processed the crib sheet based on the procedure step and vocalized report, updated the next procedure step[34, 29], and visually indicated a change has been made to the procedures as shown to the crew[30]. They stabilize their body position and try driving the bolt again with the same settings. This time they get an additional 5 turns and torque of 11.9 ft-lb, voicing their success to their remote support[24, 28]. They reconfigure per the procedure to B6 CCW2[27], drive the bolt, and call down 1 turn and torque of 1.1 ft-lb completed as expected[24].

Finally, they perform a similar set of steps on the right bolt by configuring to B1 CW2[27] and driving the bolt. Three power tool LEDs illuminate and the alpha-numeric display indicates "HI TORQ"[35]. They vocalize the details of the anomaly[33]. The informatics system records this report, interprets the words, recognizes an anomaly, and initiates a visual indicator of the anomaly[32]. The display contents update by adding the planned response for this anomaly[34, 29, 30]. The crew member performs the response steps and complete bolt operations for this task. All three bolts are successfully driven to install the device.

[31] I want to maintain situation awareness of current and completed procedure steps
[32] I want to see that a step was not completed successfully, that an anomaly occurred
[33] I want to notify remote operators of unsuccessful operations and receive strategies on how the issues may be fixed
[34] I want to know what to do if I encounter an anomaly
[35] I want to know what the fault indication means

5.2.4 Handheld Photo Documentation

Figure 5.10 shows the agents assumed for the work goal of performing handheld photo documentation.

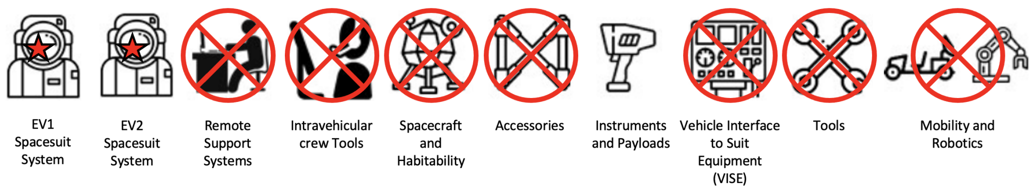

Figure 5.10: Agents depicted in the use case of performing handheld photography. All other agents play no role in performing this specific work goal.

> In addition to the verbal observations made by EV1, they are required to photo document the area to build a digital record of their observations in addition to the sampling candidates as indicated by the sample markers. As each photograph is taken, a 'quick look' view of the image appears and then automatically disappears from the display. [36] EV1 references these quick look images as they appear for framing the photograph with the object of interest. The display also provides an updated count on connectivity, memory available, and power consumption to know the handheld camera is working without issue. [37] The display also keeps count of each image that contains each sample marker deployed in the area so that the crew can ensure they have appropriately captured enough pre-sampling photography with sample markers before proceeding to sampling tasks.[38,39,16]

5.2.5 Science Payload Deployment

Figure **??** shows the agents assumed for the work goal of deploying a science payload using their informatics display.

Figure 5.11: Agents depicted in the use case of performing a science payload deployment. All other agents play no role in performing this specific work goal.

Earlier in the EVA, the EV crew and MCC discussed rationale for changing the deployment location of this payload. After making a few quick changes to the deployment procedure based on EV1 site descriptions, MCC transmitted an updated checklist to the EV crew [40, 16] EV1 sees the new

[36] I want to see the image I just took to ensure it captures what I wanted to capture
[37] I want to the current state of my handheld camera
[38] I want to know I took the minimum images required for pre-sampling
[39] I want to know that I've captured the minimum documentation data required by the mission
[40] I want to know that I'm referencing the most accurate content.

deployment procedures and places the payload base unit and begins to deploy one of the five sub units. MCC recognizes EV1's progress and commands display remotely to proceed to the next step of the checklist[41], which provides another annotated image describing where to place sub unit 1. Crew continue with the displayed content to complete the deployment

[41] I want to advance the content to the 'next phase' to continue with my work

5.3 Science Exploration Use-Cases

An informatics display could provide a high level of utility for the planning and execution of science operations. The following are hypothetical use cases of how an informatics display could support scientific operations over the course of an EVA.

- Traverse to and Upon Arrival to Science Station (Section 5.3.1)
- Making Broad Observations (Section 5.3.2)
- Deploying a Sample Marker (Section 5.3.3)
- Determining Station Sampling Priorities (Section 5.3.4)
- EVA Sample Documentation (Section 5.3.5)

5.3.1 Traverse to and Upon Arrival to Science Station

Figure 5.12 shows the agents assumed for the work goal of arriving at a scientific station.

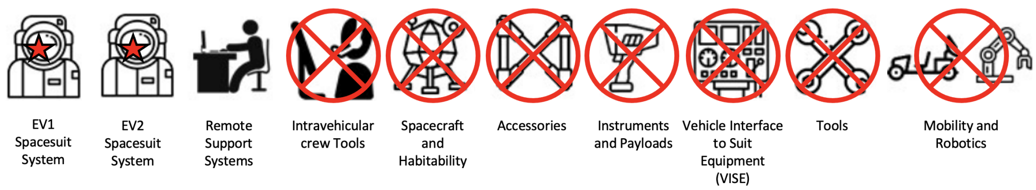

Figure 5.12: Agents depicted in the use case of a traverse to and arrival at a science station. All other agents play no role in performing this specific work goal.

EV1 and EV2 review the EVA objectives[42]. The crew use the display's map to relate the EVA objectives to specific locations based on the scientific hypotheses of the area[43]. In this EVA, the traverse is expected to cover 4 different geologic units and the contacts between them. One objective is to determine how many distinct volcanic events happened in this area. They review different map layers and annotations, noting how the traverse plan and list of stations link to EVA objectives[44]. They review specific expected features that bound their traverse paths[45]. Potential science features drive paths to go to specific areas[46]. In this EVA, there are two prominent outcrops that the scientists want to specifically visit. Potential hazards confine paths. During the traverse from the lander to the first station, the crew must avoid a deep crater with steep slopes. Otherwise, the crew have freedom to stray from their path as they react to what they might see as they walk.

As EV1 and EV2 traverse from the lander or a station to the next station, they are constantly surveying the area and making observations. They vocalize observations and how what they see either supports or refutes the working hypotheses. As they observe more and more of the surface materials first-hand, as compared to orbital reconnaissance imagery used to plan this EVA, they might suggest changes to the plan, to where a station is defined to collect samples based on the objectives and hypotheses.

As the crew approach the station, they review the station objectives and confer with MCC to determine if they should deviate from the plan in any way. In this case, the EV crew see details not evident in orbital reconnaissance imagery that cause them to suggest sampling a couple hundred meters to the East of the planned station. The EV crew decide this new area better supports the objectives intended for the station area. The informatics system records these words, interprets them, and updates the map accordingly to indicate the new station area[16].

[42] I want to know the EVA objectives
[43] I want to know how the EVA objectives relate to features in my surrounding area
[44] I want to see multiple versions of a map, quickly
[45] I want to know what boundaries constrain my movement/traverse and where they are relative to me
[46] I want to know where targeted science features are located

5.3.2 Making Broad Observations

Figure 5.13 depicts the agents utilized in the EVA task of making broad observations.

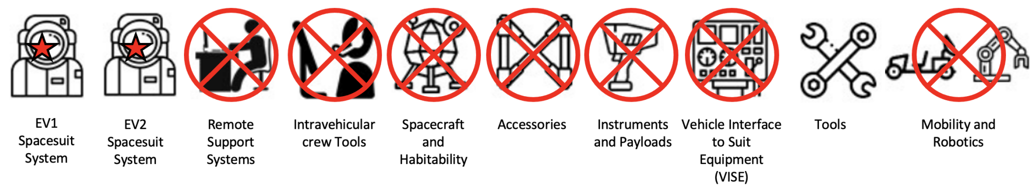

Figure 5.13: Agents depicted in the use case of making broad observations at a given science station. All other agents play no role in performing this specific work goal.

EV1 begins to make broad observations about the area, where she inspects a contact between two geologic units. She provides observations on major structures, rock and regolith properties, and her thoughts on sampling strategy. She decides she can acquire a float sample and a scoop of the regolith from the northern side of the area while EV2 gets a chip sample from an outcrop to the south, across the suspected contact line. The informatics system records these words, interprets them, and updates the station documentation in both the map and procedures to indicate the types of samples targeted, tools required for subsequent sampling actions, and their respective locations[16].

5.3.3 Deploying a Sample Marker

Figure 5.14 shows the agents assumed for the goal of deploying a sample marker.

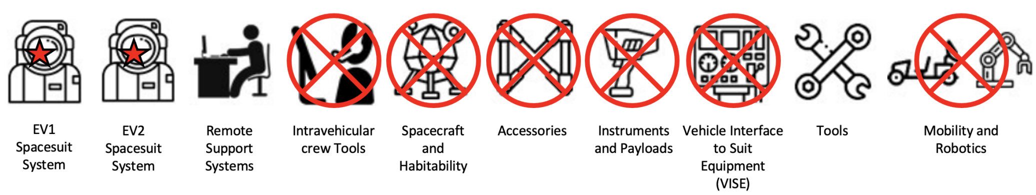

Figure 5.14: Agents depicted in the use case of deploying a sample marker. All other agents play no role in performing this specific work goal.

EV1 canvasses the region for targets of scientific interest. She places a sample marker next to a couple of baseball-sized rocks that have a green glint to them. She walks a bit further and places a second sample marker down near a smattering of golf ball sized rocks with some interesting texture. These are the candidate float samples she has identified. As each marker is deployed by the crew member, the informatics system records which marker is used and geo-tags this marker with the current location. Each sample marker now appears on the display map with location and heading information.[47,16]. Additionally, the 'sample markers available' count is updated to reflect the markers still available for deployment.

As EV1 placed each sample marker she took a couple minutes to describe her observations of the materials. During these descriptions, the display provides the observation checklist to

[47] I want to know where my marker is for the record (so I can easily find it later)

ensure crew comment on all desired aspects of the terrain features.[48] This checklist contains reminders of the different characteristics to describe and capture within the video. EV1 describes the size and shape of the rocks to be sampled. She describes the primary color and the partial secondary color tones. She comments on the grain size and vesicularity. She notices a type of mineral she has not seen elsewhere in this mission to-date and describes it. MCC follows along, watching the helmet camera video feed while listening to EV1's descriptions. The informatics system transcribes these words from EV1, associates them with the appropriate descriptors (like size, shape, color, etc), and creates the "field note" in real-time for EV1. [16] These field note annotations are automatically tagged with each sample and its location and can be referenced from the map view or by expanding the registered AR beacon for each sample. [16]

EV1 and EV2 continue canvassing the station, looking for candidate samples. As they identify each candidate, they deploy a sample marker and report sample observations.

5.3.4 Determining Station Sampling Priorities

Figure 5.15 shows the agents assumed for the work goal of determining station sampling priorities.

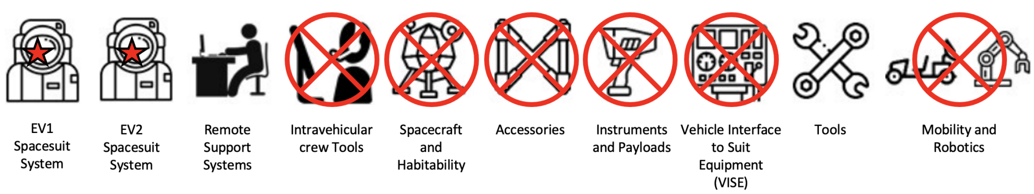

Figure 5.15: Agents depicted in the use case of determining sample priority. All other agents play no role in performing this specific work goal.

A total of 5 sample markers were deployed by EV1 and EV2 in the area during pre-sampling. EV1 identified 2 possible float samples and 1 scoop sample. EV2 identified 2 possible chip samples. The two crew and remote support review these sample marker locations on the display map and discuss the desired prioritization.[16] The team down-selects to 1 of the 2 float samples along with the scoop sample. The display updates indicating the selected candidate samples with a distinction from the declined samples.[16] The crew continue with sample collection of the prioritized samples

[48] I want to reference the major features to make sure I don't miss/forget pertinent details

5.3.5 EVA Sample Documentation

Figure 5.16 shows the agents assuming for the work goal of two crew successfully documenting an EVA sample.

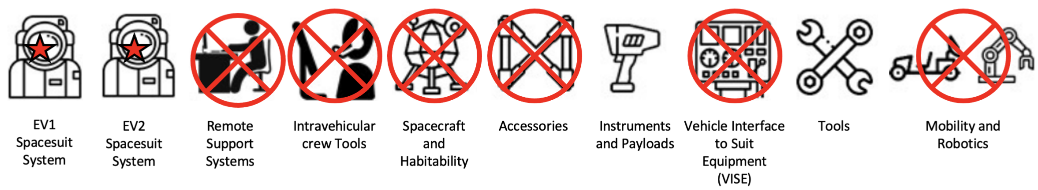

Figure 5.16: Agents depicted in the use case of documenting an EVA sample. All other agents play no role in performing this specific work goal.

EV1 retrieves the tongs and the scoop from the tool carrier based on her previous decision on which types of samples to take. The display recognizes the removal of these tools from the carrier and updates its knowledge of the state of the xEVA System. After unstowing the tool, EV1 knows exactly which tools need to be returned to the tool carrier based upon the display status.[16]

EV1 takes more photos of the first float sample at specific Sun angles and distances, referring to a diagram on display. As she spends more time looking at this sample, she notices a new distinguishing feature and snaps a close-up photo of it before the sample is disturbed. As each photo is taken, its location is tagged and the display aggregates all photos as an optional map layer.[16]

EV1 uses the tongs to pick the rock sample up and place it into sample bag number 114. She voices to IV, "Sample marker A4 float rock is going into bag number 114." The display system updates its state in both inventory details and map annotation for where this sample was obtained. The display system also associates photos taken at this location and verbal observations with this sample number, compiling a "field note."[16] EV1 stows bag 114 into her waist pack.

Once all desired samples are secured for transport EV1 and EV2 retrieve all deployed sample markers, returning them to their collection packs. [15] The display indicates when each item has been retrieved from the field and stowed in the tool carrier[16]. Before leaving the worksite, EV crew are notified by the display that not all items are accounted for in the tool carrier. It turns out a hammer remains in the field, as indicated by the display. EV1 scans from left to right, following the hammer icon in the heading compass, until it is in her field of view. The display indicates the distance and heading to the location of the hammer[16]. EV1 walks toward it, retrieves it, and stows it.

6 Joint AR Proposed User Interfaces

The following sections provide a set of conceptual solutions that align with each momentary demand described in Section 5.

6.1 Navigation Support Solutions

In total, Section 5.1 identified 14 navigation related momentary demands as shown in Figure 6.1. Additionally, a feature set was created to link each momentary demand with supporting display elements. The remainder of this section provides user interface concepts that align each momentary demand with hypothesized user interface features.”

Scenario	Momentary Demand	Feature
Navigation	I want to know exactly where I am right now	Current location Current heading
Navigation	I want to know how to get to my next planned destination	Current location Current heading Next location
Navigation	I want to have content updated dynamically	Display changeability
Navigation	I want to know I am on the right heading to my next destination	Current heading Next location
Navigation	I want to confirm the nav system data is true. I want to trust my nav system.	Current location Identifiable landmarks Scale
Navigation	I want to see indication that content was dynamically updated	Display changeability Notification
Navigation	I want to know where 'x' is relative to my current position	Current location Current heading 'X' location
Navigation	I want to know where many 'x' items are relative to my current position	Current location Current heading 'X' locations
Navigation	I want to know the location of an area I see as portrayed on a map (maybe an unplanned area of opportunistic investigation)	Identifiable landmarks Scale
Navigation	I want to consider whether I should deviate from the next planned destination to visit an unplanned destination	Current location Next location Unplanned destination location Impact of adding unplanned destination
Navigation	I want to know how far I've gone and how far I have still to go	Current location Current heading Starting location Starting heading Next location Next heading
Navigation	I want to know how to get to my lander and how long it is estimated to take	Current location Current heading Lander location Time differential based on current traverse speed
Navigation	I want to analyze different map layers to evaluation my situation	Map layers: topography, pins
Navigation	I want to know the location of my partner	Partner location Partner heading

Figure 6.1: Description of momentary demands relevant to navigation scenarios and the corresponding display features appropriate to address each momentary demand.

6.1.1 I want to know exactly where I am right now

Figure 6.2 describes the momentary demand use case of when the user wants to know "exactly where I am right now." For this momentary demand, the user is supported through the implementation of the 1) Current Location and 2) Current Heading interface features. The Joint AR user interface provides proposed solutions to address these features. Current Location (1) is shown as a filled circle. Current Heading (2) is depicted as a forward projecting beam to indicate the direction the user is facing and estimated field of view.

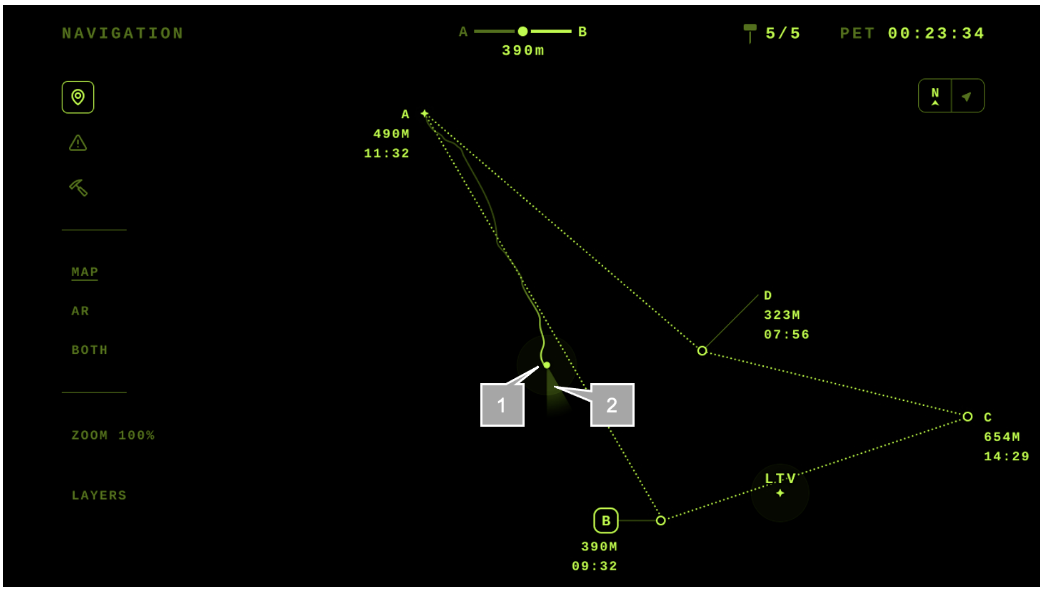

Figure 6.2: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know exactly where I am right now" using Current Location (1) and Current Heading (2).

6.1.2 I want to know how to get to my next planned destination

Figure 6.3 describes the momentary demand use case of when the user wants to know "how to get to my next planned destination." For this momentary demand, the user is supported through the implementation of the 1) Current Location, 2) Current Heading, and 3) Next Location interface features. The Joint AR user interface provides proposed solutions to address these features. Current Location (1) is shown as a filled circle. Current Heading (2) is depicted as a forward projecting beam to indicate the direction the user is facing and estimated field of view. Next Location (3) is visually designated with a frame around the next waypoint.

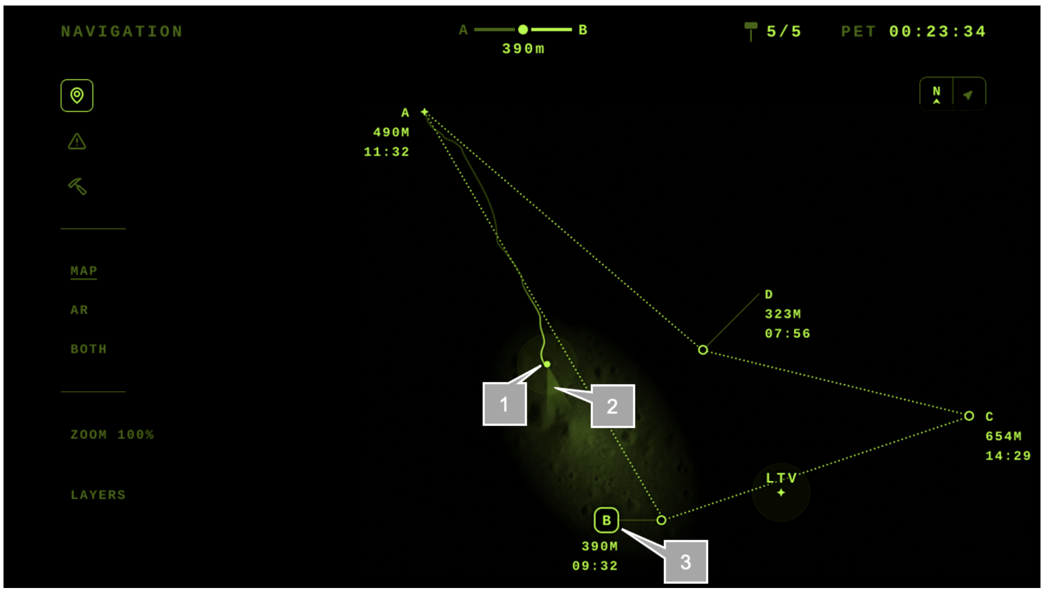

Figure 6.3: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know how to get to my next planned destination" using Current Location (1), Current Heading (2), and Next Location (3).

6.1.3 I want to have content updated dynamically

Figure 6.4 describes the momentary demand use case of when the user wants to "have content updated dynamically." For this momentary demand, the user is supported through 1) Display Changeability. The Joint AR user interface provides a proposed solution addressing Display Changeability by including updates to position and time, as well as the ability for a user to place pins along the route.

