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Design and evaluation of an Augmented Reality tool for future human space exploration aided by an Internet of Things architecture

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Abstract

Humans are embarking on a new era of space exploration with the plan of sending crewed spacecraft to the Moon, Mars, and beyond. Extravehicular activities (EVAs) will be an essential part of the scientific activities to be carried out in these missions, and they will involve extensive geological fieldwork. These EVAs entail many challenges as real-time support from ground control cannot be provided to astronauts. Hence, new human–machine interfaces are urgently needed to enhance mission autonomy for astronauts and reduce ground communication dependability for real-time operations. This study introduces an Augmented Reality (AR) Internet of Things tool for astronauts to carry out geological activities. It proposes a theoretically-informed user-centred design method supported by expert feedback and an evaluation method. The tool was assessed via questionnaires and semi-structured interviews with European Space Agency (ESA) astronauts and geological field activities experts. Content analysis of the interviews revealed that user satisfaction was the first most mentioned (32% of 139 quotes) usability aspect. Key design factors identified were: displaying solely important information in the field of view while adjusting it to the user's visual acuity, easy usage, extensibility, and simplicity. User interaction was the second most mentioned (24% of 139 quotes) usability aspect, with voice seen as the most intuitive input. Finally, this research highlights important factors determining the usability and operational feasibility of an AR tool for analogue training missions and provides a foundation for future design iterations and an eventual integration of AR into the spacesuit's visor.

Keywords: Augmented Reality; Internet of Things; Human Space Exploration; Human-Machine Interaction; Usability

1. Introduction

National agencies and private companies are looking again at the Moon as a stepping stone for Martian missions. The future lunar plans will incorporate several surface activities, most of which will be based on investigating In-Situ Resource Utilization (ISRU) techniques via in-situ geological measurements.

The present work aims to investigate how new technologies can help to improve astronauts' extravehicular activities (EVAs) while performing geological tasks. More specifically, a user-centred Augmented Reality (AR) tool aided by an Internet of Things (IoT) architecture has been developed and tested. In this context, AR refers to a technology that superimposes computer-generated data, audio, and other sensory enhancements on the user's view in such a

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way that the virtual content is aligned with real-world objects (Azuma, 1997), while IoT refers to a system of interrelated computing devices able to transfer sensor data over a network (Mohan, 2018). This AR-IoT tool focuses on the site evaluation of geological field activities. The site evaluation involves different actions, namely creating a stop description, making a geolocation site screening, and documenting the stop and the area (Bessone et al., 2018). The ultimate goal is to assess how such an AR-IoT tool can be used as an alternative to ground communication that is affected by long latencies, hence increasing crew autonomy during future human extra-terrestrial surface activities.

1.1. Augmented Reality for space applications

The benefits of AR, particularly for procedural tasks, have been identified across many industries. AR for assembly research, namely manufacturing, assembly, maintenance, and repair (for surveys, see Fernández del Amo et al., 2018; Ong et al., 2008; Wang et al., 2016), has been greatly explored. Until now, procedural instructions were mostly paper-based, which are time-consuming to consult (Henderson and Feiner, 2009) and frequently show unnecessary information (Hou et al., 2013; Okamoto and Nishihara, 2016; Ong et al., 2008). Studies investigating the usability of AR for procedural work have shown that AR leads to lower task completion times for assembly, higher accuracy, and lower mental effort (Henderson and Feiner, 2011a, 2011b; Richardson et al., 2014; Tang et al., 2003; Uva et al., 2018). Furthermore, users considered AR intuitive (Henderson and Feiner, 2009, 2011a, 2011b).

Even though research and development of AR for space applications are at an early stage, several studies examining the benefits in this context have been conducted. The majority of these projects focused on AR for procedural work on the ISS, such as the pilot study by Markov-Vetter and Staadt (2013), mobiPV (Helin et al., 2019b), and later on, tested on the Microsoft HoloLens, MobiPV4-HoloLens (Helin et al., 2019a), WEKIT (Vizzi et al., 2017), EdcAR (Helin, 2017), WEAR (Cardano et al., 2009), Sidekick (Ramsey, 2015), and T2 AR (Byrne et al., 2019). Next to AR studies focusing on ISS operations, other space-related AR applications have been investigated. WEKIT and OnSight looked at AR for rover operations (Ramsey, 2015; Ravagnolo et al., 2019a, 2019b), Furuya et al. (2018) explored the benefits of AR for stowage operations and logistics, and Karasinski et al. (2017) investigated the use of a tool combining AR and the IoT for just-in-time training. Lastly, a study called Holo-SEXTANT entailed the development of an AR tool aimed at helping extravehicular (EV) crewmembers while navigating a planned traverse. The SEXTANT (Surface Exploration Traverse Analysis and Navigational Tool) (Norheim et al., 2018) was integrated with the Microsoft HoloLens and tested during NASA's BASALT field campaign in November 2017 (Anandapadmanaban et al., 2018). This study concluded that AR could enhance situational awareness and provide information on the terrain and the path that can otherwise not be offered to the user (Beaton et al., 2019b). An overview of space-related AR studies can be found in Table A1.