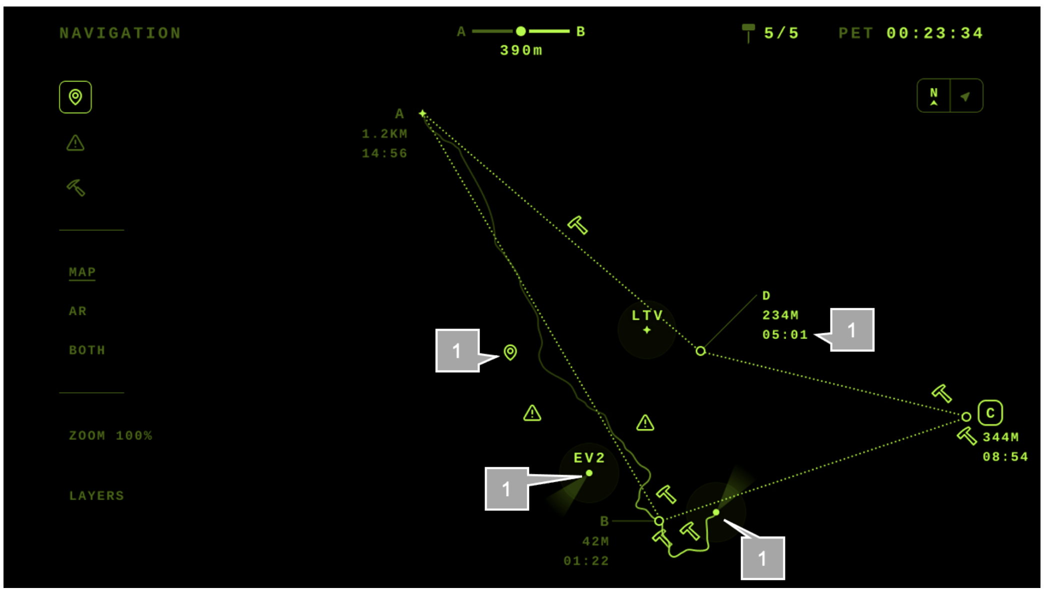

Figure 6.4: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to have content updated dynamically" with Display Changeability (1).

6.1.4 I want to know I am on the right heading to my next destination

Figure 6.5 describes the momentary demand use case of when the user wants to know "I am on the right heading to my next destination." For this momentary demand, the user is supported through the implementation of the 1) Current Heading and 2) Next Location interface features. The Joint AR user interface provides proposed solutions to address these features. Current Heading (1) is depicted as a forward projecting beam to indicate the direction the user is facing and estimated field of view. Next Location (2) is designated with a frame around the next waypoint as well as distance to the next waypoint.

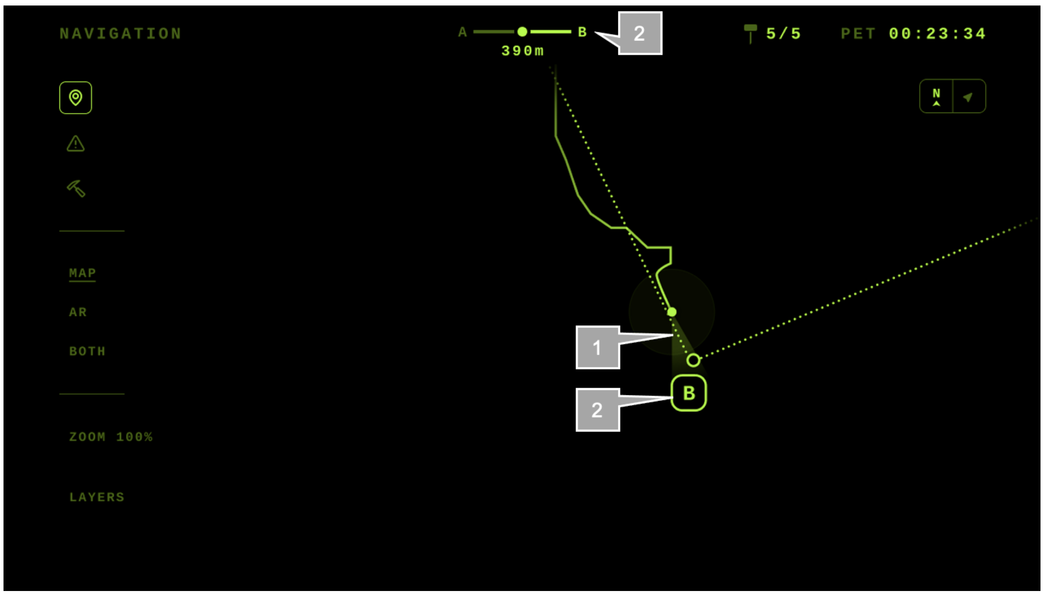

Figure 6.5: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know I am on the right heading to my next destination" using Current Heading (1) and Next Location (2).

6.1.5 I want to confirm the navigation system data is accurate

Figure 6.6 describes the momentary demand use case of when the user wants to confirm "my navigation system data is accurate." For this momentary demand, the user is supported through the implementation of the 1) Current Location, 2) Identifiable Landmarks, and 3) Scale interface features. The Joint AR user interface provides proposed solutions to address these features. Current Location (1) is shown as a filled circle. Identifiable Landmarks (2) (e.g., boulders, craters) are shown on the map. (3) Scale is not shown in the image below.

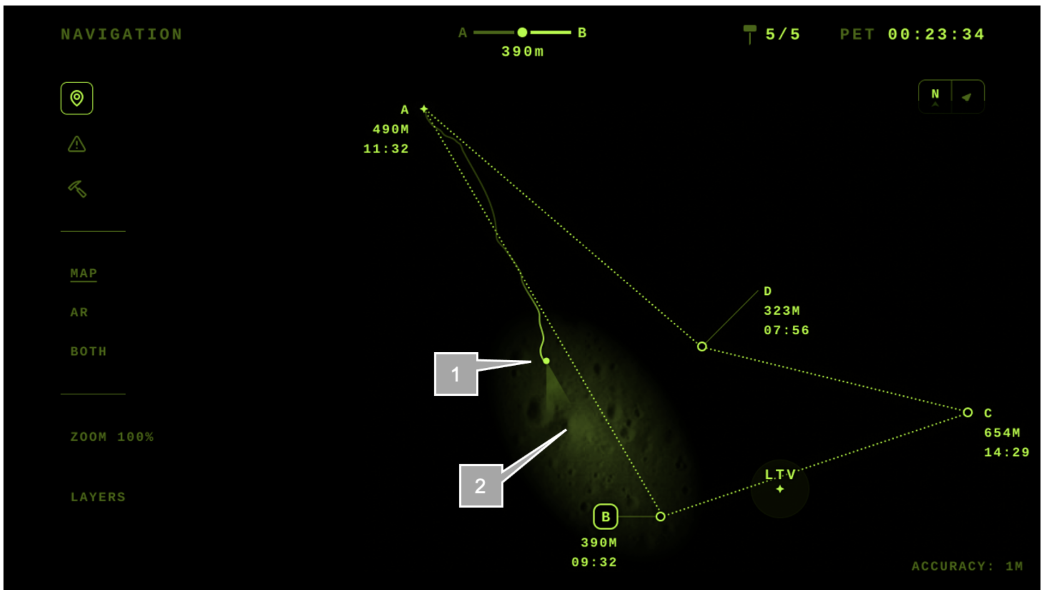

Figure 6.6: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to confirm my navigation system data is accurate" using Current Location (1) and Current Heading (2).

6.1.6 I want to see indication that content was dynamically updated

Figure 6.7 describes the momentary demand use case of when the user wants to "have content updated dynamically." For this momentary demand, the user is supported through the implementation of the 1) Display Changeability and 2) Notification interface features. The Joint AR user interface provides proposed solutions to address these features. Display Changeability (1) is shown with dynamically updating location information. Notifications (2) are shown underneath the traverse progress bar and can indicate when a user leaves or arrives at a station, as well as other useful momentary information.

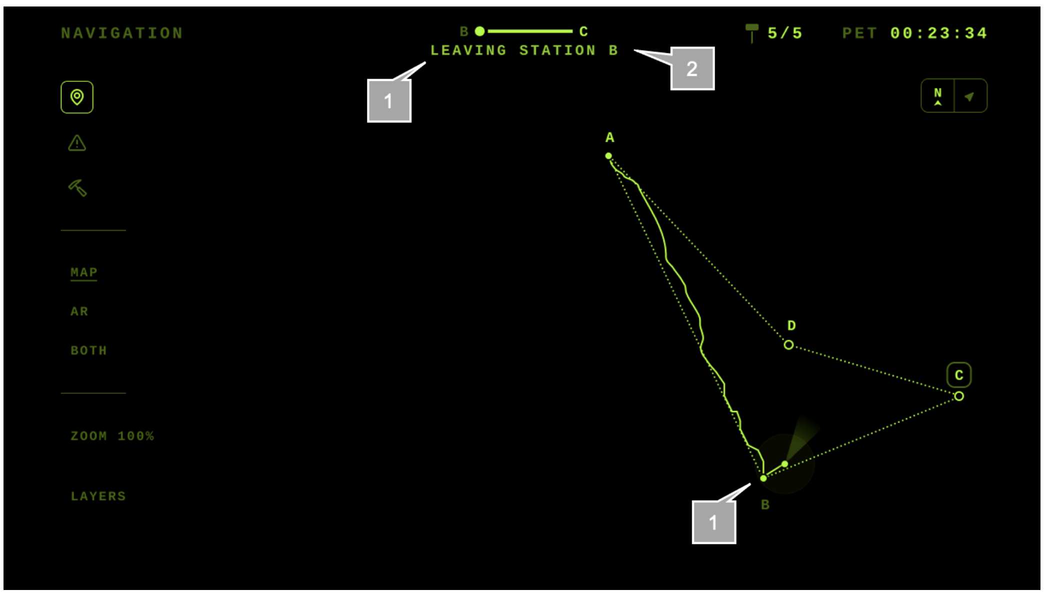

Figure 6.7: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to have content updated dynamically" using Display Changeability (1) and Notification (2).

6.1.7 I want to know where X is relative to my current position

Figure 6.8 describes the momentary demand use case of when the user wants to know "where 'x' is relative to my current position." For this momentary demand, the user is supported through the implementation of the 1) Current Location, 2) Current Heading, and 3) 'X' Location interface features. The Joint AR user interface provides proposed solutions to address these features. Current Location (1) is shown as a filled circle. Current Heading (2) is depicted as a forward projecting beam to indicate the direction the user is facing and estimated field of view. 'X' Location (3) is indicated as distance (in meters) to travel from current location to reach 'X'.

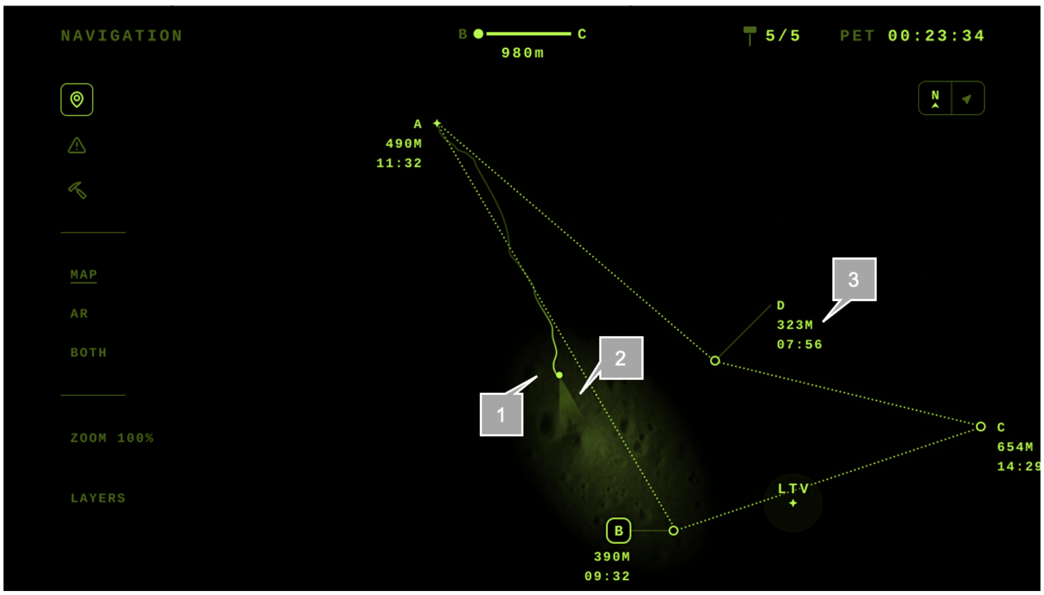

Figure 6.8: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know where 'x' is relative to my current position" using Current Location (1), Current Heading (2), and 'X' Location (3).

6.1.8 I want to know where many X items are relative to my current position

Figure 6.9 describes the momentary demand use case of when the user wants to know "where many 'x' items are relative to my current position." For this momentary demand, the user is supported through the implementation of the 1) Current Location, 2) Current Heading, and 3) 'X' Location interface features. The Joint AR user interface provides proposed solutions to address these features. Current Location (1) is shown as a filled circle. Current Heading (2) is depicted as a forward projecting beam to indicate the direction the user is facing and estimated field of view. 'X' Locations (3) is depicted as distance (in meters) to reach multiple 'X' items.

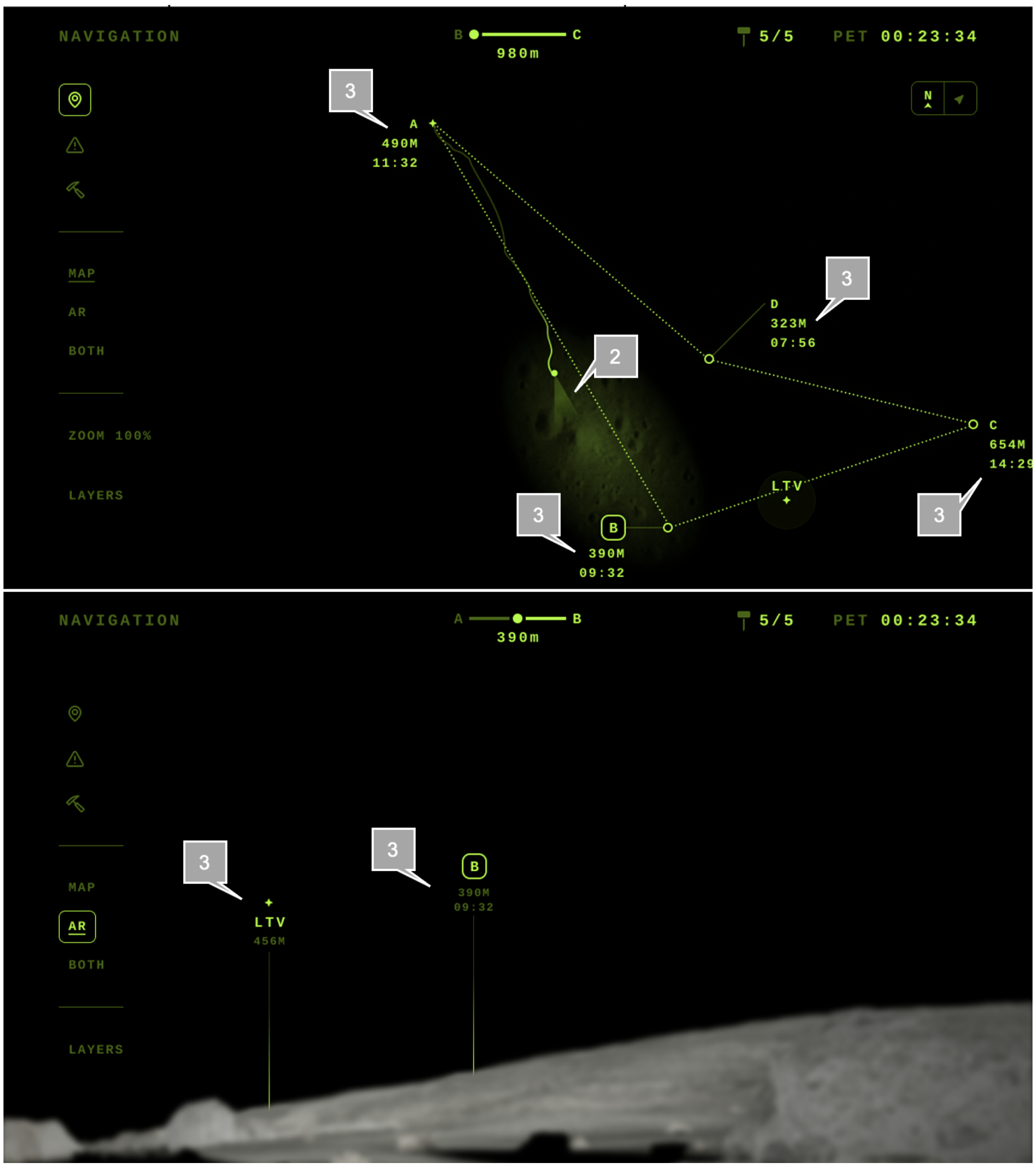

Figure 6.9: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know where many 'x' items are relative to my current position" using Current Location (1), Current Heading (2), and 'X' Locations (3).

6.1.9 I want to know the location of an area I see as portrayed on a map

Figure 6.10 describes the momentary demand use case of when the user wants to know "the location of an area I see as portrayed on a map." For this momentary demand, the user is supported through the implementation of 1) Identifiable Landmarks and 2) Scale interface features. The Joint AR user interface provides proposed solutions to address Identifiable Landmarks (1) (e.g., boulders, craters) by displaying them on the map. Scale (2) is shown in meters.

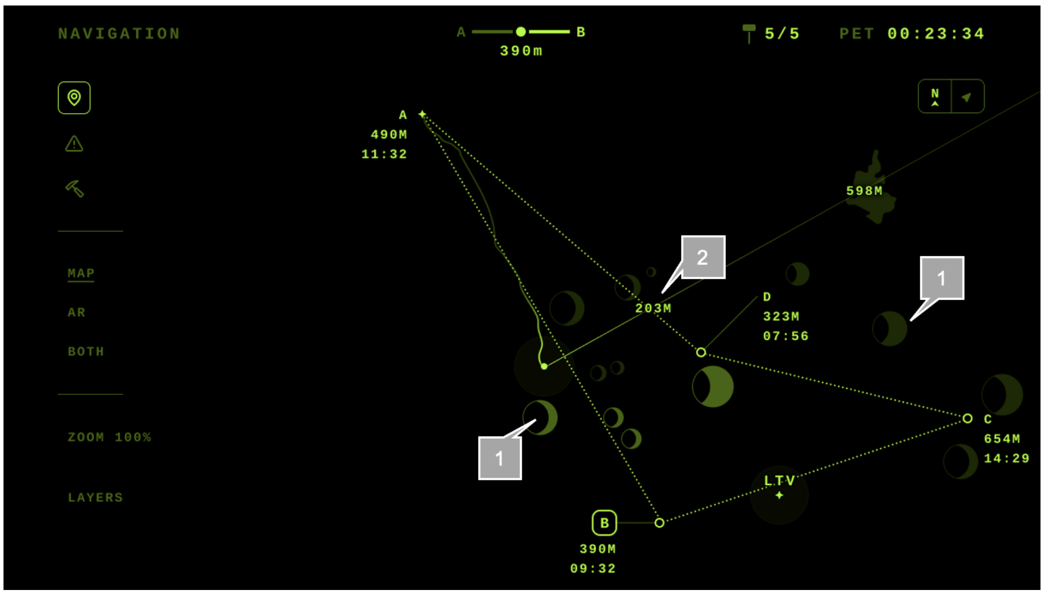

Figure 6.10: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know the location of an area I see as portrayed on a map" using Identifiable Landmarks (1) and Scale (2).

6.1.10 I want to consider whether I should deviate from the next planned destination to visit an unplanned destination

Figure 6.11 describes the momentary demand use case of when the user wants to consider "whether I should deviate from the next planned destination to visit an unplanned destination." For this momentary demand, the user is supported through the implementation of the 1) Current Location, 2) Next Location, 3) Unplanned Destination Location, and 4) Impact of Adding Unplanned Destination interface features. The Joint AR user interface provides proposed solutions to address these features. Current Location (1) is shown as a filled circle. Next Location (2) is depicted with a frame around the label of the next waypoint. Unplanned Destination Location (3) can be determined with an overlay of distance intervals along the user's heading. The Impact of Adding an Unplanned Destination (4) is not shown in the below image.

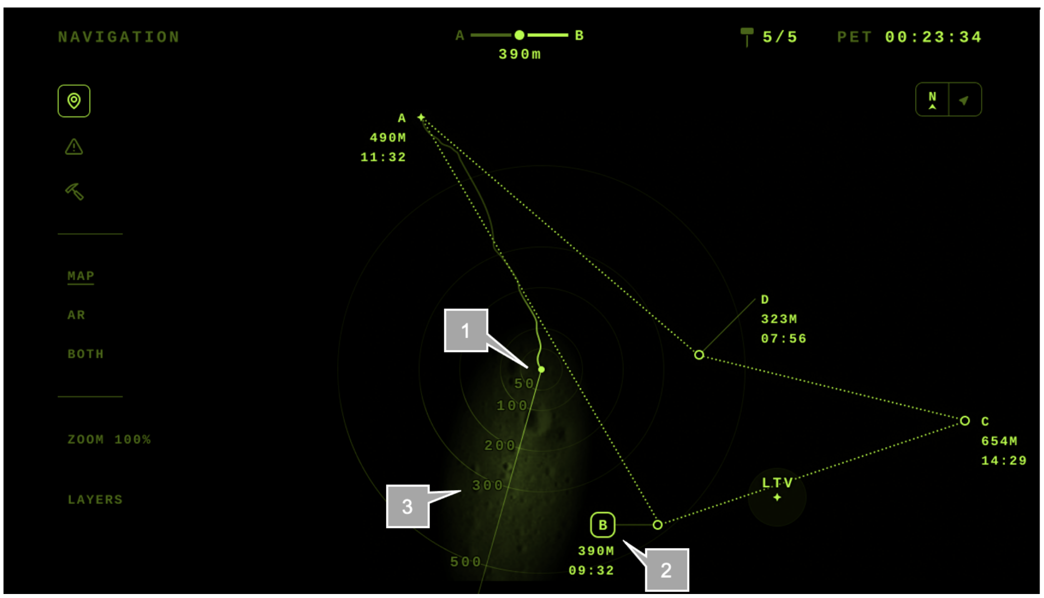

Figure 6.11: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to consider whether I should deviate from the next planned destination to visit an unplanned destination" using Current Location (1), Next Location (2), and Unplanned Destination Location (3).

6.1.11 I want to know how far I have gone and how far I have still to go

Figure 6.12 describes the momentary demand use case of when the user wants to know "how far I've gone and how far I have still to go." For this momentary demand, the user is supported through the implementation of the 1) Current Location, 2) Current Heading, 3) Starting Location, 4) Starting Heading, 5) Next Location, and 6) Next Heading interface features. The Joint AR user interface provides proposed solutions to address these features. Current Location (1) is shown as a filled circle. Current Heading (2) is depicted as a forward projecting beam to indicate the direction the user is facing and estimated field of view. Starting Location (3) is visually designated as waypoint 'A' and with a distinct visual icon. Next Location (5) is depicted with a frame around the label of the next waypoint. Starting Heading (4) and Next Heading (6) are not shown in the image below.

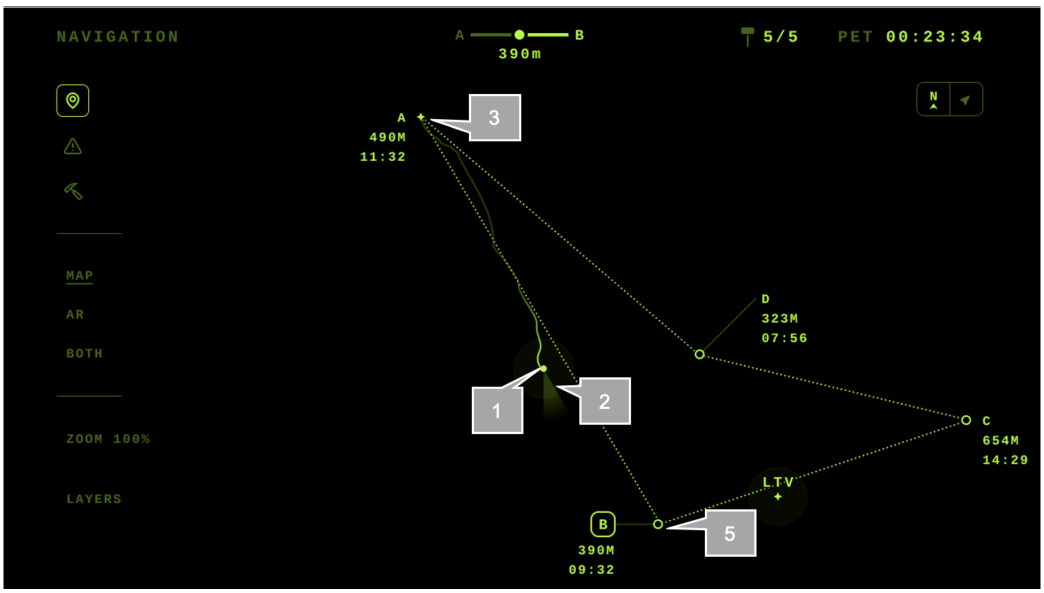

Figure 6.12: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know how far I've gone and how far I have still to go" using Current Location (1), Current Heading (2), Starting Location (3), and Next Location (5).

6.1.12 I want to know how to get to my lander and how long it is estimated to take

Figure 6.13 describes the momentary demand use case of when the user wants to know "how to get to my lander and how long it is estimated to take." For this momentary demand, the user is supported through the implementation of the 1) Current Location, 2) Current Heading, 3) Lander Location, 4) Time Differential Based on Current Traverse Speed interface features. The Joint AR user interface provides proposed solutions to address these features. Current Location (1) is shown as a filled circle. Current Heading (2) is depicted as a forward projecting beam to indicate the direction the user is facing and estimated field of view. Lander Location (3) is visually designated as waypoint 'A' and with a distinct visual icon. Time Differential Based on Current Traverse Speed (4) is shown as the delta between the planned and estimated time, based on traverse speed, to reach a destination in minutes:seconds.

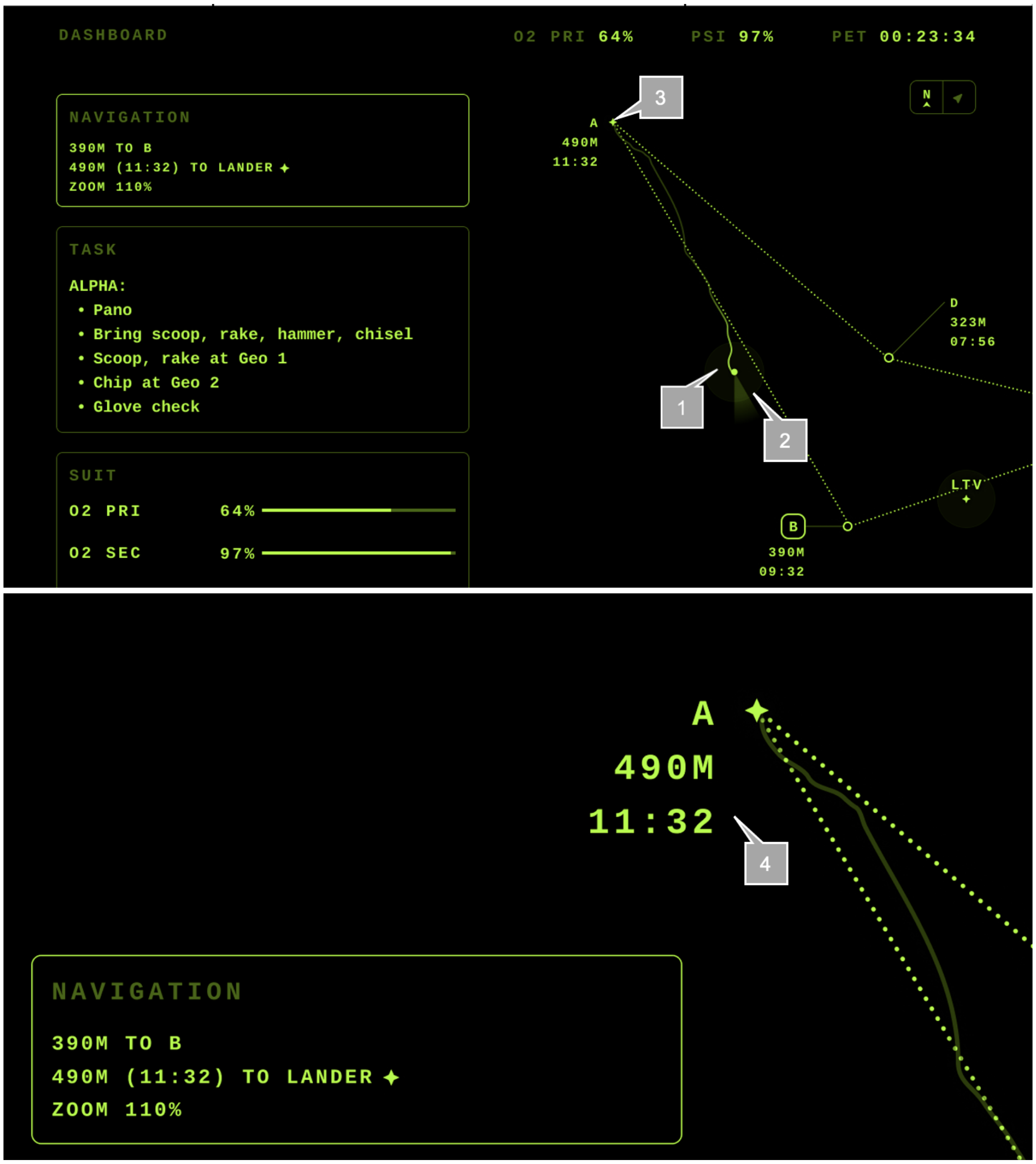

Figure 6.13: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know how to get to my lander and how long it is estimated to take" using Current Location (1), Current Heading (2), Lander Location (3), and Differential Based on Current Traverse Speed (4).

6.1.13 I want to analyze different map layers to evaluate my situation

Figure 6.14 describes the momentary demand use case of when the user wants to "analyze different map layers to evaluate my situation." For this momentary demand, the user is supported through the implementation of the 1) Map Layers, 2) Topography, and 3) Pin interface features. The Joint AR user interface provides proposed solutions to address these features. Map Layers (1) are selectable and the currently visible layers are indicated with higher salience on the left side of the display. Topography (2) is shown as an overlay. The Pins (3) map layer option is shown on the left side of the screen, but is not currently visible.

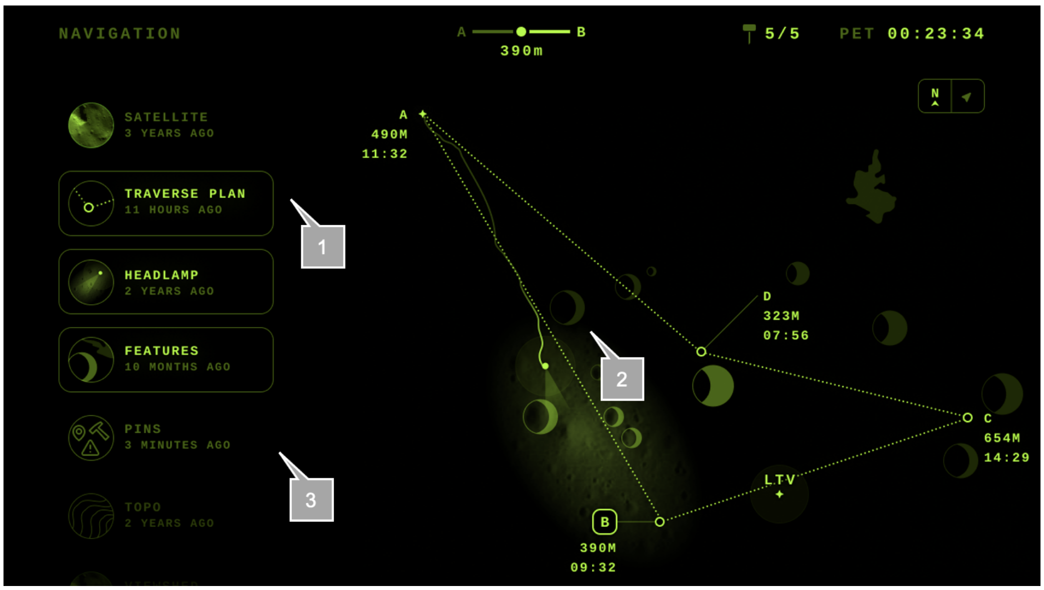

Figure 6.14: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to analyze different map layers to evaluate my situation" using Map Layers (1) and Topography (2)."

6.1.14 I want to know the location of my partner

Figure 6.15 describes the momentary demand use case of when the user wants to "know the location of my partner." For this momentary demand, the user is supported through the implementation of the 1) Partner Location and 2) Partner Heading interface features. The Joint AR user interface provides proposed solutions to address these features. Partner Location (1) is shown as a filled circle, labeled as the partner EV (i.e., in this case "EV 2"). Partner Heading (2) is depicted as a forward projecting beam to indicate the direction the partner is facing and estimated field of view.

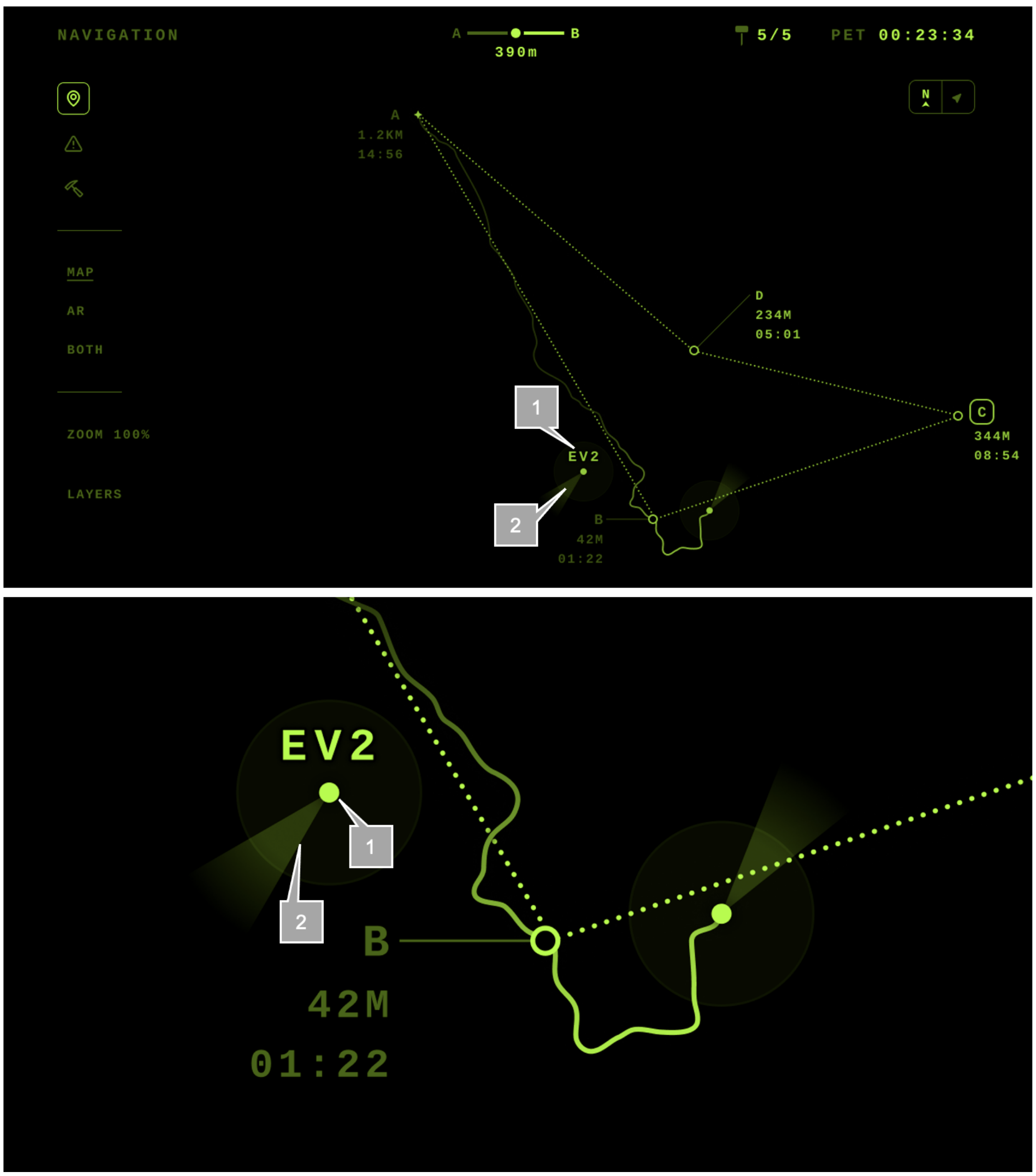

Figure 6.15: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to analyze know the location of my partner" using Partner Location (1) and Partner Heading (2).

6.1.15 I want to know that I am referencing the most accurate content

Figure 6.16 describes the momentary demand use case of when the user wants to "I want to know that I am referencing the most accurate content." For this momentary demand, the user is supported through the implementation of the 1) Display Changeability. The Joint AR user interface provides proposed solutions to address these features. Display Changeability (1) is viewed in multiple ways. Both in textual notifications of when syncing and updates have been made. Additionally, icons are added to the map to indicate a change.

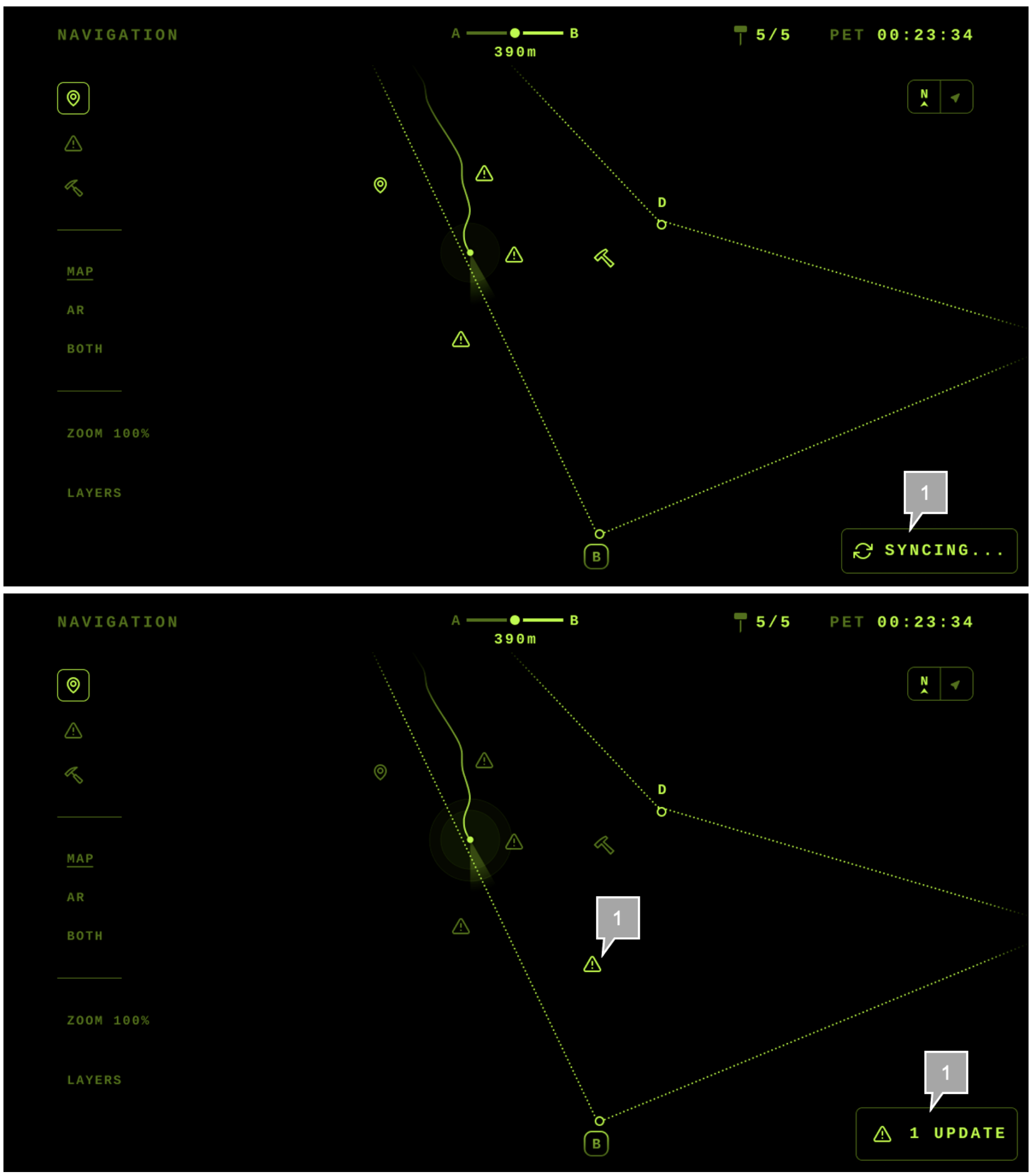

Figure 6.16: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know that I'm referencing the most accurate content"

6.2 Tool and Hardware Support Solutions

In total, Section 5.2 identified thirty-four tool and hardware related momentary demands. These aggregated demands are shown in Figure 6.17. Additionally, a feature set was created to link each momentary demand with supporting display elements. The remainder of this section provides user interface concepts that align each momentary demand with hypothesized user interface features.

Scenario	Momentary Demand	Feature
Tool and Hardware	I want to verify I have all items stowed and accounted for	Logged list of tools and instruments Logging capability for collected samples
Tool and Hardware	I want to know my photo overlap is sufficient to stitch a panorama	Photos application with check-marked requirements
Tool and Hardware	I want to know the current camera settings	Photos application settings displayed (i.e. zoom, perspective, etc.)
Tool and Hardware	I want to know the recommended camera settings	Photos application settings reset option
Tool and Hardware	I want to know what my helmet camera sees	Live camera feed
Tool and Hardware	I want to know if IV and MCC can see what I see via my helmet camera	Comm
Tool and Hardware	I want to know the smallest resolvable scale captured by my helmet camera	Live scale on camera feed with indication of approaching limitation
Tool and Hardware	I want to view my EV partner's helmet camera feed	Partner live camera feed
Tool and Hardware	I want to know I captured a photo	Photos application easily accessible Pop-up of most recently taken photo
Tool and Hardware	I want to see my handheld camera imagery	Photos application easily accessible Pop-up of most recently taken photo
Tool and Hardware	I want to zoom in on an image to see the smallest scale features	Photos application settings displayed (i.e. zoom, perspective, etc.)
Tool and Hardware	I want to compare a previously taken handheld photograph with my current image	Photos application easily accessible Pop-up of most recently taken photo
Tool and Hardware	I want to know the state of my suit telemetry as it relates to expected ranges and limits, and knowing how close the value is to a lower or upper limit, or when it is within expected ranges	Suit telemetry in graphical format Marked limits
Tool and Hardware	I want to know the estimated time remaining for EVA based on all relevant suit consumables	Pre-calculated estimated time remaining
Tool and Hardware	I want to view the trend data in a plot format for relevant suit consumables. I'd like to see the slope and how it relates to time left in the EVA.	Suit telemetry in graphical format Marked limits
Tool and Hardware	I want to see a visual cue of an alert	Pop-ups or notification markings
Tool and Hardware	I want to know exactly what procedures are needed for the current task at hand.	Up-to-date procedures
Tool and Hardware	I want to receive caution or warning notifications related to sensitive/hazardous environments/equipment that could be inadvertently disturbed while completing the current task	Pop-ups or notification markings
Tool and Hardware	I want to know how many tasks will be completed before changing/altering the equipment configuration	Up-to-date procedures
Tool and Hardware	I want to know how to get to the correct location to perform operations	Current location Current heading Next location
Tool and Hardware	I want to know what the bolt/equipment/hardware looks like (visual aid)	Visual aids in procedures
Tool and Hardware	I want to know the range or characteristics of acceptable "success criteria" for each specific task	Clear goals
Tool and Hardware	I want to know the required equipment configuration (socket, TM, etc.)	Equipment configuration
Tool and Hardware	I want to receive prompts for specific information that must be delivered to remote operators	Pop-ups or notification markings
Tool and Hardware	I want to know exact device setting(s), if applicable	Up-to-date procedures
Tool and Hardware	I want to see that a step was completed successfully	Up-to-date procedures
Tool and Hardware	I want to maintain situation awareness of current and completed procedure steps	Up-to-date procedures
Tool and Hardware	I want to see that a step was not completed successfully, that an anomaly occurred	Pop-ups or notification markings
Tool and Hardware	I want to notify remote operators of unsuccessful operations and receive strategies on how the issues may be fixed	Pop-ups or notification markings
Tool and Hardware	I want to know what to do if I encounter an anomaly	Up-to-date procedures
Tool and Hardware	I want to know what a fault indication means	Reference page
Tool and Hardware	I want to receive notifications related to known tool or equipment design flaws that could impact successful operations	Pop-ups or notification markings
Tool and Hardware	I want to have access to training procedures if I need a memory aid	Reference page
Tool and Hardware	I want to have content updated dynamically	Display changeability

Figure 6.17: Description of momentary demands relevant to tools and hardware scenarios and the corresponding display features appropriate to address each momentary demand

6.2.1 I want to verify I have all items stowed and accounted for

Figure 6.18 depicts how the Joint AR solution can be utilized to take an inventory of tool cart items.