1.2. Astronaut geological field activities

Starting with the Artemis III mission, humans will set foot on the Moon after more than 50 years since the last time. Science objectives are currently being defined by NASA (2020), and surface EVAs will certainly be an important part of *in situ* measurements.

Thanks to the considerable progress of technology, future astronauts will benefit from updated aiding tools when performing an EVA. In this sense, digitalisation of the former cuff checklist attached to the astronauts' spacesuits during the Apollo program is expected (Hodges and Schmitt, 2011; Kain et al., 1971). Besides, future extra-terrestrial exploration missions, such as Martian sorties and even beyond, cannot entirely rely on real-time ground support. Therefore, an urgent need is arising for smart devices and sensor tools that can assist astronauts on distant planetary surfaces. One example of this kind of tool is the Electronic Field Book (EFB) (Turchi et al., 2021), an innovative information system able to provide real-time situational awareness to support teams by collecting and distributing information (e.g., images, text, and audio notes collected in the field) to the relevant users. The system also integrates decision support features, such as geological reference information and mineral classification tools to enhance crew autonomy. Another one is the Holo-SEXTANT (Beaton et al., 2019b), an AR tool developed to help navigate during a planned traverse for EVAs.

To test those innovative technologies, dedicated test campaigns, so-called terrestrial analogues (Osinski et al., 2006), are used, which are able to simulate some of the geological features of distant planetary bodies. ESA is successfully running two such initiatives, CAVES (ESA, 2013; Sauro et al., 2021; Strapazzon et al., 2014) and PANGAEA (ESA, 2018).

Most of the existing AR space applications have been tested for procedural work on the ISS (see Table A1), but only one has been specifically developed for geological field exploration, and it fully focuses on navigation and traverse planning (Anandapadmanaban et al., 2018). As a result, the AR-IoT tool presented here is the first of its kind conceived to support astronaut geological site inspection activities. The research aimed to investigate whether an AR user interface is a usable and valuable concept for future human extra-terrestrial surface exploration missions. The findings were compared to existing tools and media to assess the AR-IoT tool's usefulness, helpfulness, and operational feasibility.

2. Methods

A theoretically-informed user-centred design methodology conforming with the human-centred design methodology used by NASA (2010) and the model suggested by Lee et al. (2018) was adopted for this research.

First, a user and task analysis were performed to define crucial design considerations and requirements and relevant surface EVA scenarios, with a special focus on Apollo operations (Connors et al., 1994; NASA, 1975; Scheuring et al., 2008) (see Table 1).

During the interface design, special focus was put on the user, the user's cognitive load, the user's surroundings, and foreseen interactions. As illustrated in Fig. 1, the design process was iterative. Concepts I-III were evaluated via expert reviews, and concept IV was evaluated via heuristic evaluations, requirements compliance questionnaires, and semi-structured interviews. The evaluations were carried out with experts and target group users, and iterations followed each evaluation. It should be noted that the focus of the conceptual phase (concepts I-IV) was primarily on the user interface layout and user interactions; the IoT architecture was implemented in the AR application for prototype I.

2.1. Expert reviews

Expert reviews were performed to ensure the tool's consistency with standard display design principles (Lee et al., 2018). The reviews were held in the form of informal

Table 1
AR-IoT tool design requirements.

#	Description
1	The tool shall assist astronauts and intravehicular (IV) crew during geological site inspection tasks
2	The tool shall display EVA task instructions, more specifically geological site inspection tasks
3	The tool shall be capable of assisting the astronaut crew with navigation
4	The tool shall allow hands-free interaction, more specifically hands-free data/field notes taking
5	The astronaut crew must be able to access spacesuit diagnostics, e.g., consumable levels, at any time
6	The user interface shall not be obtrusive nor a danger to the mission
7	The user interface shall be legible by the astronaut crew outdoors
8	The user interface shall allow the astronaut crew to save and delete recorded/logged information