Figure 6.18: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to verify I have all items stowed and accounted for"

6.2.2 I want to know my photo overlap is sufficient to stitch a panorama

Figure 6.19 depicts how the Joint AR solution can inform an EVA crew member that there is sufficient overlap between photos to stitch together a panorama. This can be seen at (1) which is the boundary between the two images.

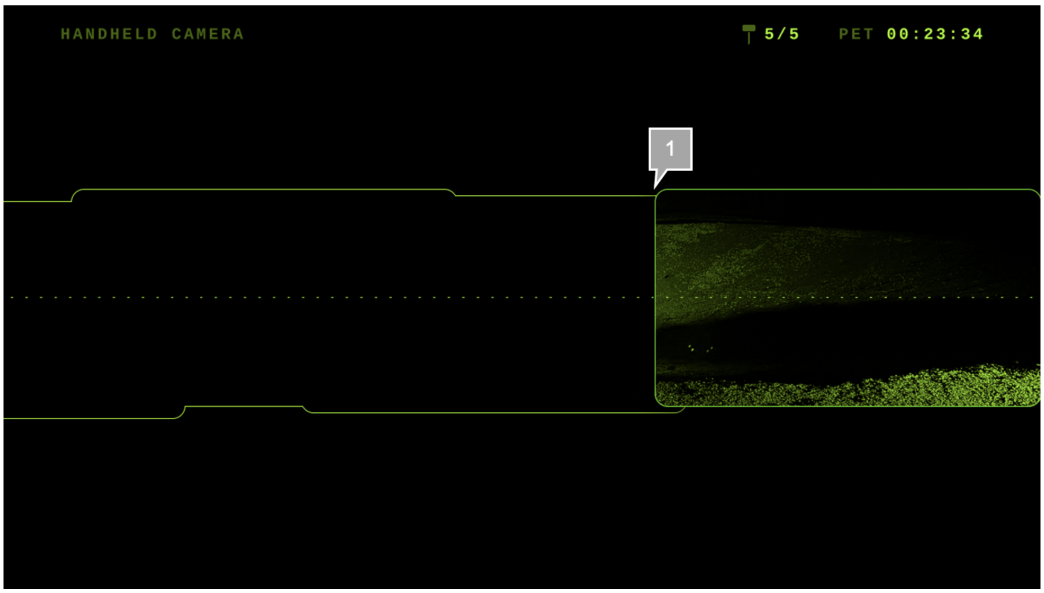

Figure 6.19: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know my photo overlap is sufficient to stitch a panorama"

6.2.3 I want to know the current camera settings

Figure 6.20 depicts how the Joint AR solution can inform users of their camera settings. This can be seen at (1) which depicts key camera settings in an easily readable table.

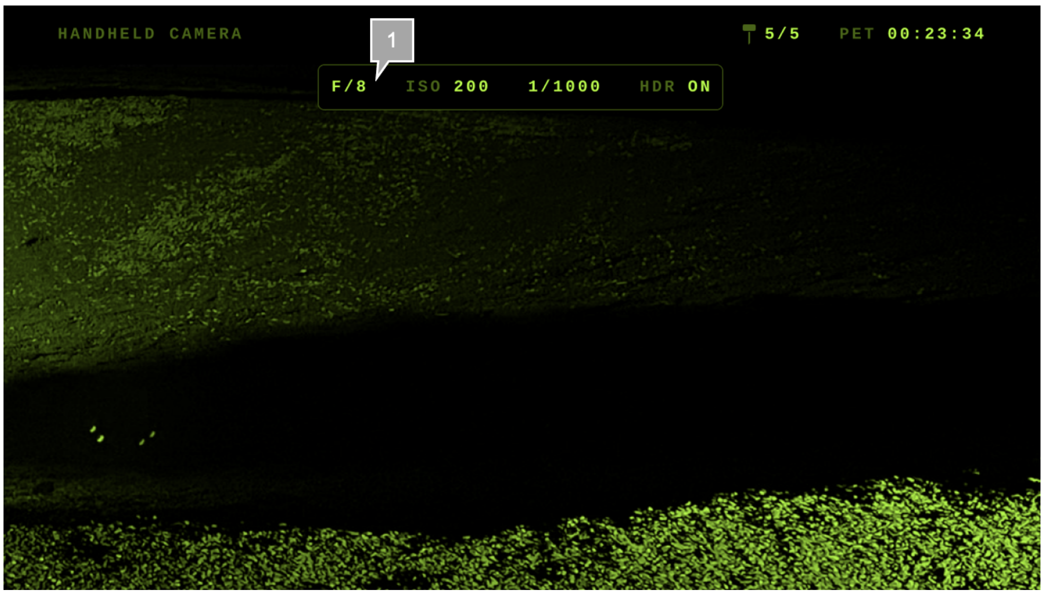

Figure 6.20: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know the current camera settings"

6.2.4 I want to know the recommended camera settings

Figure 6.21 depicts a concept for how the Joint AR solution could recommend camera settings for a given situation. This can be seen in the object depicted at (1) which shows the recommended ISO for a the given condition.

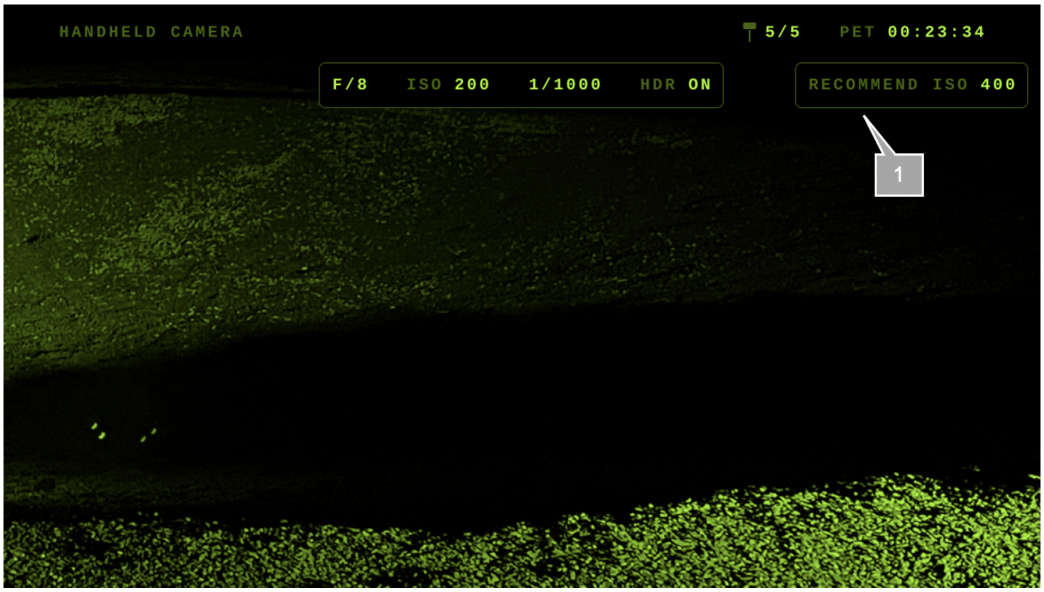

Figure 6.21: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know the recommended camera settings"

6.2.5 I want to know what my helmet camera sees

Figure 6.22 depicts how the Joint AR display could interface with the helmet mounted camera. While on an EVA, the EV may want to view their helmet mounted camera view and the Joint AR display can bring up the camera view.

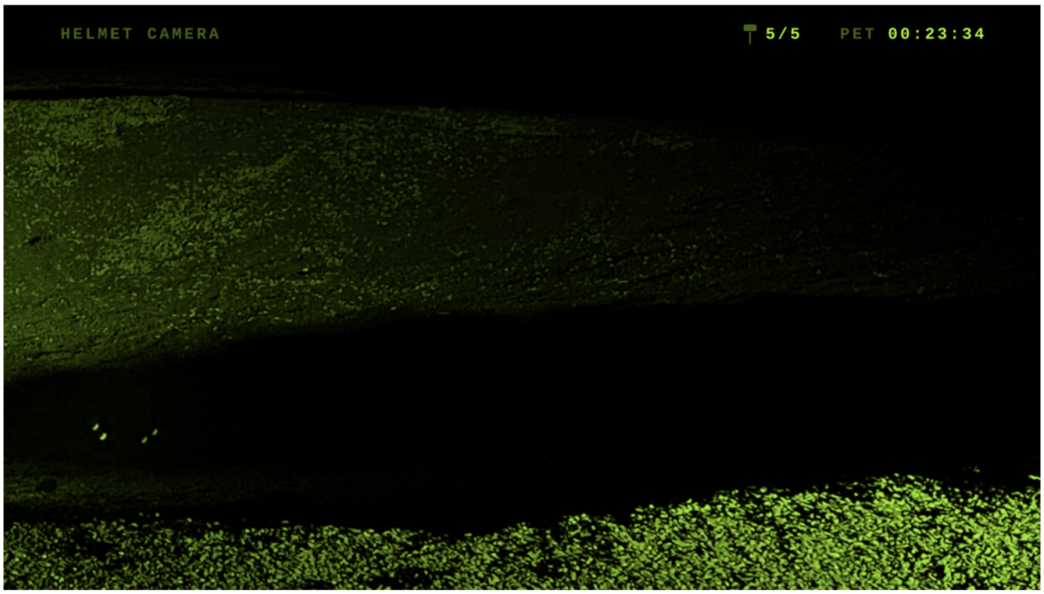

Figure 6.22: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know what my helmet camera sees"

6.2.6 I want to know if IV and MCC can see what I see via my helmet camera

Figure 6.23 depicts the status of whether other EVs, the IV, or MCC can view the feed from the helmet mounted camera (1). It is likely that IV's and MCC back in Houston would want to be able to view what the EVs see from their helmet camera. Viewing the feed would provide MCC and the IV awareness as to where the EV is and what they are seeing. This feature would provide the EV with awareness as to who is viewing their camera feed.

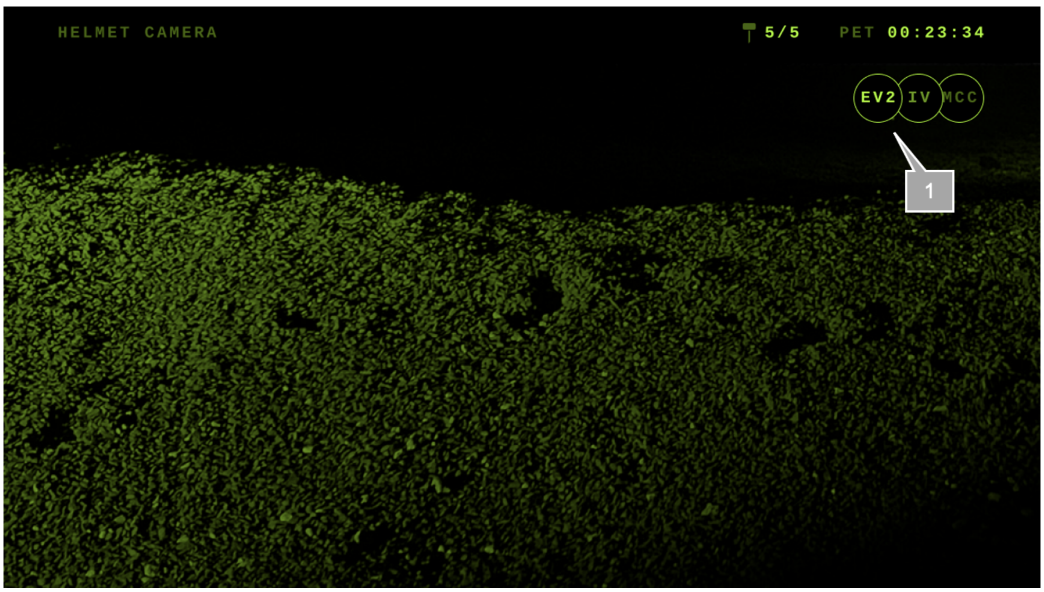

Figure 6.23: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know if IV and MCC can see what I see via my helmet camera"

6.2.7 I want to know the smallest resolvable scale captured by my helmet camera

Figure 6.24 depicts how the Joint AR display can provide insight into the smallest resolvable scale capture by the helmet camera (1).

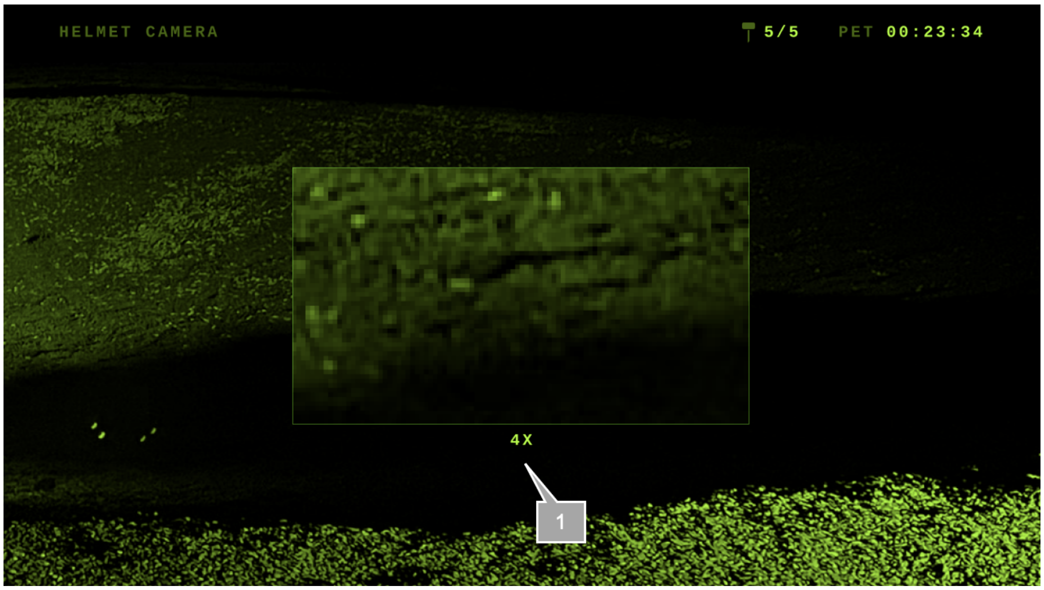

Figure 6.24: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know the smallest resolvable scale captured by my helmet camera"

6.2.8 I want to view my EV partner's helmet camera feed

Figure 6.25 depicts how the Joint AR solution could allow an EV to view from their EV partner's helmet camera feed. (1) depicts a label informing the EV that they are viewing their partner's helmet camera feed and not their own.

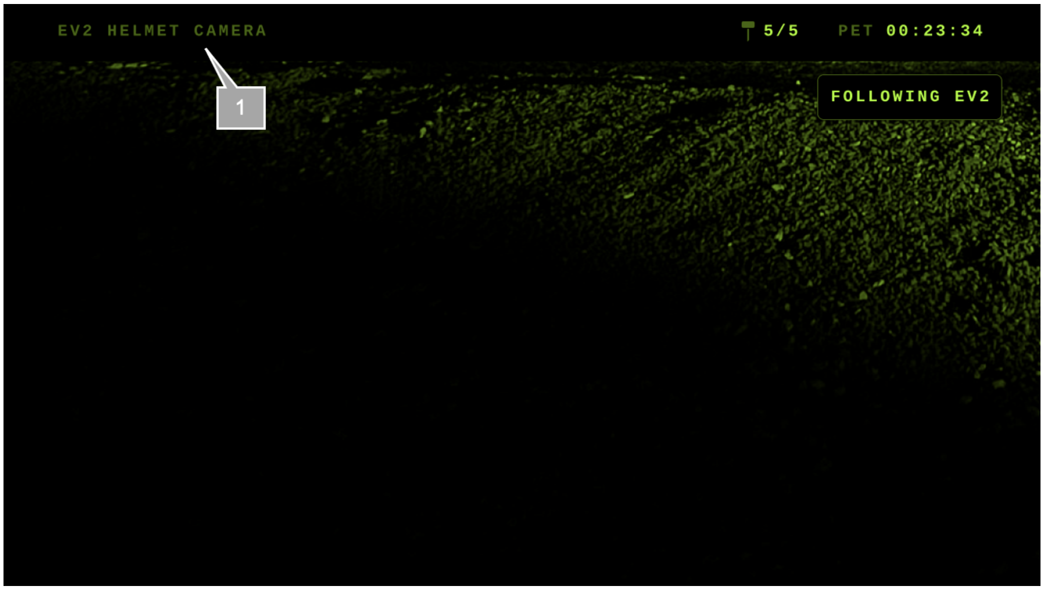

Figure 6.25: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to view my EV partner's helmet camera feed"

6.2.9 I want to know I captured a photo

Figure 6.26 depicts how the Joint AR solution could inform users that a photo was taken. (1) shows the pop up of an image after it was captured.

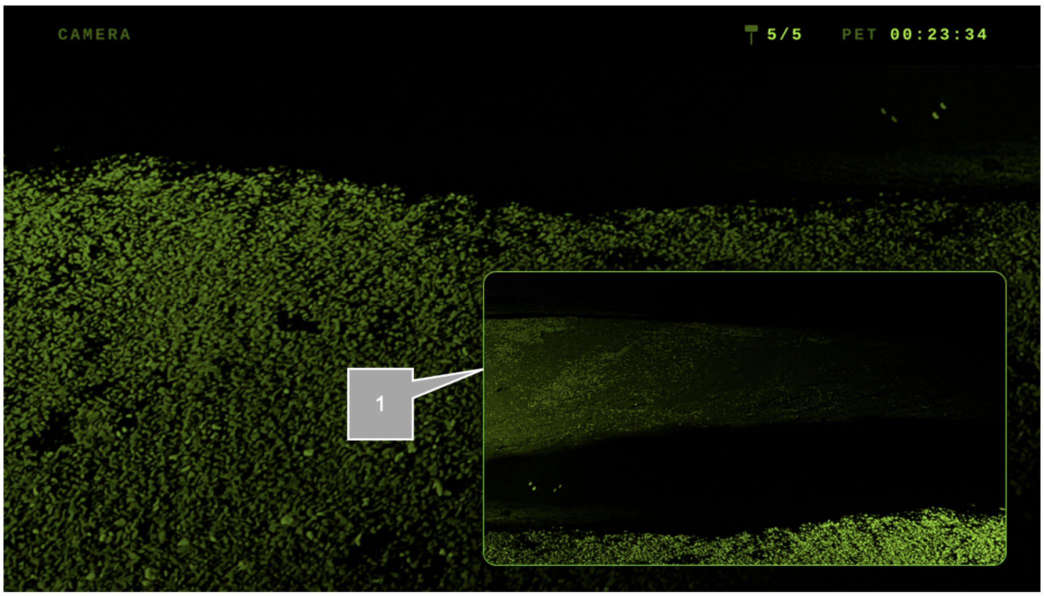

Figure 6.26: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know I captured a photo"

6.2.10 I want to see my handheld camera imagery

Figure 6.27 depicts how the Joint AR solution could allow for users to view their handheld camera imagery. (1) depicts a photo gallery from the handheld camera.

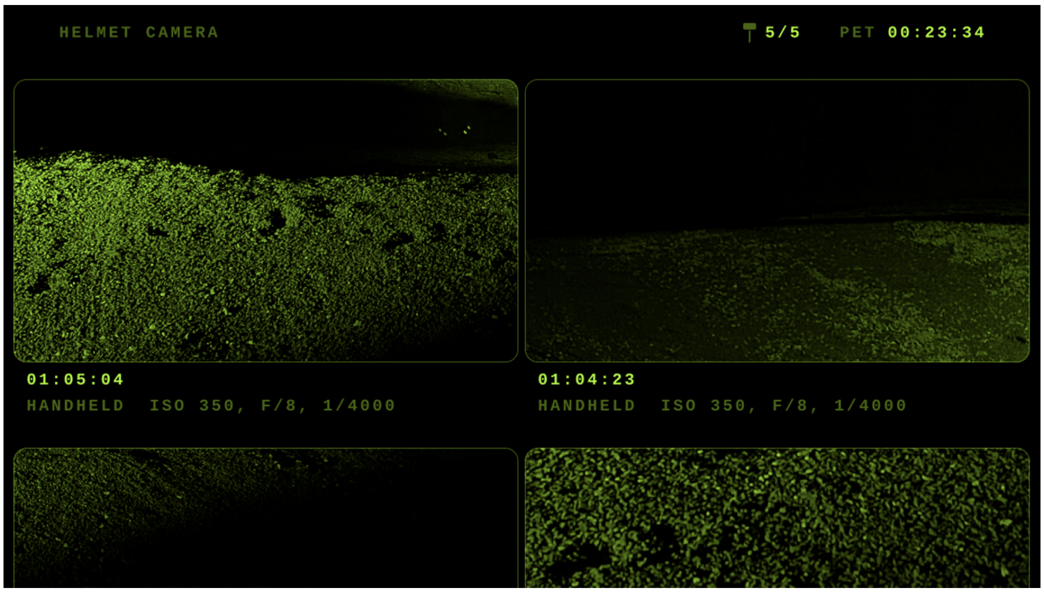

Figure 6.27: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to see my handheld camera imagery"

6.2.11 I want to zoom in on an image to see the smallest scale features

Figure 6.28 depicts how the Joint AR solution can allow users to zoom in onto an area of interest. (1) depicts the zoom button.

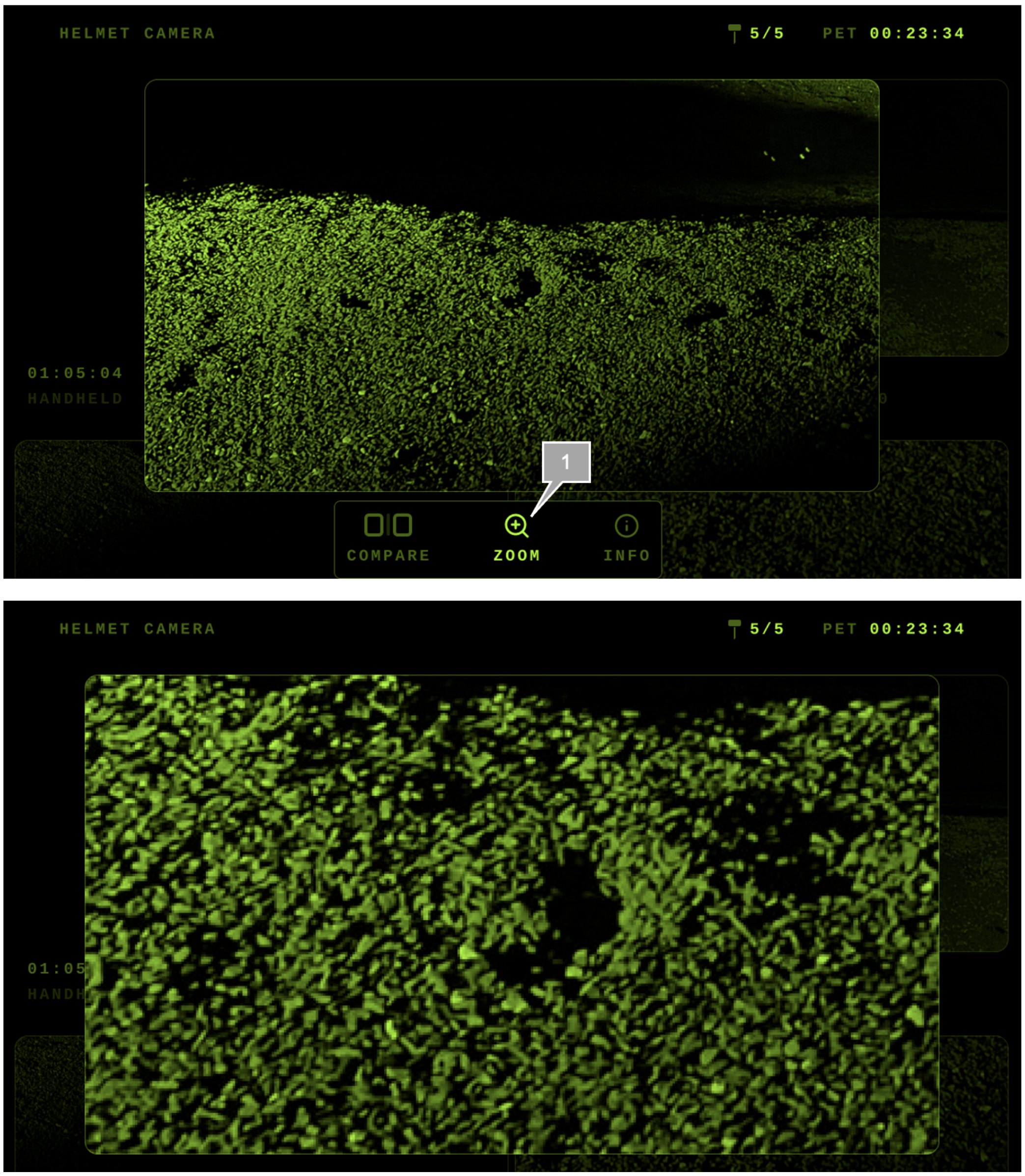

Figure 6.28: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to zoom in on an image to see the smallest scale features"

6.2.12 I want to compare a previously taken handheld photograph with my current image

Figure 6.29 depicts how the Joint AR system can provide the ability to compare a previously taken photo with the current image view. (1) refers to the current helmet camera feed, while (2) refers to a recently taken photo that was called up.

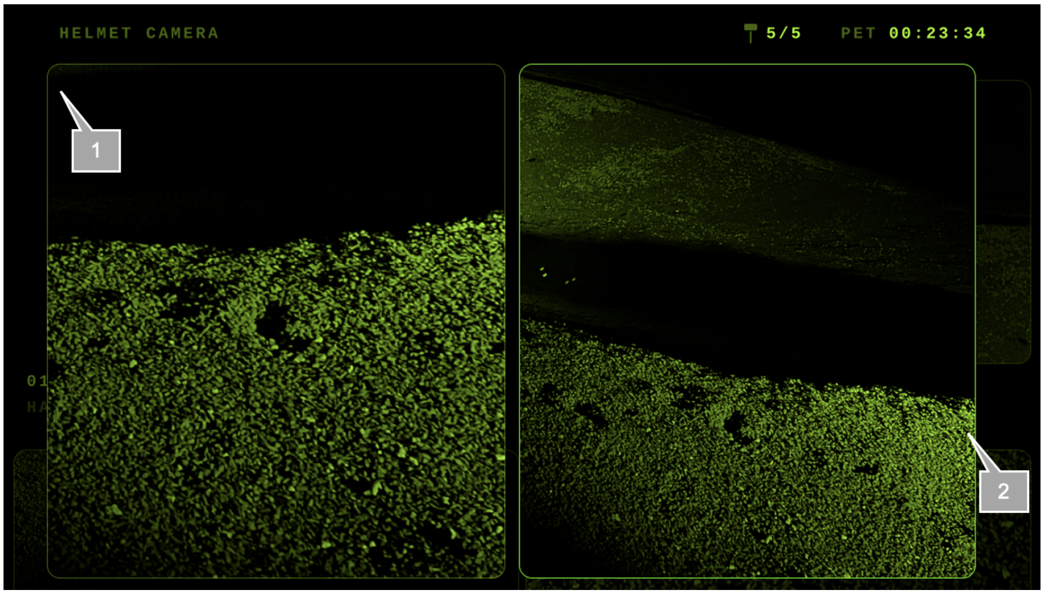

Figure 6.29: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to compare a previously taken handheld photograph with my current image"

6.2.13 I want to know the state of my suit telemetry as it relates to expected ranges and limits, and knowing how close the value is to a lower or upper limit, or when it is within expected ranges

Figure 6.30 depicts a concept how the Joint AR solution can show suit telemetry. (1) depicts graphical forms of telemetry and (2) depicts limits.

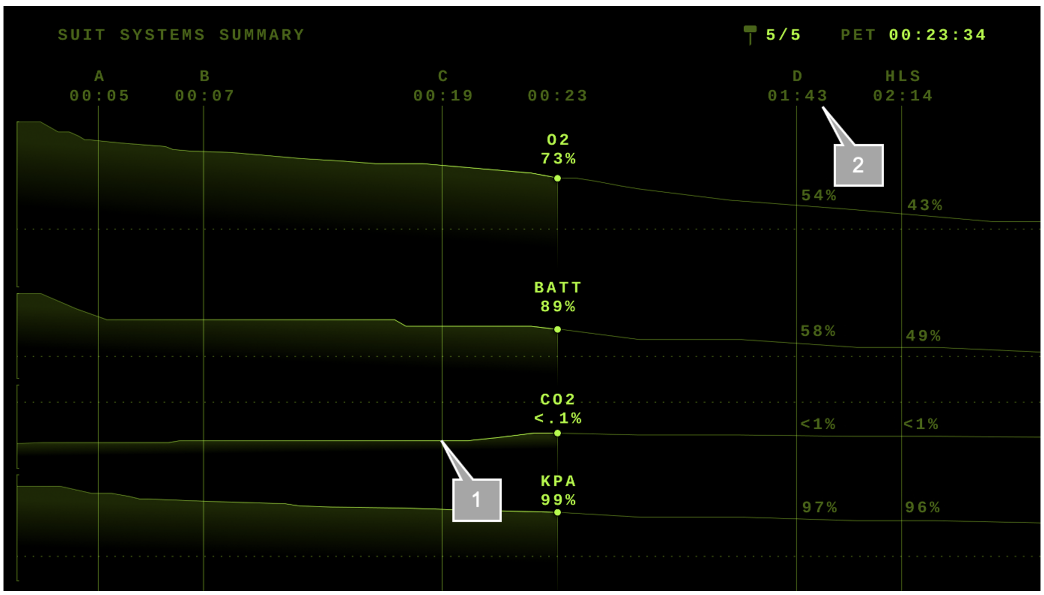

Figure 6.30: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know the state of my suit telemetry as it relates to expected ranges and limits, and knowing how close the value is to a lower or upper limit, or when it is within expected ranges"

6.2.14 I want to view the trend data in a plot format for relevant suit consumables

Figure 6.31 depicts a concept for how the Joint AR solution could provide a trend plot data relevant suit consumable telemetry.

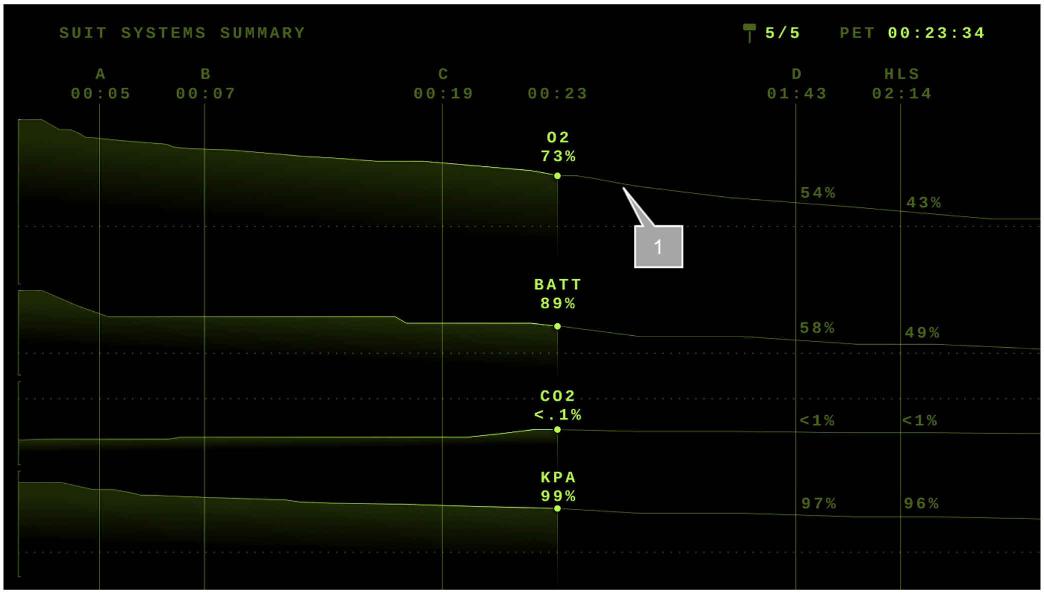

Figure 6.31: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to view the trend data in a plot format for relevant suit consumables"

6.2.15 I want to see a visual cue of an alert

Figure 6.32 depicts a concept for how the Joint AR solution could provide a visual cue for an alert. Area 1 refers to the popup that contains the visual notification.

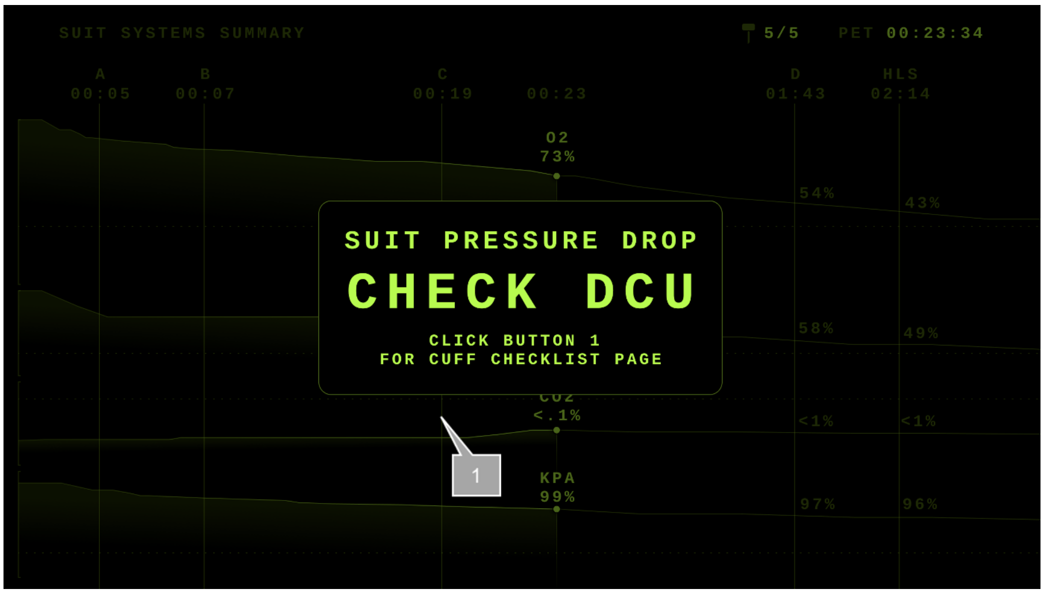

Figure 6.32: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to see a visual cue of an alert"

6.2.16 I want to know exactly what procedures are needed for the current task at hand

Figure 6.33 depicts a concept for how the Joint AR could depict procedures for a given task (Area 1).

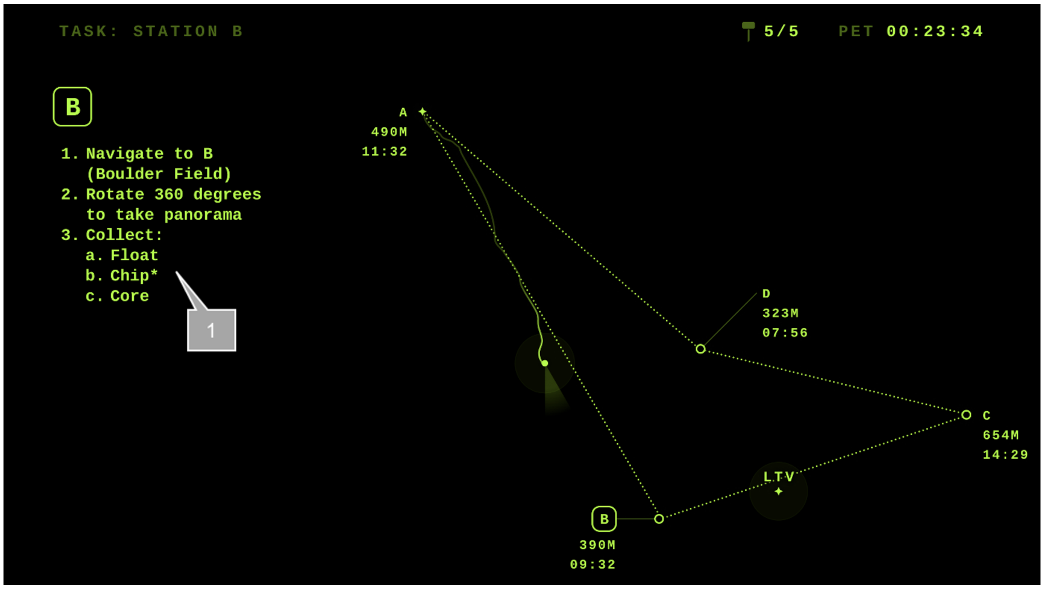

Figure 6.33: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know exactly what procedures are needed for the current task at hand"

6.2.17 I want to receive caution or warning notifications related to sensitive or hazardous environments or equipment that could be inadvertently disturbed while completing the current task

Figure 6.34 depicts in area 1 a concept for how the Joint AR solution could depict caution or warning notifications.

Figure 6.34: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to receive caution or warning notifications related to sensitive or hazardous environments or equipment that could be inadvertently disturbed while completing the current task"

6.2.18 I want to know how many tasks will be completed before changing or altering the equipment configuration

Figure 6.35 depicts (area 1) how the Joint AR solution could depict how procedures could be authored in such a way that they indicate how many tasks will be completed before an equipment or configuration change.

Figure 6.35: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know how many tasks will be completed before changing or altering the equipment configuration"

6.2.19 I want to know how to get to the correct location to perform operations

Figure 6.36 depicts how the Joint AR solution could provide location (1) and heading (2) information to aid a user in getting to the correct location to perform science operations.

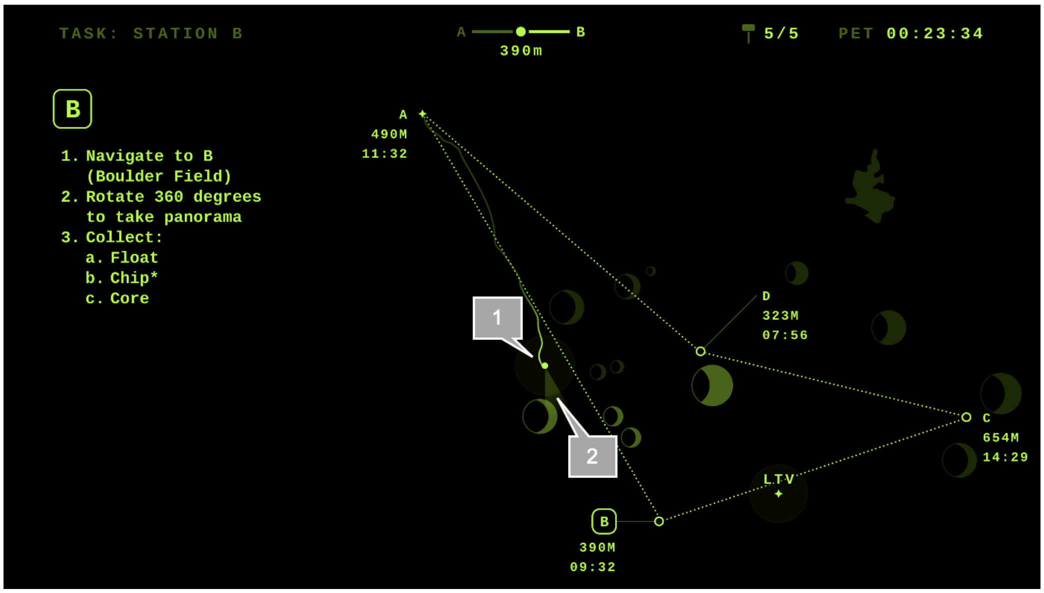

Figure 6.36: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know how to get to the correct location to perform operations"

6.2.20 I want to know what the bolt, equipment, hardware looks like (visual aid)

Figure 6.37 depicts how the Joint AR solution could provide visual aids (1) to assist EV crew members in completing their procedure tasks.

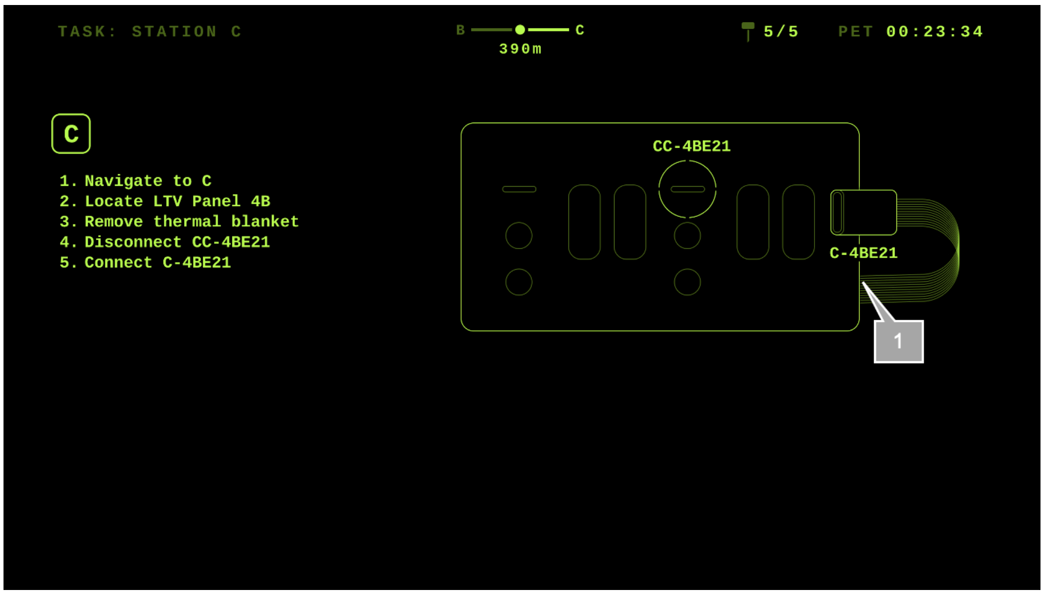

Figure 6.37: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know what the bolt, equipment, hardware looks like (visual aid)"

6.2.21 I want to know the range or characteristics of acceptable success criteria for each specific task

Figure 6.38 depicts how the Joint AR solution could be utilized to provide acceptable success criteria for specific tasks.

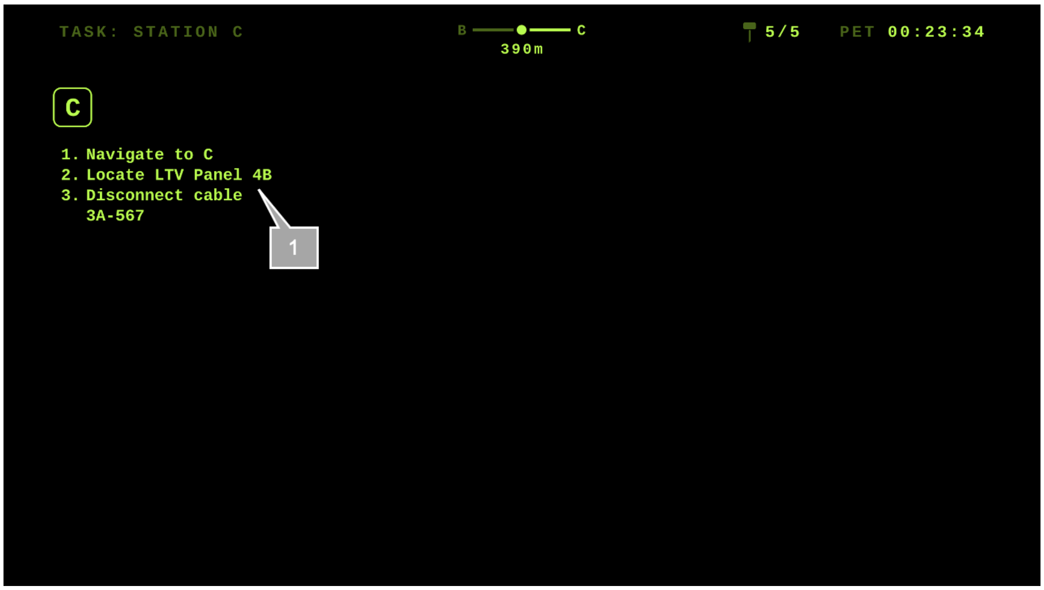

Figure 6.38: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know the range or characteristics of acceptable success criteria for each specific task"

6.2.22 I want to know the required equipment configuration

Figure 6.39 depicts how the Joint AR display could be used to depict the required equipment configuration for the specified task. Area one depicts the exact specifications for the socket provides a graphic for how to install the socket to the tool.