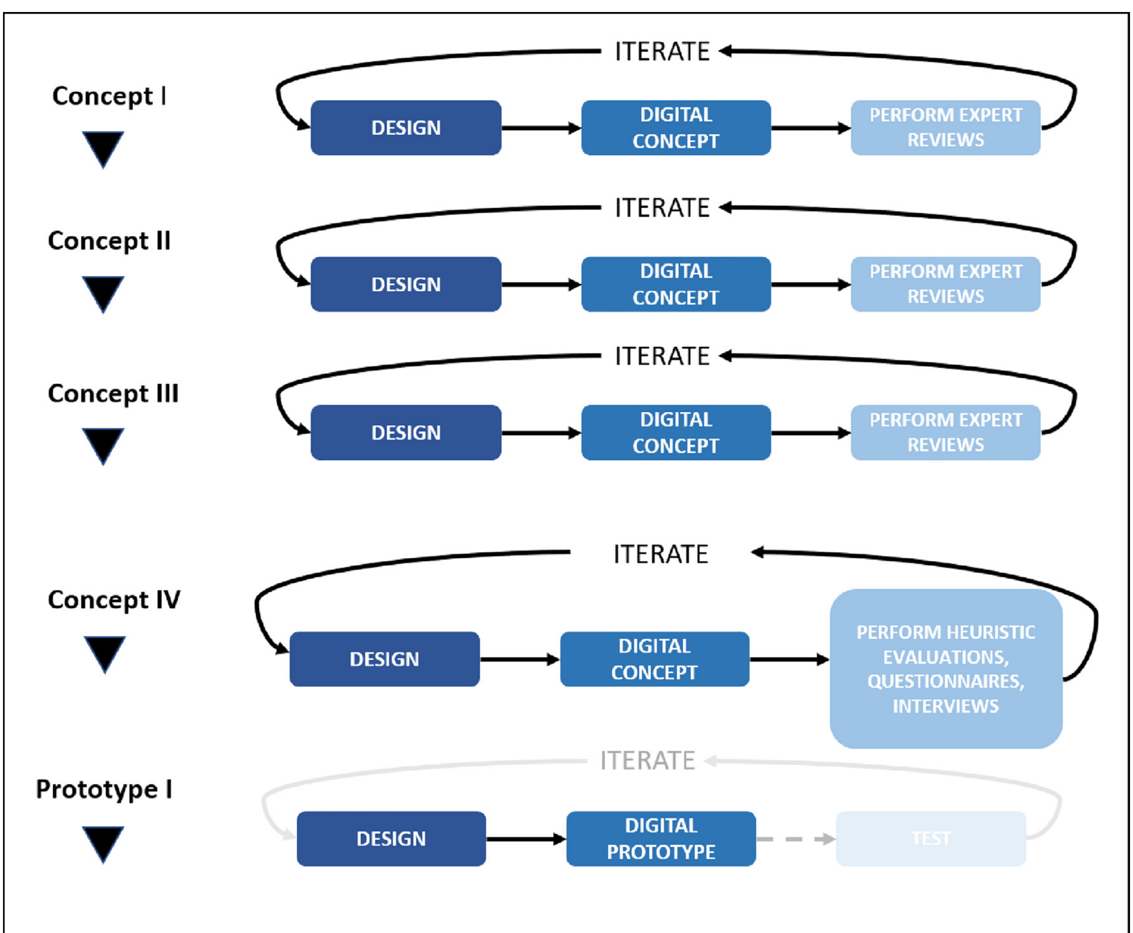


Fig. 1. Iterative user-centred design process used to design the AR-IoT tool. Four digital concepts were created before the design of the first prototype, which includes the IoT architecture.

discussions between the interface developer (first author) and each of the experts. Every new concept was subject to two to three reviews by human–machine interaction and geological astronaut training experts. The experts were instructed on the actions to be performed with the AR interface and were asked to mention positive and negative aspects of the interface design and suggestions for further implementation. The expert reviews were helpful in understanding which activities are relevant during astronaut geological fieldwork and feasible for the user interface. The reviews also clarified which type of information is required to accomplish a given task.

2.1.1. Heuristic evaluations

After several expert reviews, which led to a more defined concept (concept IV), three heuristic evaluations, each with a different evaluator, were performed. For these evaluations, a questionnaire with relevant design principles, so-called "heuristics", was created. The questionnaire was based on the ten usability heuristics identified by Nielsen (1995), the 15 display design principles stated by Lee et al. (2018), and the requirements mentioned in NASA's Space Flight Human-System Standard Volume 2 (NASA, 2015). Each evaluator was requested to fill out the questionnaire and rate each principle on a 5-point Likert scale (strongly disagree, disagree, neutral, agree, and strongly agree) as well as add comments and explanations to each rated principle. The observer (first author) recorded the comments and discussions as the evaluator went through the interface and made sure that the expert argued and reasoned each rating. Upon completion of the individual heuristic evaluations, the questionnaire ratings were merged to get a better overview. Then, the comments were combined to identify redundant feedback and allow for a time-efficient yet complete discussion with all evaluators. The discussion focused on possible redesigns to address major usability problems and general problematic design aspects.

2.1.2. Expert requirements compliance questionnaire

A customized questionnaire (see Appendix C) for astronauts and astronaut geological field training experts was generated to assess whether the developed AR-IoT application is in line with the specified usability requirements and whether it has the potential to be used by astronauts in the future. This assessment approach is common practice in the space industry. The questionnaire was created based on the following guidelines, standards, design principles, and requirements:

- Usability and learnability requirements from guidelines and standards specified in the SSP 50313 - Display and Graphics Commonality Standard Revision F Document (NASA, 2001)
- Usability principles proposed by Nielsen (2004)
- The System Usability Scale (Bangor et al., 2008; Brooke, 2013)
- A cross-check with the design principles identified from the heuristic evaluations to ensure that all principles that are considered applicable and feasible for this evaluation are addressed in the usability questionnaire.