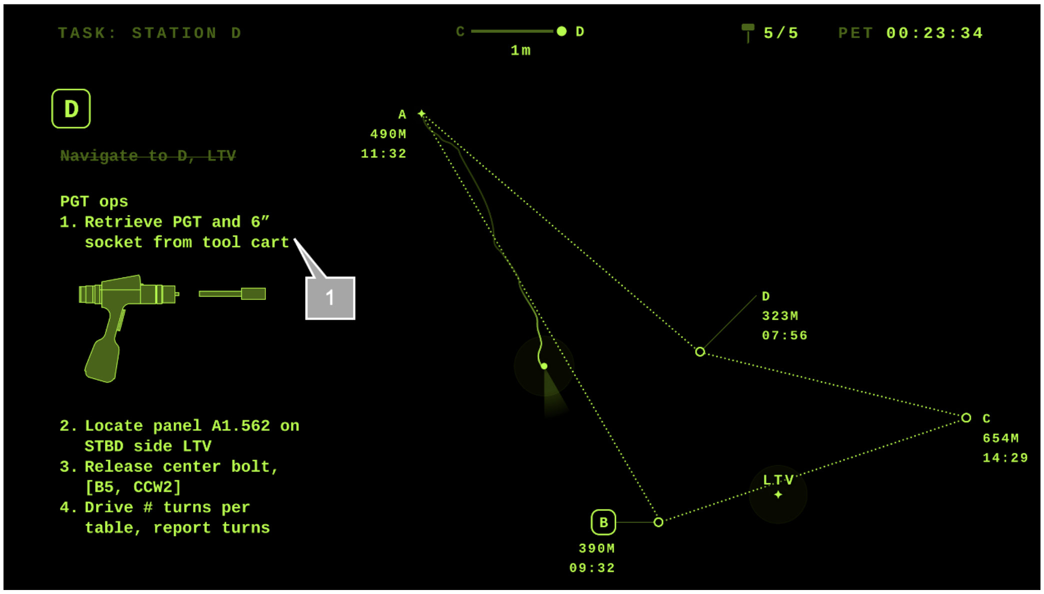

Figure 6.39: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know the required equipment configuration"

6.2.23 I want to receive prompts for specific information that must be delivered to remote operators

Figure 6.40 depicts a concept for how the Joint AR solution could prompt users to provide specific information and reports to MCC.

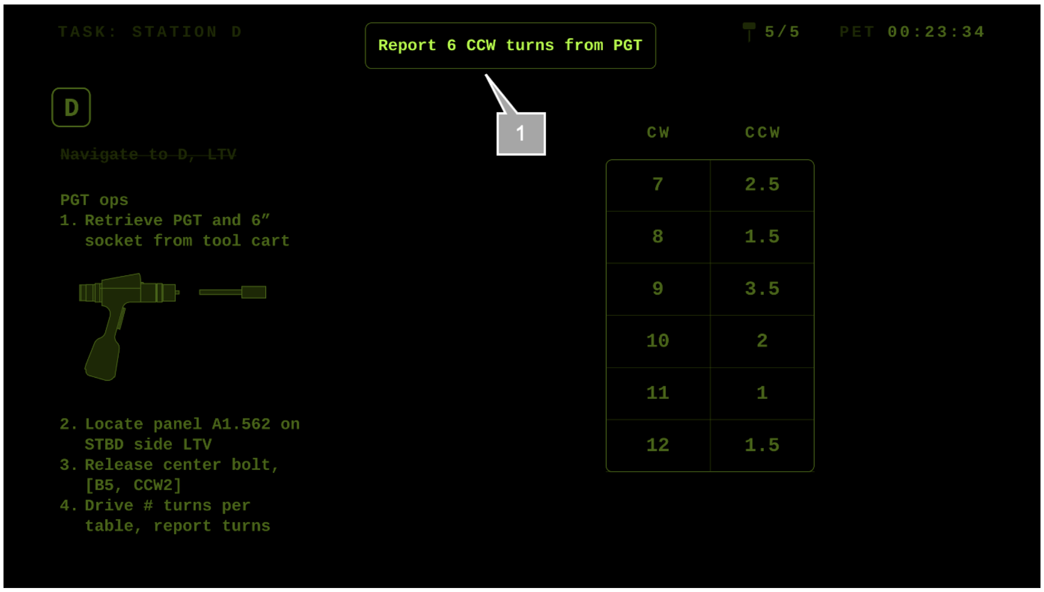

Figure 6.40: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to receive prompts for specific information that must be delivered to remote operators"

6.2.24 I want to know exact device setting(s), if applicable

Figure 6.41 depicts how the Joint AR solution could be used to communicate exact device settings to the crew. A table of settings is provided to the crew (Area 1).

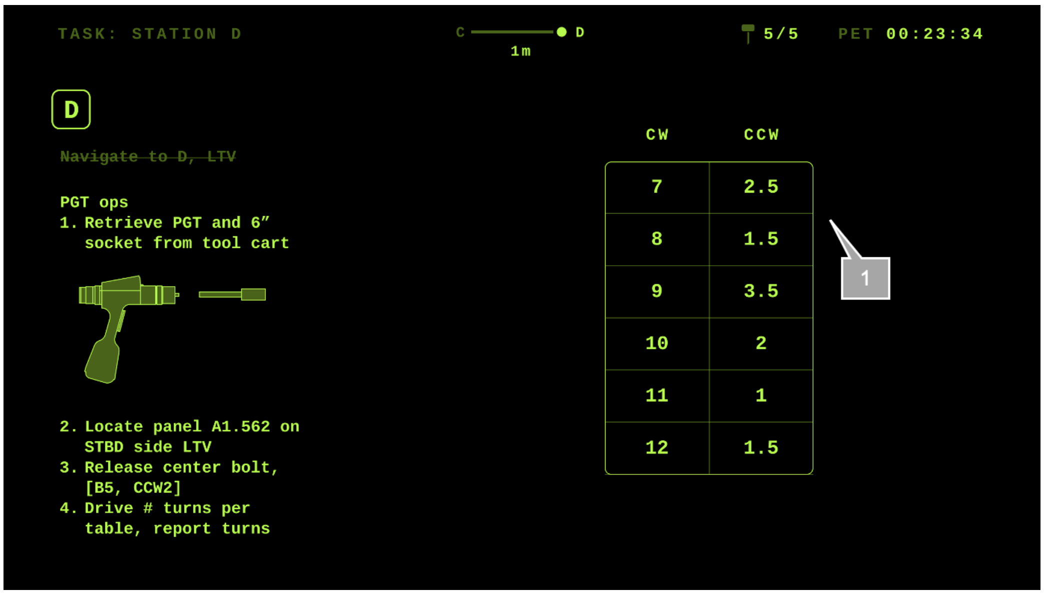

Figure 6.41: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know exact device setting(s), if applicable"

6.2.25 I want to see that a step was completed successfully

Figure 6.42 depicts how the Joint AR solution could depict successful completion of a task. In this concept, the check box is checked off and the text goes dark (1).

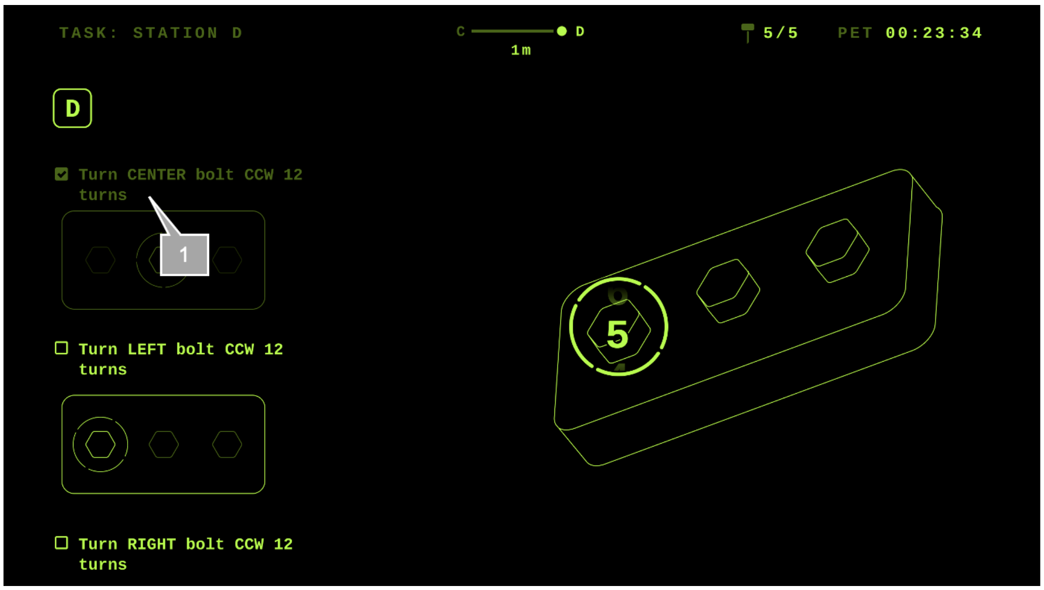

Figure 6.42: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to see that a step was completed successfully"

6.2.26 I want to maintain situation awareness of current and completed procedure steps

Figure 6.43 depicts how the Joint AR solution could be used to maintain situation awareness of what step an EV is on. The current step is depicted in bright green, while previous steps are in dark green. The previous step is not immediately decluttered upon completion.

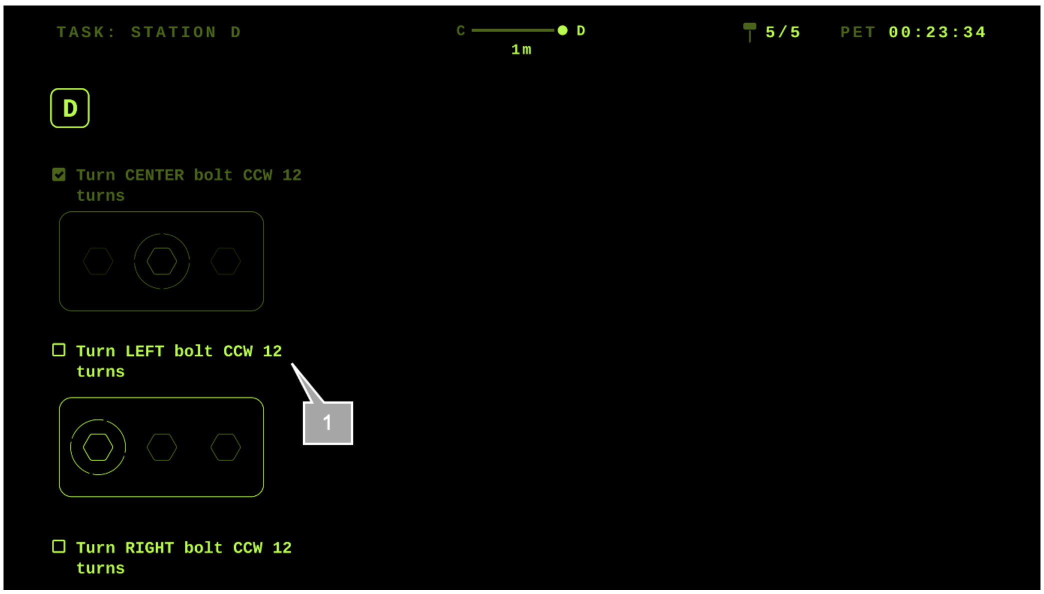

Figure 6.43: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to maintain situation awareness of current and completed procedure steps"

6.2.27 I want to see that a step was not completed successfully, that an anomaly occurred

Figure 6.44 depicts how the Joint AR solution could communicate to an EV crew that an anomaly occurred. The procedure step informs the crew of the anomaly and informs them of the steps to take to correct it in order to ensure task completion (1).

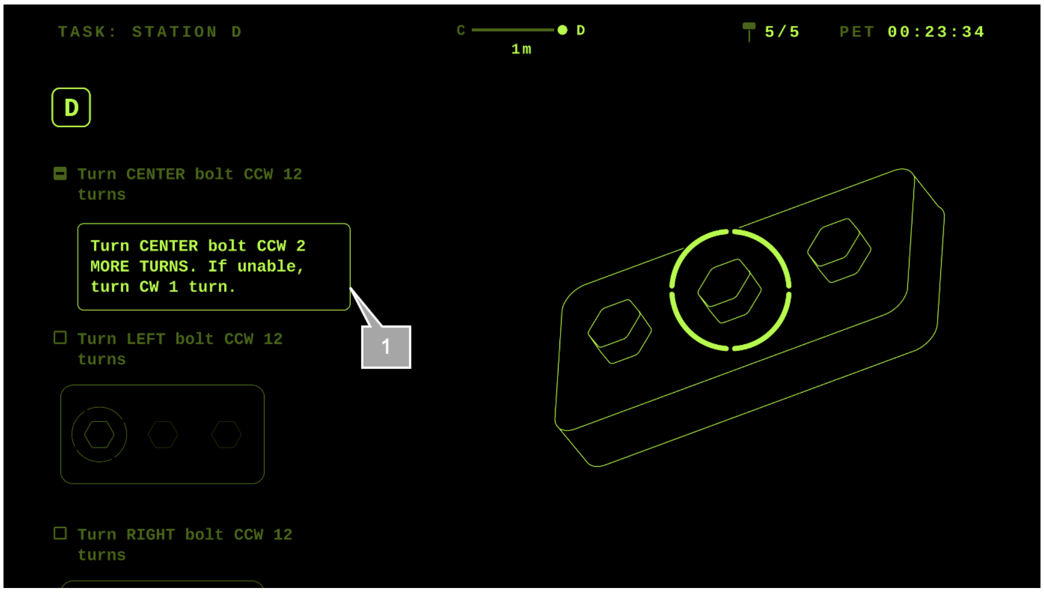

Figure 6.44: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to see that a step was not completed successfully, that an anomaly occurred"

6.2.28 I want to notify remote operators of unsuccessful operations and receive strategies on how the issues may be fixed

Figure 6.45 depicts how the Joint AR solution could communicate to an EV crew that an anomaly occurred. The procedure step informs the crew of the anomaly and informs them of the steps to take to correct it in order to ensure task completion (1). More work should be performed to understand how to receive a broader set of response strategies.

Figure 6.45: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to notify remote operators of unsuccessful operations and receive strategies on how the issues may be fixed"

6.2.29 I want to know what to do if I encounter an anomaly

Figure 6.46 depicts how the Joint AR solution could be used to convey anomaly information. In this concept, the procedure informs the crew that an anomaly has occurred and provides specific actions to resolve it (1).

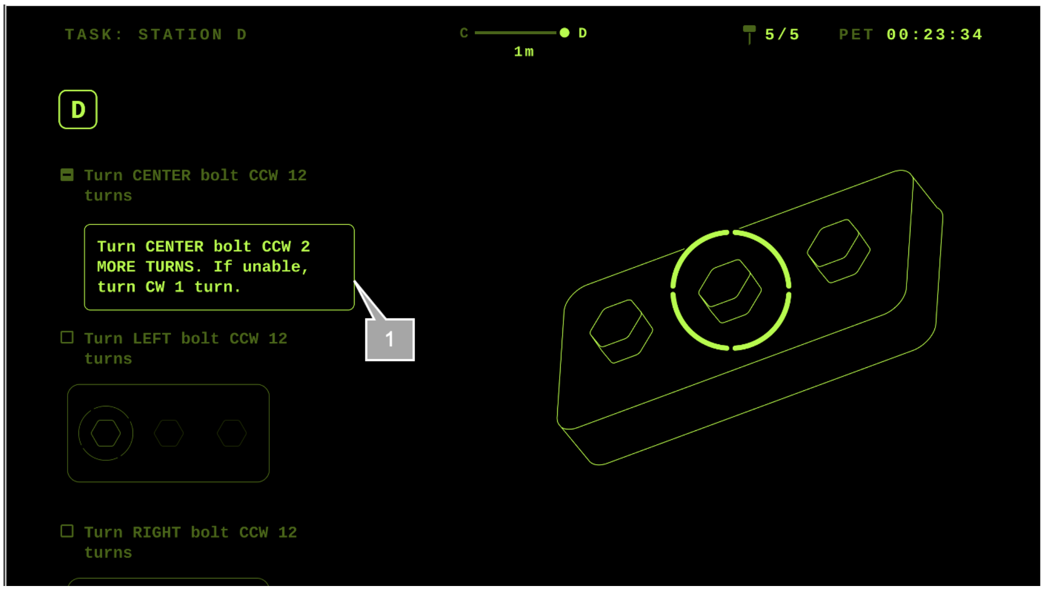

Figure 6.46: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know what to do if I encounter an anomaly"

6.2.30 I want to know what a fault indication means

Figure 6.47 depicts how the Joint AR solution could provide insight into the meaning of specific fault indications. In this concept, not only is the numerical fault indication given but a plain text description is also provided (1). In this example, not only does the crew know that spectrometer error 1202 is occurring but they also know what that means and what is being done to resolve it.

Figure 6.47: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know what a fault indication means"

6.2.31 I want to receive notifications related to known tool or equipment design flaws that could impact successful operations

Figure 6.48 depicts how the Joint AR solution could provide notification related to tool issues that could impact successful operations. In this concept, there is a notification that provides instructions as to what to do if the problem persists after taking the recommended actions (1).

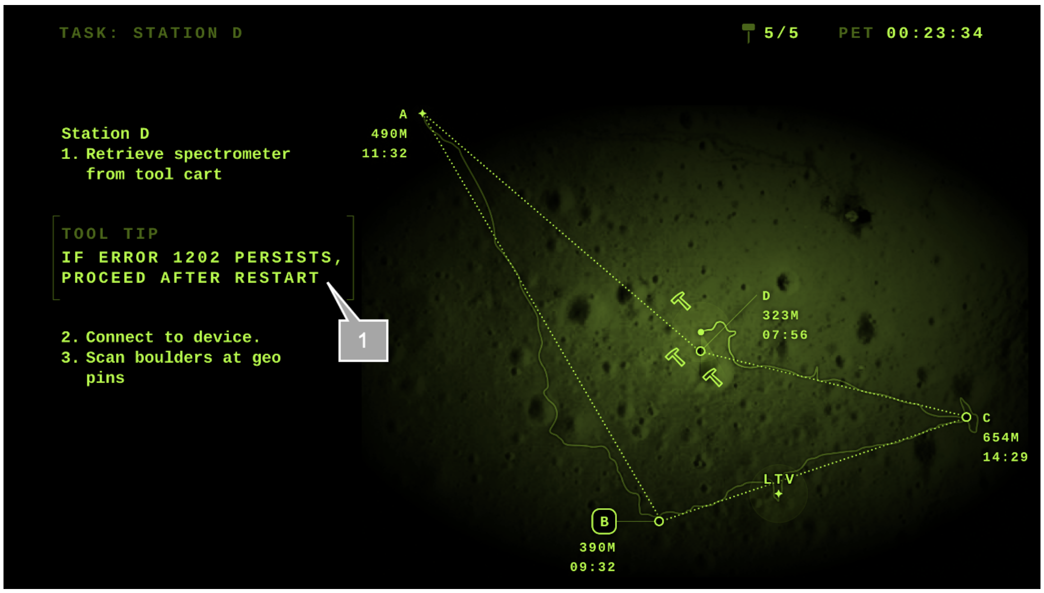

Figure 6.48: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to receive notifications related to known tool or equipment design flaws that could impact successful operations"

6.2.32 I want to have access to training procedures if I need a memory aid

Figure 6.49 depicts how the Joint AR solution could provide access to training procedures for use as a memory aid. During an EVA task, crew could possibly desire a memory aid to assist them during their tasks. In this concept, the step by step training procedure is depicted to give jog crews' memory (1).

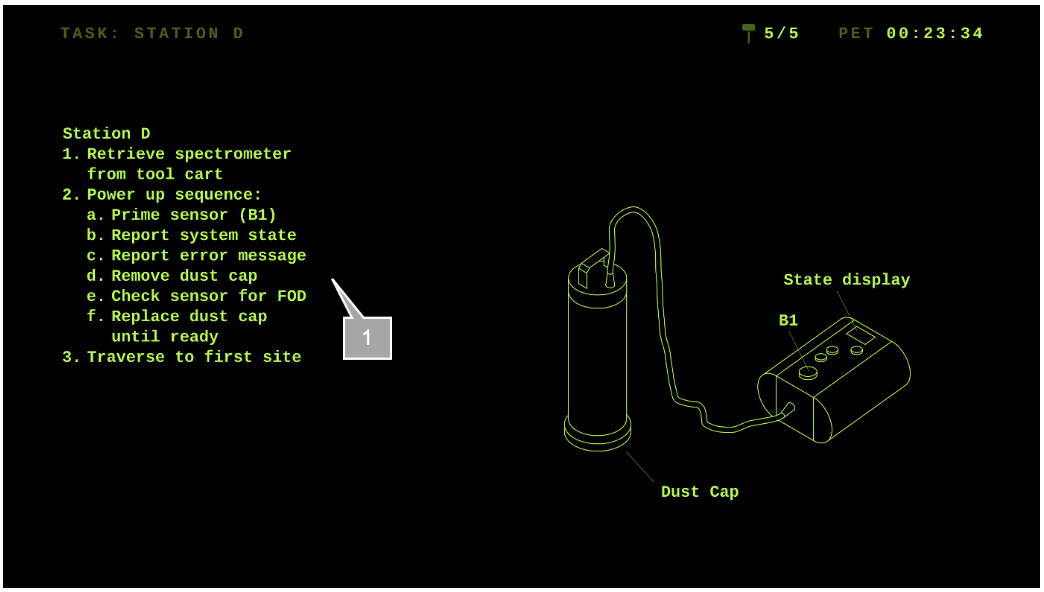

Figure 6.49: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to have access to training procedures if I need a memory aid"

6.2.33 I want to have content updated dynamically

Figure 6.50 depicts how the Joint AR solution could display dynamically updating information. In this concept, a station was updated and the distance/time to it changed so the Joint AR system provided insight into that with the trash can icon and the strike through of the data (1).

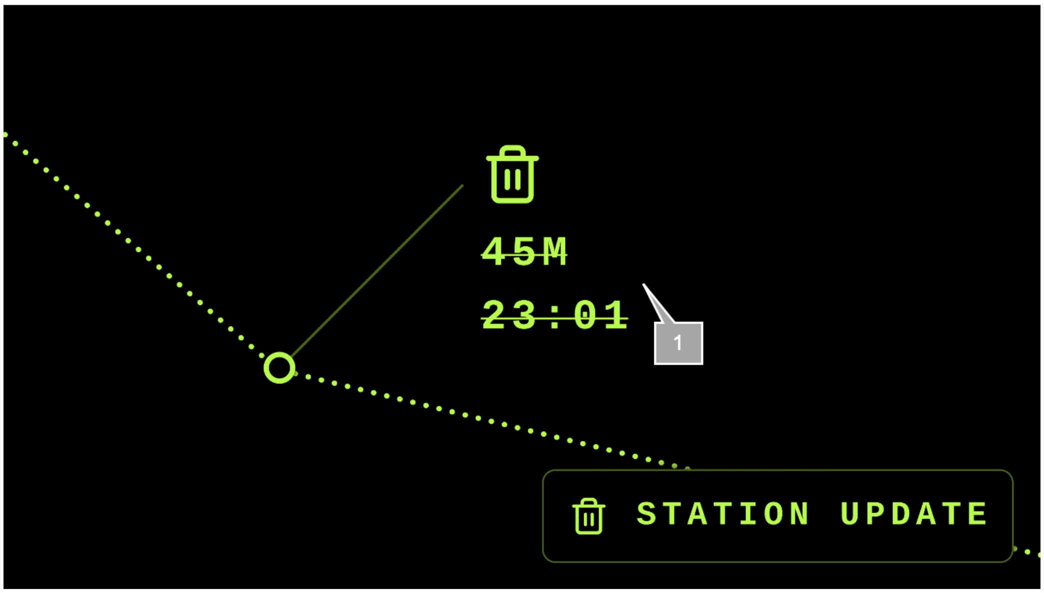

Figure 6.50: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to have content updated dynamically"

6.3 Science Exploration Support Solutions

In total, Section 5.3 identified 15 science related momentary demands. These aggregated demands are shown in Figure 6.51. Additionally, a feature set was created to link each momentary demand with supporting display elements. The remainder of this section provides user interface concepts that align each momentary demand with hypothesized user interface features.

Scenario	Momentary Demand	Feature
Science	I want to know the EVA objectives	Procedure page
Science	I want to know how the EVA objectives relate to features in my surrounding area	Procedure page with referenced features Dynamic map with referenced features
Science	I want to see multiple versions of a map, quickly	Map layers: topography, pins
Science	I want to know what boundaries constrain my movement/traverse and where they are relative to me	Identifiable landmarks Scale
Science	I want to know where targeted science features are located	X' locations Procedure page with target features
Science	I want to know where my marker is for the record (so I can easily find it later)	X' locations Dynamically updating map
Science	I want to know how many markers I have remaining to use	Logged list of tools and instruments Logging capability for collected samples
Science	I want to reference the major features to make sure I don't miss/forget pertinent details	Identifiable landmarks Scale
Science	I want to see the image I just took to ensure it captures what I wanted to capture	Photos application easily accessible Pop-up of most recently taken photo
Science	I want to know the current state of my handheld camera	Configuration Details
Science	I want to know I took the minimum images required for pre-sampling	Procedure page with live count of images taken Photos application
Science	I want to know that I've captured the minimum documentation data required by the mission	Procedure page with specific data capture and live updates, if applicable
Science	I want to advance the content to the 'next phase' to continue with my work	Display controllability
Science	I want to have content updated dynamically	Display changeability
Science	I want to know that I'm referencing the most accurate content.	Display changeability

Figure 6.51: Description of momentary demands relevant to science exploration scenarios and the corresponding display features appropriate to address each momentary demand

6.3.1 I want to know the EVA objectives

Figure 6.52 depicts a concept Joint AR user interface that provides the EVA crew with the EVA objectives. This provides crew with insight into the high level objectives of their EVA.

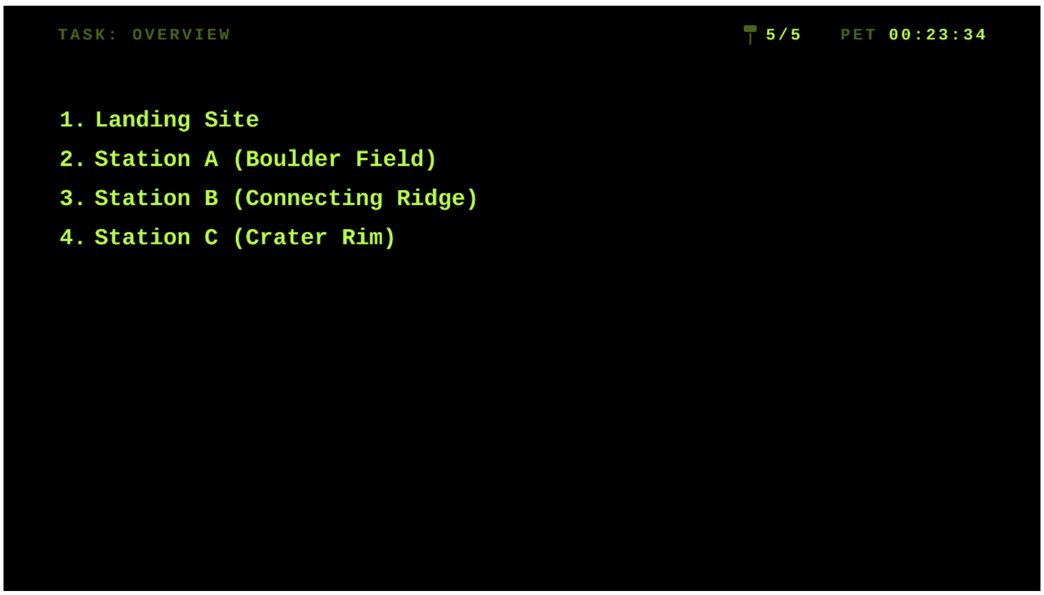

Figure 6.52: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know the EVA objectives"

6.3.2 I want to know how the EVA objectives relate to features in my surrounding area

Figure 6.53 shows how the Joint AR solution provides the EVA crew with insight into how the EVA objectives relate to features in the surrounding area. The concept display provides crew with their procedure (1) and a dynamic map with referenced features (2).

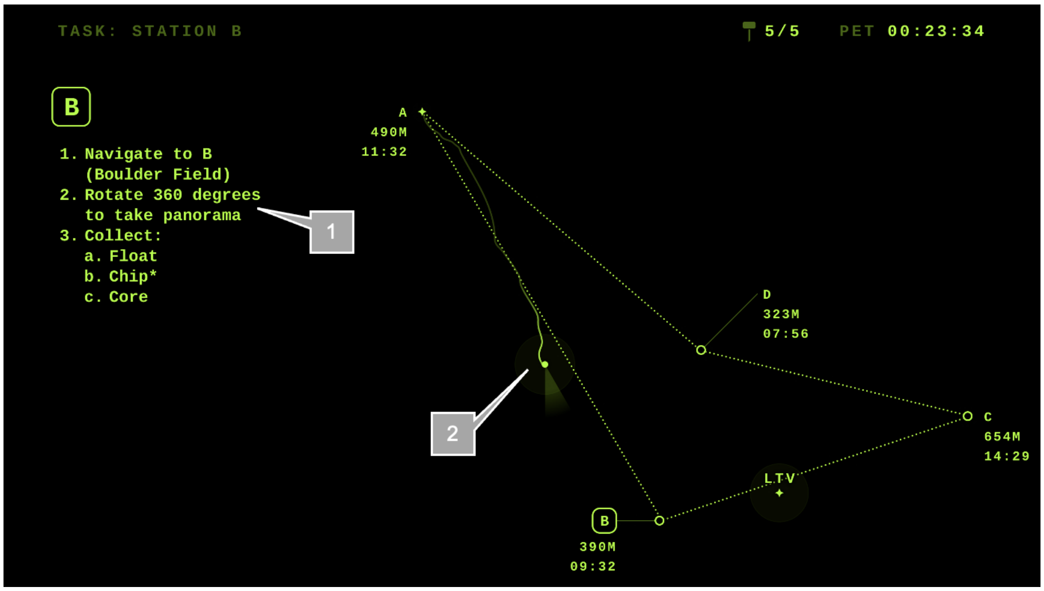

Figure 6.53: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know how the EVA objectives relate to features in my surrounding area"

6.3.3 I want to see multiple versions of a map

Figure 6.54 shows how the Joint AR solution can quickly facilitate the viewing of multiple versions of a map. In this concept image, the EV can choose to include features including terrain, pins, the user heading. This is executed by changing map layers (1), topography (2), and dropping pins from the pin menu (3).

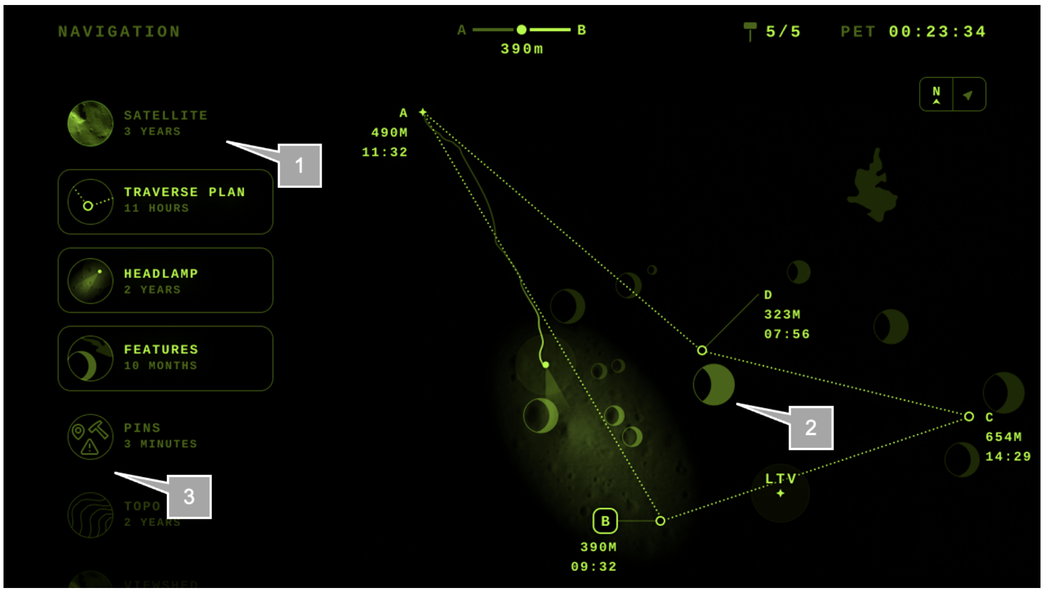

Figure 6.54: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to see multiple versions of a map"

6.3.4 I want to know what boundaries constrain my movement/traverse and where they are relative to me

Figure 6.55 shows how the Joint AR solution can depict boundaries for the traverse (1). The shaded region shows the extent of where the crew should be in relation to their planned destinations.

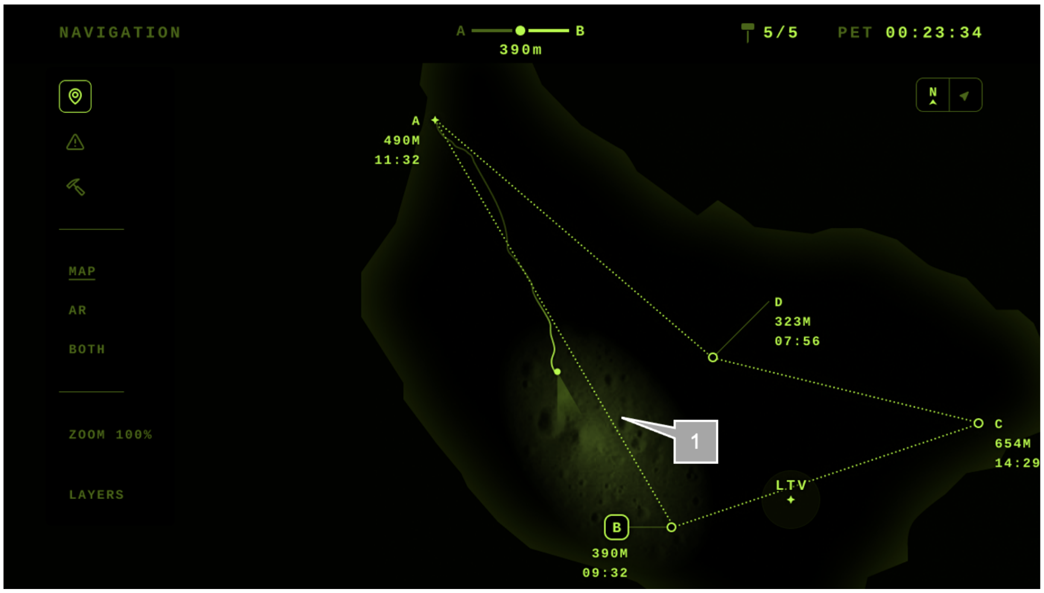

Figure 6.55: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know what boundaries constrain my movement/traverse and where they are relative to me"

6.3.5 I want to know where targeted science features are located

Figure 6.56 depicts how the Joint AR solution can be used to depict targeted science features. In this concept, targeted science features are called out using a custom pin icon shaped like a rock hammer (1).

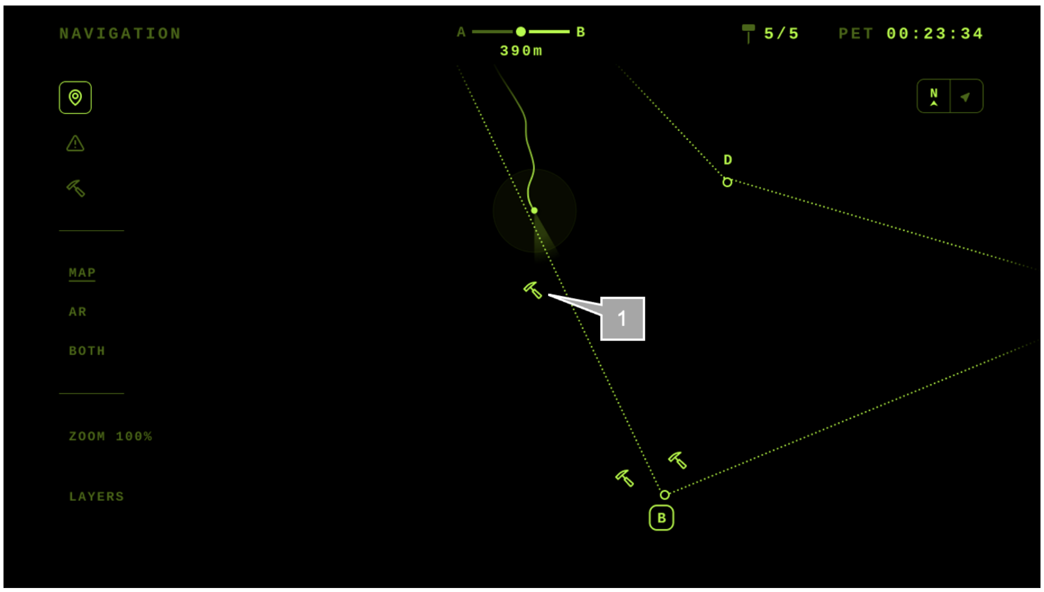

Figure 6.56: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know where targeted science features are located"

6.3.6 I want to know where my marker is for the record so I can easily find it later

Figure 6.57 depicts how the Joint AR solution makes it easy to relocate a dropped marker at a region of interest. In this concept, the dropped region of interest is depicted by the location icon (1).

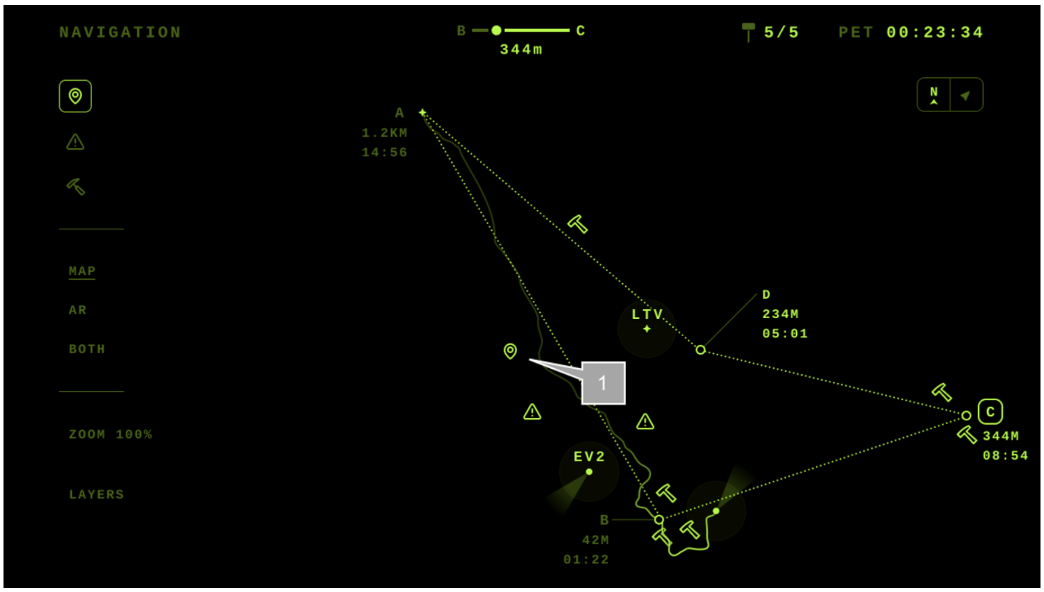

Figure 6.57: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know where my marker is for the record so I can easily find it later"

6.3.7 I want to know how many markers I have remaining to use

The user interface in Figure 6.58 depicts how many sample markers are remaining. The user can see the number remaining in the page header, as well as in the sample marker deployment step in their procedure (1).

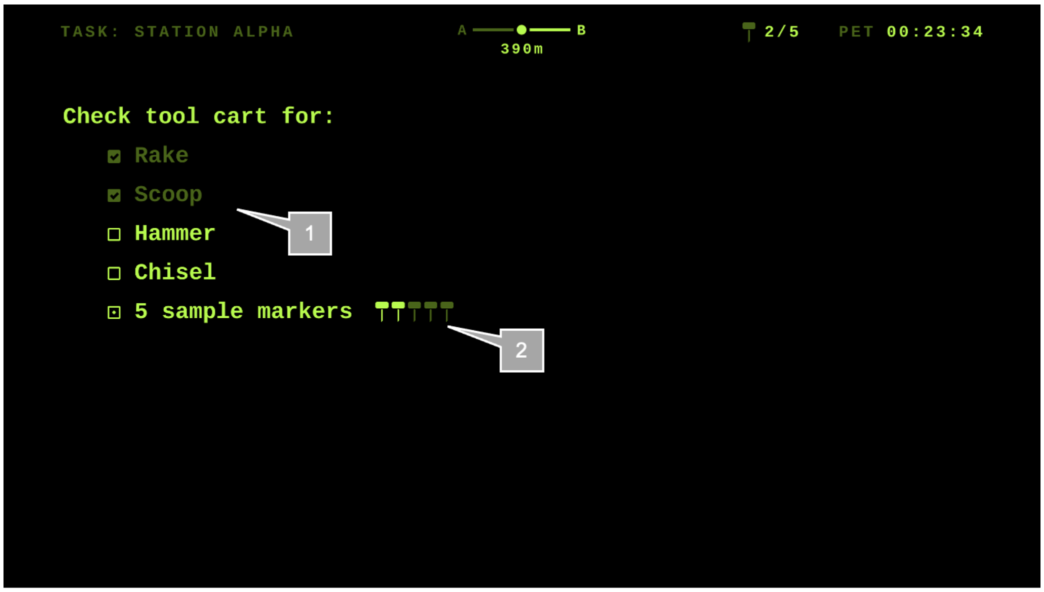

Figure 6.58: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know how many markers I have remaining to use"

6.3.8 I want to reference the major features to make sure I don't miss or forget pertinent details

Figure 6.59 depicts how the Joint AR solution could facilitate the ability to reference major features and landmarks so the crew does not forget pertinent details. The major terrain features, such as craters, are depicted on the map pictorially (1).

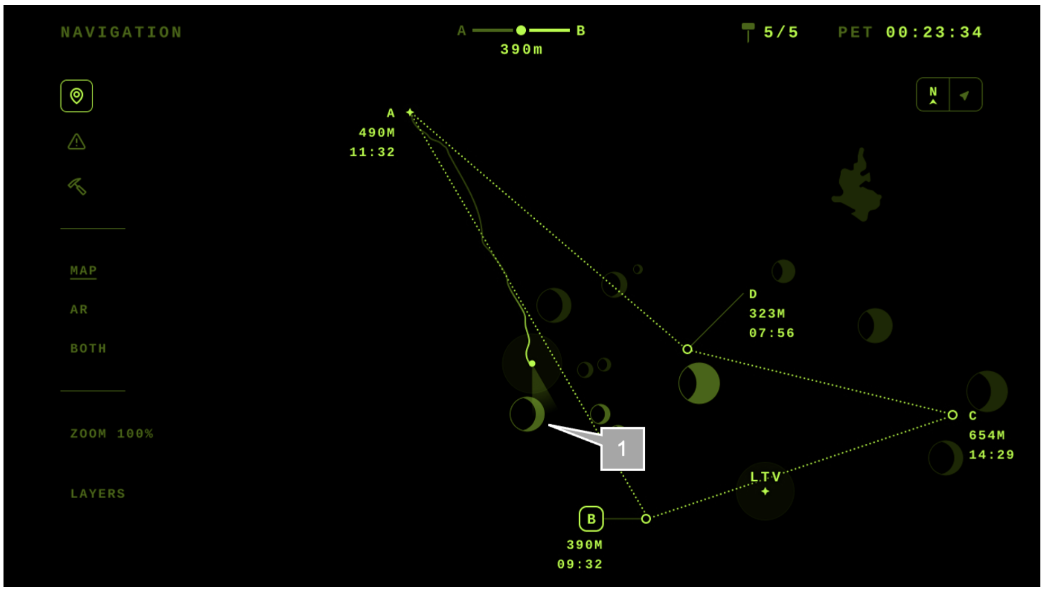

Figure 6.59: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to reference the major features to make sure I don't miss or forget pertinent details"

6.3.9 I want to see the image I just took to ensure it captures what I wanted to capture

Figure 6.60 depicts how the Joint AR solution could provide the EV crew with the ability to see the image they just took to ensure it captures everything desired. In this concept, a photo that was recently taken appears in a popup that partially overlays the out the camera view (1).