Certain usability aspects can only be assessed if the HoloLens is worn with the application running on it. This, however, was not possible due to COVID-19 restrictions the that time. Instead, experts were contacted via email and asked whether they would like to participate in the study. The email included a brief explanation of the research project, the aim and capabilities of the AR-IoT tool, the estimated duration of the evaluation, and instructions and video demonstrations (see Supplementary Videos S1 and S2). The instructions consisted of a short introduction to the evaluation itself, a more detailed description of the aim and capabilities of the AR-IoT tool, and a request to watch the video demonstrations as often as required before completing the provided questionnaire and sending it back.

To describe the data obtained from the questionnaire, the median of the responses, as a measure of central tendency (Jamieson, 2004; Sullivan and Artino, 2013), and the frequencies/percentages of the responses for each point in the questionnaire (Sullivan and Artino, 2013) were calculated. The Interquartile Range (IQR) was calculated to measure the dispersion in the responses. Questionnaire comments were analysed for additional insights and clarifications.

2.1.3. Semi-structured interviews

Semi-structured interviews were performed with experts from the European Astronaut Centre (EAC) after completing the requirements compliance questionnaire and watching the video demonstrations. The interviews were based on a pre-defined protocol comprising seven open-ended questions. The interviewees included experts in astronaut EVA training, particularly ESA astronauts who participated in analogue missions such as CAVES & PANGAEA, and CAVES & PANGAEA support engineers. Consent to audio-record the interview was gathered before the interview via verbal or written consent, depending on the participant's preference. First, introductory questions were asked to understand what kind of experiences the interviewee had with AR technology, astronaut geological field training, and/or EVAs in general during analogue missions, as well as testing of and exposure to new technology during these missions. Other questions focused on required and useful new technology that could enhance the preparatory training for future human lunar and planetary surface exploration and planned missions. General questions on the application and specifically on its usability and the experts' opinion on the future outlook on innovative technology development and integration were addressed.

The audio-recorded interviews were transcribed verbatim according to the guidelines mentioned by McLellan et al. (2003). The software Atlas.ti 8.4 was used as a support tool for the qualitative interview analysis, particularly to enable a structured text analysis.

The qualitative content analysis, a well-established approach for text analysis, first described by Mayring (1983), was adopted. The principles for inductive category development (Mayring, 2000) were used for the coding process as the scope of this analysis was explorative.

First, the transcripts of the interviews were examined line-by-line, applying the usual steps of text analysis, e.g., highlighting text, writing notes, and seeking keywords in the text (Mayring, 2000) using Atlas.ti 8.4. The transcripts were then reread to define initial categories. Secondly, the identified categories were grouped into categories and subcategories. This step was performed deductively by introducing theoretical considerations while formulating the main categories and assigning the subcategories (Mayring, 2000). Thirdly, the number of quotes and classified quotes were counted. If the quote was referring to more than one subcategory, the quote was assigned to every subcategory it belonged. Successively, subcategory frequencies and respective main category frequencies within the material were evaluated. Then, the number of respondents per subcategory was counted. Subcategories with one respondent only were omitted. Finally, illustrative quotes from each subcategory were selected (Graham-Rowe et al., 2012; Graneheim and Lundman, 2004; Mays and Pope, 1995); for this purpose, the principle of ''prototypical and outlier illustrations'' for each subcategory (Graham-Rowe et al., 2012) was used. The assumption was made that the importance of a subcategory is proportional to the number of times it gets mentioned by the respondents. Consequently, it was decided to report the number of quotes such that these are proportional to the number of respondents mentioning the corresponding subcategory. One quote per respondent was accepted for each subcategory as the maximum to avoid a subcategory being dominantly described by a single respondent. Illustrative quotes were therefore selected as follows: subcategories mentioned by 2 to 3 respondents are represented by a minimum of 1 and a maximum of 2 quotes, and subcategories mentioned by all 4 respondents are represented by a minimum of 2 and a maximum of 3 quotes. As can be seen in Table A1, this evaluation strategy, namely gathering user feedback through direct observations, surveys, and questionnaires, is common practice for space-related AR studies.

3. The AR-IoT tool

3.1. Hardware

The following off-the-shelf hardware components have been used for the development of the AR-IoT tool:

- Microsoft HoloLens 1st gen (Microsoft, 2021a);
- Microsoft HoloLens 1st gen clicker;
- Raspberry Pi 3.

3.2. Software architecture

The tool runs the Unity 3D game engine to visualize and render on top of the real-world environment. The application has been developed using the Unity framework (2018.4.13) and C# as the scripting language, along with the open-source 2017.4.1.0 version of the Mixed Reality Toolkit. The toolkit provides components and features used to accelerate the development of Mixed Reality applications. For instance, it provides solvers that facilitate calculating an object's position and orientation according to a predefined algorithm. For the AR-IoT application, the far interaction component ''tap to place'' was specifically used to place a game object on a spatial mesh. The HoloLens is able to accurately scan its surroundings, a capability known as spatial mapping, and save the world mapping data on the device. The mapping data can be used across multiple applications within the HoloLens and after the device is restarted (Microsoft, 2021b).

An IoT client–server architecture via Message Queuing Telemetry Transport (MQTT) protocol was adopted (see Fig. 2) to guarantee the communication between the HoloLens and the IoT devices, which in this case are represented by a Raspberry Pi and sensors providing biomedical and consumables data. The HoloLens and the server, also called broker, communicate via MQTT, a lightweight publish/subscribe protocol frequently used to send information to a specific topic and a device or sensor belonging to the IoT network. The communication between the Raspberry Pi and the HoloLens is as follows: the MQTT broker receives information to send to the HoloLens from the Raspberry Pi, which gets data directly from the sensors. The open-source message broker Mosquitto (Light, 2017), which implements the MQTT protocol and has a command-line publisher/subscriber client, was chosen. For the HoloLens, the open-source M2Mqtt library (Patierno, 2015) was implemented. The Raspberry Pi and the broker also communicate via MQTT protocol. The open-source Python MQTT client Paho Eclipse (Eclipse PahoTM and Python Client, 2019) was embedded in the Raspberry Pi; additionally, an MQTT publishing Python script capable of sending dummy sensor values (due to the lack of actual life support system sensory data) was written and implemented. No actual sensors could be used; hence, the sensory data were simulated. The setup permits actual sensors, e.g., as part of the life-support system of a spacesuit used during an analogue test, to publish meaningful data once these data were available. The sensors must have Wi-Fi capabilities to send data to the Raspberry Pi. The setup (see Fig. 2) described above has been tested successfully. For this, all devices were connected to the same network, and the server IP address, as well as the topic to subscribe/publish to, were specified for the embedded MQTT client in the HoloLens and Raspberry Pi. In Fig. 2, an arbitrary display with an embedded MQTT client is shown; this show-

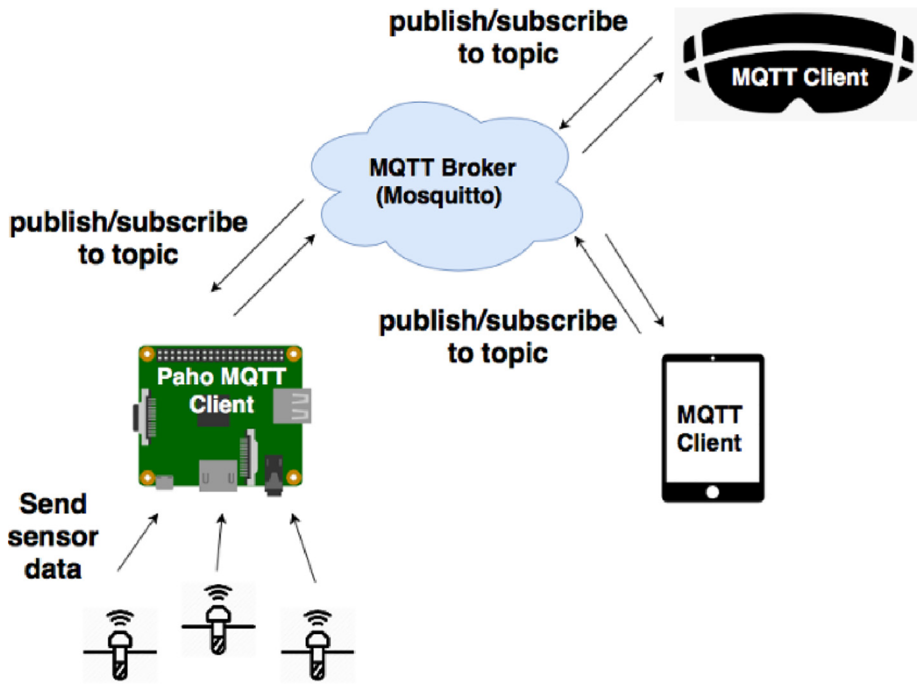


Fig. 2. AR-IoT architecture: Mosquitto MQTT broker managing telemetry transfer between the Microsoft HoloLens, arbitrary display, and Raspberry Pi 3. All devices have an embedded MQTT client.

cases the possibility of connecting different types of devices meant for different experimental scenarios, or concepts of operations, needed for effective comparison and evaluation of the investigated technologies.