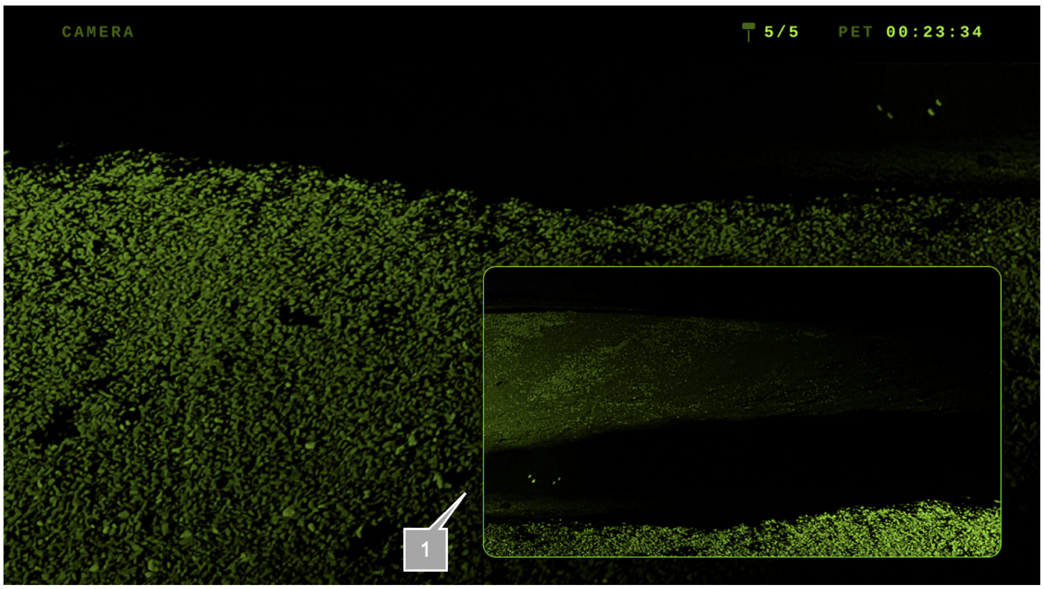

Figure 6.60: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to see the image I just took to ensure it captures what I wanted to capture"

6.3.10 I want to know the current state of my handheld camera

Figure 6.61 depicts how the Joint AR solution could provide the EV crew with the ability to see the image with the corresponding camera settings. In this concept, a banner displays the current camera settings (1)

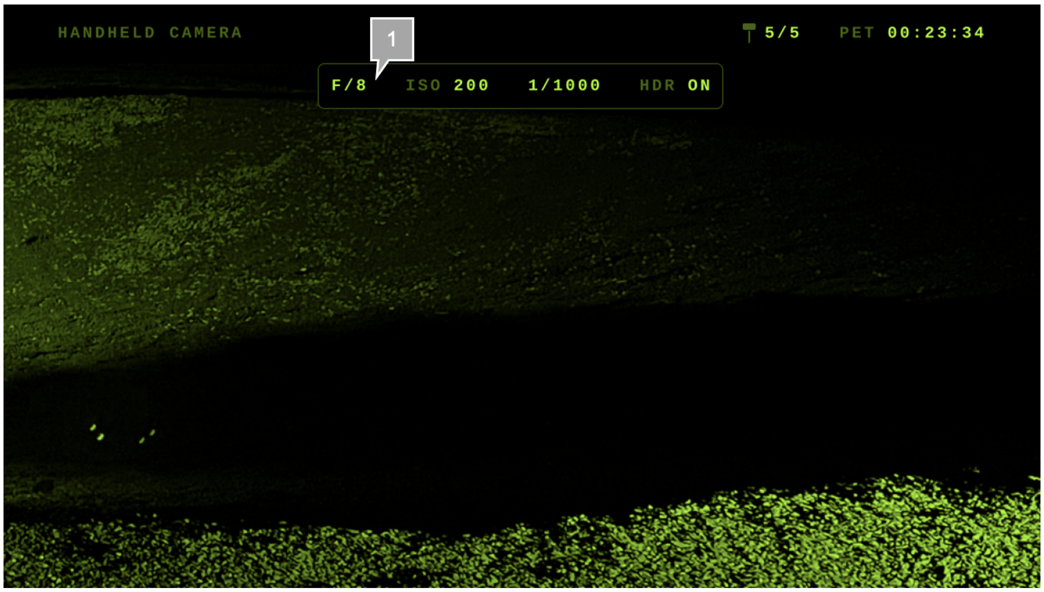

Figure 6.61: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know the current state of my handheld camera"

6.3.11 I want to know I took the minimum images required for pre-sampling

Figure 6.62 depicts how the Joint AR solution could inform the EVA crew that they took the minimum number of images required for pre-sampling. In this concept, this was done by providing a number of images required and checking the photos app to make sure the proper number of images of each type was located (1). It also allows the EV to view the photos in the photos app to ensure adequate photos were captured (2).

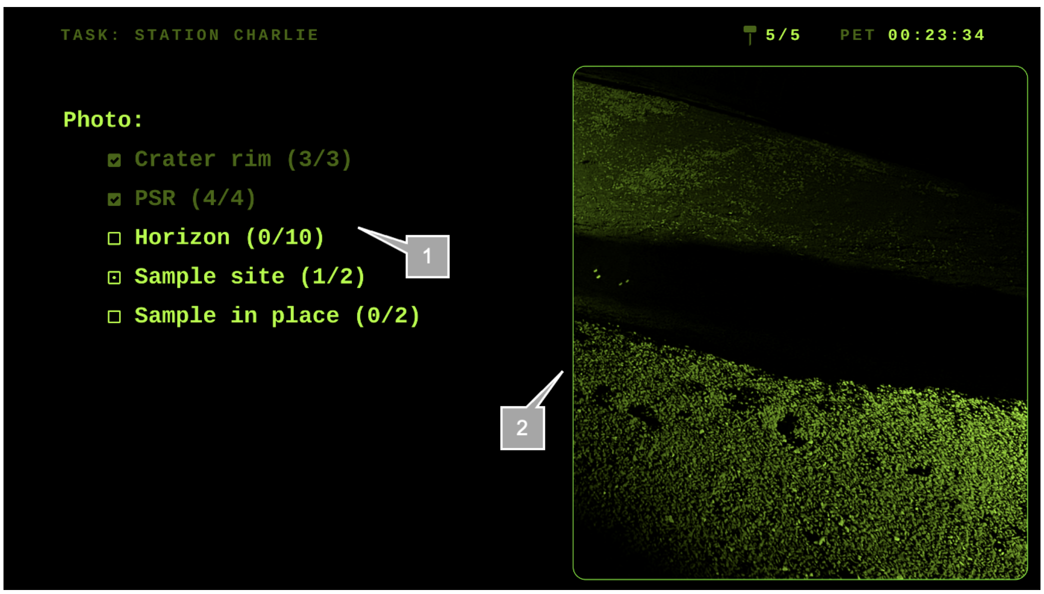

Figure 6.62: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know I took the minimum images required for pre-sampling"

6.3.12 I want to know that I've captured the minimum documentation data required by the mission

Figure 6.63 depicts how the Joint AR solution could inform the EVA crew on the actual coverage of what was captured with some minimum resolution or quality of the surface from their image capture devices (1). These illuminated breadcrumbs could serve as an indication of what was sufficiently 'captured' in terms of imagery as they progress through their traverse

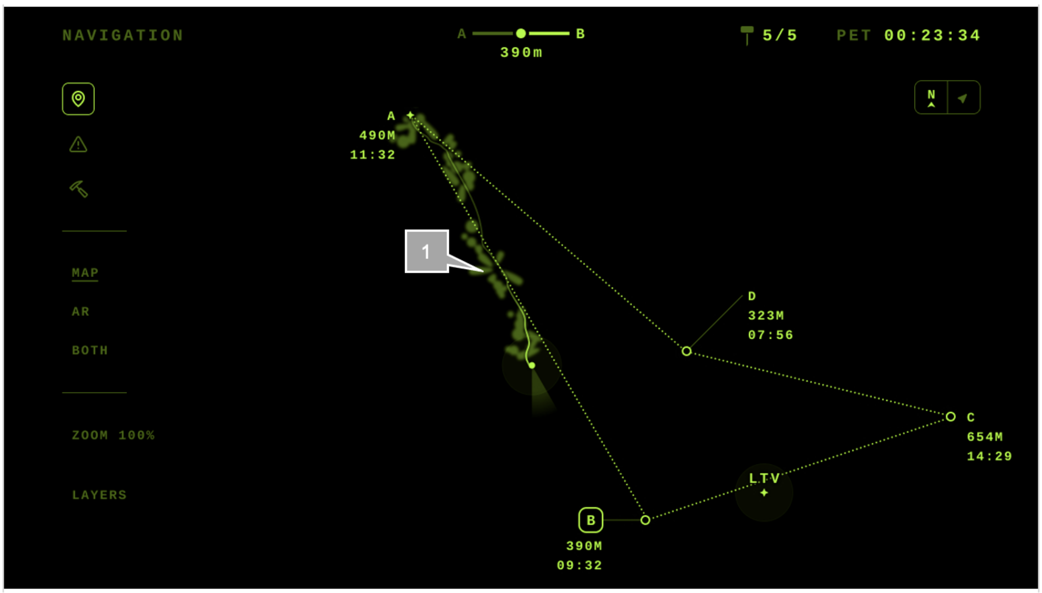

Figure 6.63: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know that I've captured the minimum documentation data required by the mission"

6.3.13 I want to advance the content to the next phase to continue with my work

Figure 6.64 depicts the concept image highlighting the functionality of the Joint AR hand controller (1) which would allow the crew to advance content to the next phase of the EVA.

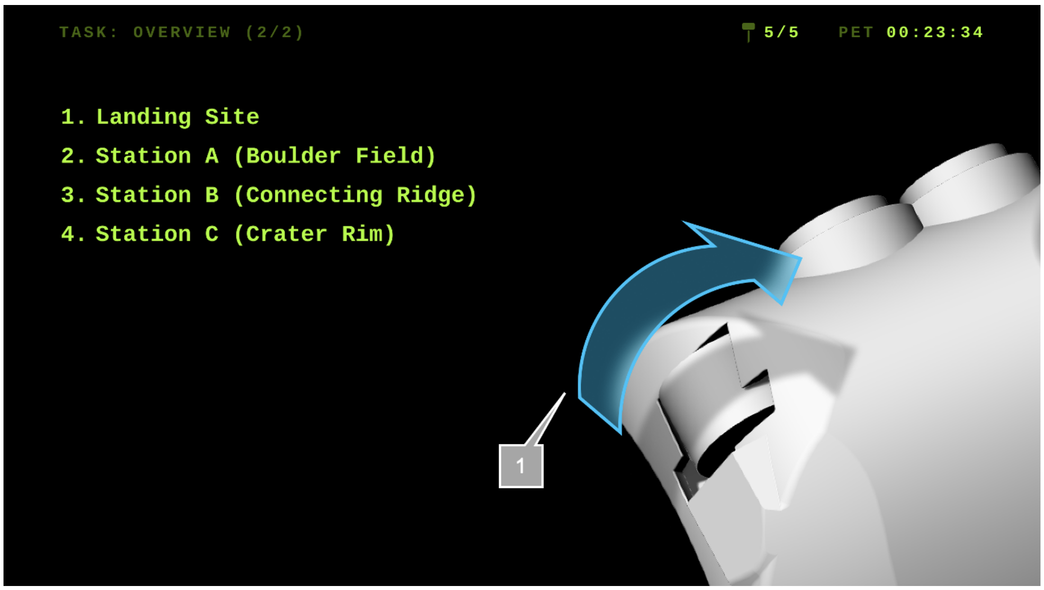

Figure 6.64: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to advance the content to the next phase to continue with my work"

6.3.14 I want to have content updated dynamically

Figure 6.65 depicts how the Joint AR solution can depict the dynamic updating of content on the display. In this concept, data that is OBE is depicted as being struck out and with a trashcan icon (1). This allows the EV to know on the fly that the subject content is no longer valid.

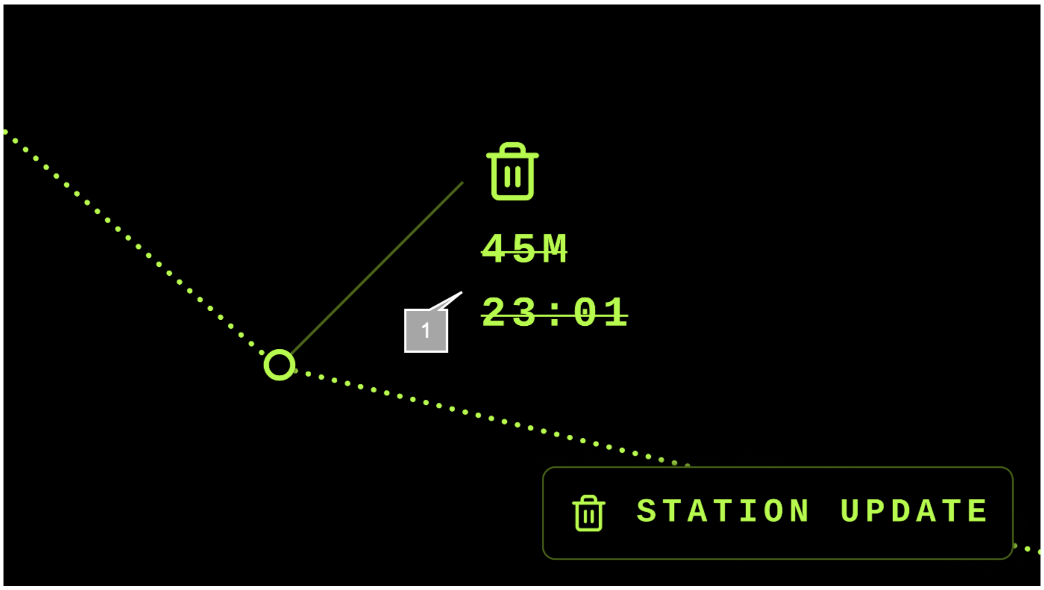

Figure 6.65: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to have content updated dynamically"

6.3.15 I want to know that I'm referencing the most accurate content

Figure 6.66 depicts how the Joint AR solution could convey to users that updates have occurred to the content. In this concept, there is an asterisk located next to the content that is changed (1) and there is a notification with an asterisk that says "1 Update" (2).

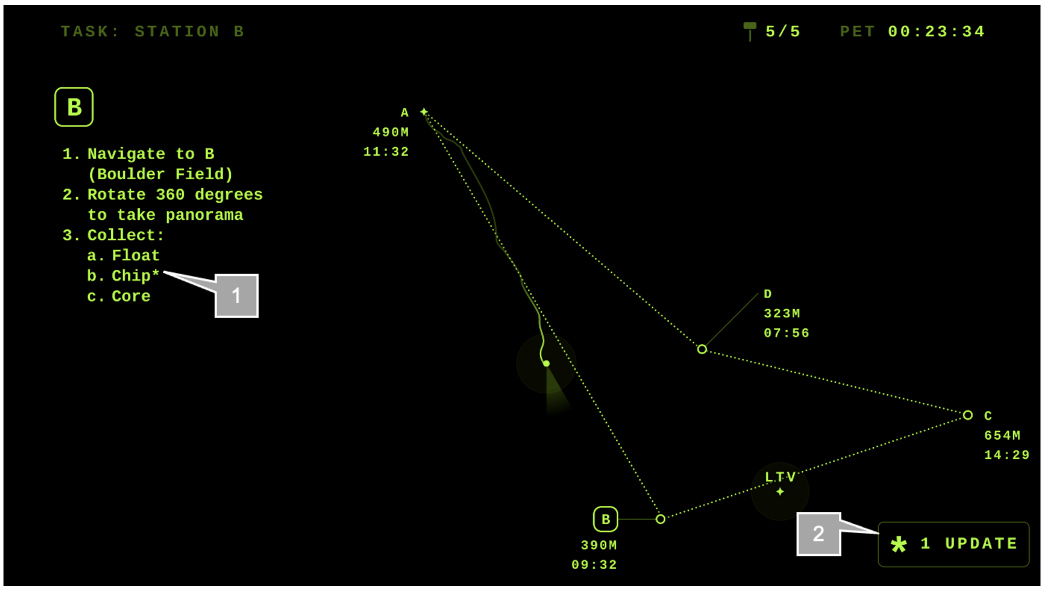

Figure 6.66: Annotated Joint AR user interface solution that addresses the momentary demand: "I want to know that I'm referencing the most accurate content"

7 References

[1] Shelley Evenson, Michael Muller, and Emilie M. Roth. "Capturing the Context of Use to Inform System Design". In: *Journal of Cognitive Engineering and Decision Making* 2.3 (Sept. 2008), pp. 181–203. ISSN: 1555-3434. DOI: 10.1518/155534308X377072. URL: http://journals.sagepub.com/doi/10.1518/155534308X377072 (visited on 05/26/2023).

[2] Karen M Feigh and Amy R Pritchett. "Requirements for Effective Function Allocation: A Critical Review". In: *Journal of Cognitive Engineering and Decision Making* 8.1 (2013), pp. 23–32. DOI: 10.1177/1555343413490945.

[3] Erik Hollnagel and David Woods. *Joint Cognitive Systems: Patterns in Cognitive Systems Engineering*. Publication Title: Joint Cognitive Systems. 2005. 113–133. ISBN: 978-0-8493-2871-8. DOI: 10.1201/9781420038194.ch6.

[4] Erik Hollnagel and David D. Woods. "Cognitive Systems Engineering: New wine in new bottles". In: *International Journal of Man-Machine Studies* 18.6 (June 1, 1983), pp. 583–600. ISSN: 0020-7373. DOI: 10.1016/S0020-7373(83)80034-0. URL: https://www.sciencedirect.com/science/article/pii/S0020737383800340 (visited on 10/04/2023).

[5] *Human Integration Design Handbook (HIDH)*. NASA/SP-2010-3407/REV1. Washington, D.C.: National Aeronautics and Space Administration, June 5, 2014. URL: https://www.nasa.gov/wp-content/uploads/2015/03/human_integration_design_handbook_revision_1.pdf.

[6] *Human Integration Design Process (HIDP)*. NASA/TP-2014-218556. National Aeronautics and Space Administration, Sept. 2014.

[7] James W. McBarron. "Past, present, and future: The U.S. EVA Program". In: *Acta Astronautica* 32.1 (Jan. 1994), pp. 5–14. ISSN: 00945765. DOI: 10.1016/0094-5765(94)90143-0. URL: https://linkinghub.elsevier.com/retrieve/pii/0094576594901430 (visited on 05/26/2023).

[8] Matthew J. Miller and Karen M. Feigh. "Addressing the envisioned world problem: a case study in human spaceflight operations". In: *Design Science* 5 (2019), e3. ISSN: 2053-4701. DOI: 10.1017/dsj.2019.2. URL: https://www.cambridge.org/core/product/identifier/S2053470119000027/type/journal_article (visited on 08/23/2022).

[9] Matthew J. Miller, Kerry M. McGuire, and Karen M. Feigh. "Information flow model of human extravehicular activity operations". In: *2015 IEEE Aerospace Conference*. 2015 IEEE Aerospace Conference. Big Sky, MT: IEEE, Mar. 2015, pp. 1–15. ISBN: 978-1-4799-5379-0. DOI: 10.1109/AERO.2015.7118942. URL: http://ieeexplore.ieee.org/document/7118942/ (visited on 05/27/2023).

[10] Matthew J. Miller et al. "Realizing a Spacesuit Compatible Augmented Reality System to Meet the Work Needs of Future Human Spaceflight Exploration". In: ASCEND 2022. _eprint: https://arc.aiaa.org/doi/pdf/10.2514/6.2022-4235. American Institute of Aeronautics and Astronautics, 2022. DOI: 10.2514/6.2022-4235. URL: https://arc.aiaa.org/doi/abs/10.2514/6.2022-4235 (visited on 04/05/2023).

[11] Paromita Mitra et al. "Trades, Architecture, and Design of the Joint Augmented Reality Visual Informatics System (Joint AR) Product". In: (July 16, 2023). Accepted: 2023-06-20T15:28:55Z Publisher: 2023 International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/94711 (visited on 08/14/2023).

[12] A.M. Pejtersen and S. Rasmussen. "Cognitive work analysis of new collaborative work". In: *2004 IEEE International Conference on Systems, Man and Cybernetics (IEEE Cat. No.04CH37583)*. 2004 IEEE International Conference on Systems, Man and Cybernetics. Vol. 1. The Hague, Netherlands: IEEE, 2004, pp. 904–910. ISBN: 978-0-7803-8567-2. DOI: 10.1109/ICSMC.2004.1398418. URL: http://ieeexplore.ieee.org/document/1398418/ (visited on 05/27/2023).

[13] Richard W. Pew. "Some New Perspectives for Introducing Human-Systems Integration into the System Development Process". In: *Journal of Cognitive Engineering and Decision Making* 2.3 (Sept. 2008), pp. 165–180. ISSN: 1555-3434. DOI: 10.1518/155534308X377063. URL: http://journals.sagepub.com/doi/10.1518/155534308X377063 (visited on 05/27/2023).

[14] Richard W. Pew and Anne S Mavor, eds. *Human-System Integration in the System Development Process: A New Look*. Washington, D.C.: National Academies Press, June 15, 2007. ISBN: 978-0-309-10657-3. DOI: 10.17226/11893. URL: http://www.nap.edu/catalog/11893 (visited on 06/01/2023).

[15] Richard C Wilde et al. "One hundred US EVAs: A perspective on spacewalks". In: *Acta Astronautica* 51.1 (July 2002), pp. 579–590. ISSN: 00945765. DOI: 10.1016/S0094-5765(02)00096-6. URL: https://linkinghub.elsevier.com/retrieve/pii/S0094576502000966 (visited on 05/26/2023).

[16] David Woods and Sidney Dekker. "Anticipating the effects of technological change: A new era of dynamics for human factors". In: *Theoretical Issues in Ergonomics Science* 1.3 (Jan. 2000), pp. 272–282. ISSN: 1463-922X, 1464-536X. DOI: 10.1080/14639220110037452. URL: http://www.tandfonline.com/doi/abs/10.1080/14639220110037452 (visited on 05/26/2023).