3.3. User interface

The AR-IoT tool is aimed at supporting future extravehicular crews during geological field activities, in particular geological site inspections. Geological fieldwork involves different activities, such as site evaluation, site preparation and documentation, and sampling (Bessone et al., 2018; Hodges and Schmitt, 2011). The developed AR-IoT tool focuses on the site evaluation aspect of geological field activities, which involves creating a stop description, making a geolocation site screening, and documenting the stop and the area (Bessone et al., 2018). The capabilities of the AR-IoT tool are based on the hierarchical structure of the activities integrated into the EFB (Bessone et al., 2018) and proposed improvements and/or desired capabilities and recommendations gathered during analogues such as BASALT-2 (Lim et al., 2019) as well as from the testing of the Holo-SEXTANT concept (Anandapadmanaban et al., 2018). Identified capabilities and needs for such a tool are hands-free data/field notes gathering, providing suit diagnostics, overlays of virtual traverse waypoints and annotations, and generally guiding non-geologists during geological inspection tasks. The AR-IoT tool is the first tool of its kind featuring all these capabilities, and it allows scientists that are off-site to keep track of the operations performed. Fig. 3 shows the sequence of geological activities performed during a traverse and the corresponding supporting features and capabilities provided by the AR-IoT for geological site evaluations.

The AR-IoT user interface (see Fig. 4) offers the following functionalities:

3.4. Constant access to the main menu

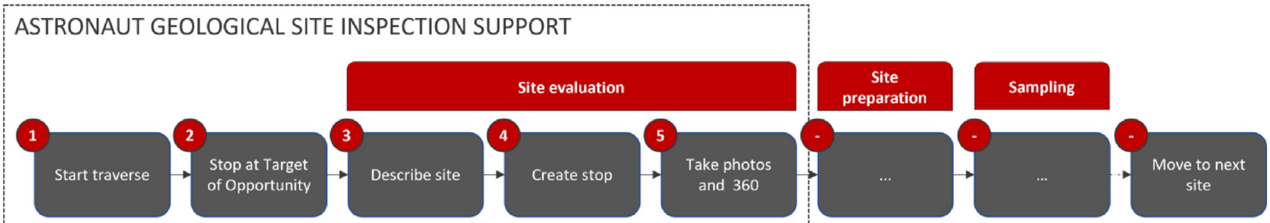
The main menu offers users the following options at any point in time: log data during their planned traverse, recall their health status, including biomedical data and consumable levels, and perform site evaluations when required. The geological sampling option was not implemented for this proof of concept; it was added to the interface for purposes of completeness.

3.5. Hands-free interaction

The tool offers users hands-free interaction. The users avail themselves of gaze input (Microsoft, 2022b) to pick the action to be performed. A cursor is used to indicate the direction of gaze. The chosen action is then highlighted upon selection and requires double confirmation through one simple click performed by pressing on the given clicker once, while gazing at the item of choice (Microsoft, 2022a).

3.6. Hands-free logging of data

The log data capability allows the user to record data hands-free (e.g., via speech recognition). The data log can be geospatially pinned to the desired location where the user has recorded the data. This way, the user can create



	AR-IoT Tool Features and Capabilities	Astronaut tasks	Activity
	Hands-free field notes taking tool via voice recognition	Describe site	3
	Waypoint placing capability and hands-free field notes taking tool via voice recognition	Create stop, record coordinates and TOP description	4
	Built-in photo/video taking capability and storage on device	Take photos and panoramic 360	5
	Real-time stream of HoloLens for assisting crew	Communicate with ground or IV crew	1-5
	Display of consumable levels from connected biomedical sensors (via MQTT)	Check health status & consumable levels	1-5
	Access to tutorials in form of references/procedures	Perform activities correctly	3-5

Fig. 3. Overview of geological activities and corresponding supporting features and capabilities provided by the AR-IoT tool for geological site evaluations.

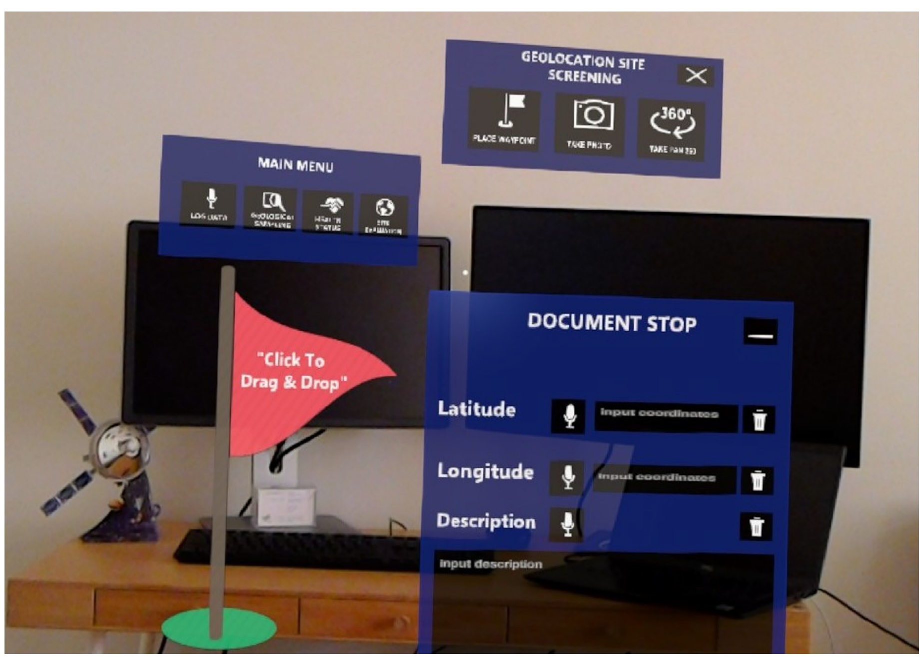


Fig. 4. AR-IoT tool user interface. Top left: main menu with log data, geological sampling, health status, and site evaluation functionality. Top right: Geolocation site screening with waypoint placement, photo, and video recording options. Bottom left: Drag and drop waypoint. Bottom right: document stop window to record coordinates and site description.

linked electronic field notes to increase efficiency and reduce workload. In fact, the users do not have to take their hands off the tools they are momentarily using. The interaction is based on gaze input and a simple button click to start the recording. The pin function is on a drag-and-drop basis: the user should gaze on the pin button, click to enable dragging, and gaze to drag-and-drop by clicking again.

3.7. Saving logged data

The logged data, namely the text recorded and transcribed via speech recognition, can be saved to a .txt file in a HoloLens' local folder and is then accessible via the Windows Device Portal by other ground control crewmembers or intravehicular (IV) crew which is located, e.g., in a lunar base.

3.8. Deletion of recorded/logged information

The interface allows the user to make corrections on the recorded information. The user is free to delete recorded text when necessary.

3.9. Access on-demand to consumables levels and biomedical data

The health status button provides a simple text-based display showing the users' critical suit consumables and biomedical data.

3.10. Access to tutorials in the form of references/procedures

The users have access to the so-called *site evaluation guide*, a tutorial outlining the actions to be taken during a site evaluation step by step (see Fig. 5), aimed at reducing mental workload and increasing efficiency. The users can readily perform the action required at each step without having to switch to different windows; this reduces the users' workload and time required to perform an action.

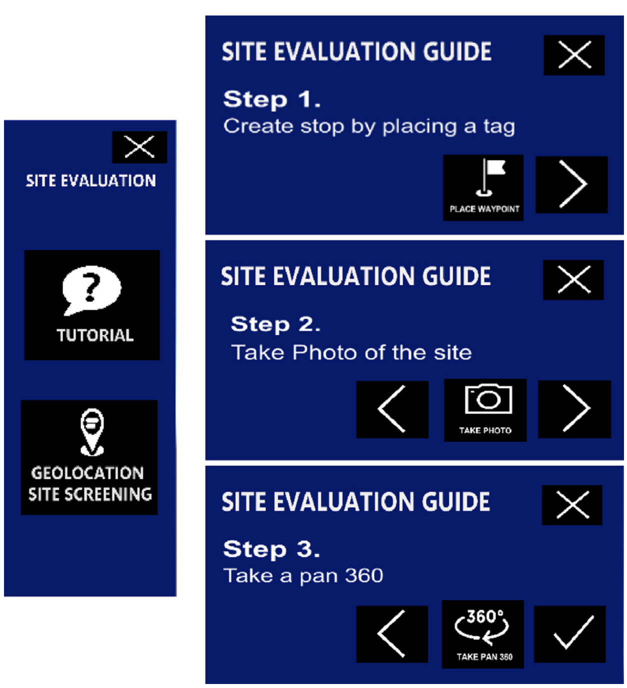


Fig. 5. Site evaluation menu with two options: tutorial and geological site screening (left). The tutorial includes three steps (right): place a waypoint, take a normal photo, and take a panoramic 360° photo.

3.11. Hands-free taking photographs and panoramic views/videos

The users can take photos of desired locations and record videos in the form of panoramic views hands-free (see Fig. 6). The photographs and videos/panoramic 360° photos are automatically saved to a local folder on the HoloLens and can be accessed via the Windows Device Portal by any other ground control crewmember or IV crew.

3.12. Hands-free creation of waypoints

The users can easily and promptly mark field locations of interest without the need to take their hands off the tools they are using in the field at that specific instant in time. The users can readily link data to the waypoint represented by a flag (see Fig. 7), such as location information and area descriptions. This is meant to help the EV crew map an area and highlight features during a traverse while making it accessible/visible not only to a subsequent EV crew but also a crew inside the habitat or on the ground.

3.13. Real-time stream of HoloLens

Other crewmembers, e.g., IV crewmembers, can potentially see what the HoloLens user sees, including the surrounding environment and holograms. This would allow IV crew to constantly monitor the EV crew and increase the IV crew's situational awareness.

Two video demonstrations of the AR-IoT prototype I, proof of concept Demo 1 and Demo 2, can be found in Supplementary Videos S1 and S2 (in Supplementary Material).

4. Results

This section shows the results obtained from the requirements compliance questionnaire and semi-structured interviews.

4.1. Requirements compliance questionnaire results

In total, seven of the experts, also referred to as respondents (R), who had been contacted provided the filled-in

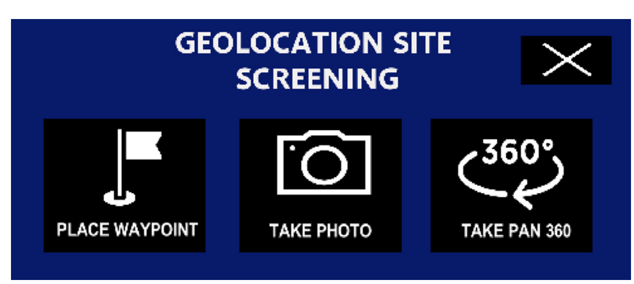


Fig. 6. Geolocation site screening with three options: placing a waypoint, taking a normal photo, and taking a panoramic 360° photo.

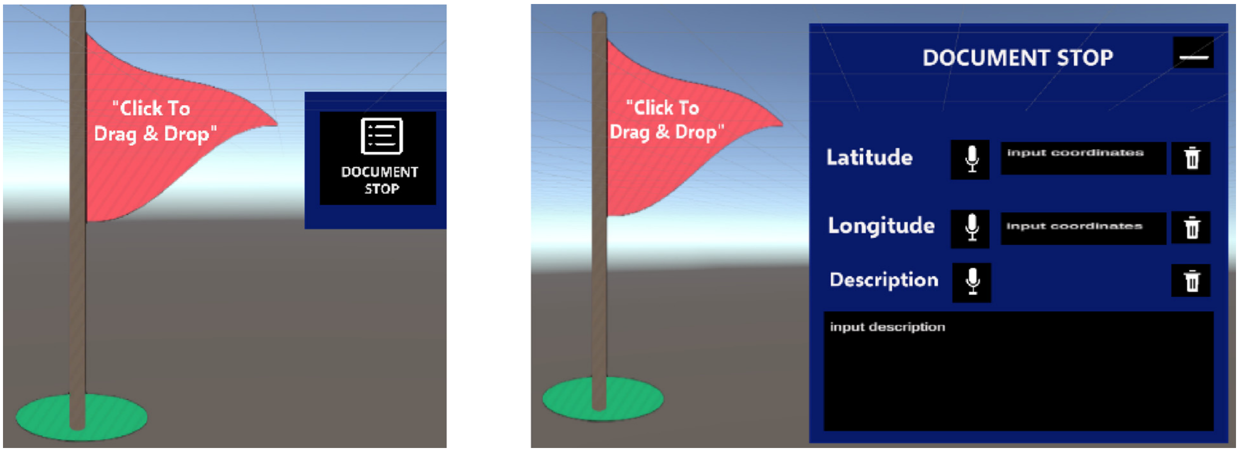


Fig. 7. Placement of a waypoint and documentation of the stop with three options: logging latitude, longitude, and general description via voice input and the option to delete incorrect entries.

questionnaire. All in all, the experts were satisfied with the layout of the user interface as information was perceived to be clear, consistent, and easily accessible. Experts had different opinions regarding the information density: some suggested including additional information for a more complete set of tasks for geological activities, whereas others suggested only including important data in the field of view and adjusting the latter to the user's visual acuity.

Overall, experts were satisfied with the capabilities of the interface; they stated that all the capabilities necessary for geological inspection tasks were present. One expert added a comment stating that *"the HoloLens reduces that [one of the most tedious but important tasks in terrestrial field geology, which is taking site coordinates and detailed photo-documentation and descriptions of the sites] by having the GPS and verbal "field notebook" easily accessible in one application*" (R06). Another expert appreciated the tool's "*capability to recall photos*" and mentioned that it would be useful to "*visualise them before recording them*" (R05). Suggested features to further enhance the AR-IoT tool's usefulness include geological sampling support tools, planning tools displaying "*real calculated time allowance to reach a safe haven (based on suit consumable left, consumables consumption, distance, calculated consumables consumption required to reach the safe haven)*" (R05), as well as navigation and mapping tools displaying "*AR name and distance overlays of horizon features (craters, mountains, hills) and of vital assets (lander position, rover position, EVA buddy position)*" and providing "*access to maps*" (R05).

Finally, experts rated the interface useful, helpful, and operationally feasible. They were satisfied with the feedback provided by the interface and stated that the navigation through the interface was clear and intuitive. Experts' opinions seemed divided on whether the tool allows for efficient task completion as this heavily depends on the implemented means of user interaction. Experts suggested different means of interaction and combinations: voice input only, gazing and clicking, voice and clicking, eye blinking, and tongue clicking.

4.2. Semi-structured interview results

A total of four interviews were conducted with two ESA astronauts and two support engineers of the CAVES & PANGAEA team. The semi-structured interviews ranged from 20 to 70 minutes. The qualitative content analysis of the four interviews led to the identification of 113 quotes. Twenty-two quotes were assigned to two subcategories and two quotes to three subcategories. Therefore, the total number of classified quotes is 139 constituting 25 subcategories. The quotes were then assigned to nine main categories relevant to the experts' experiences and opinions with new technologies focusing on aspects related to usability, user interaction, and implementation, as well as experiences with new concepts of operations. In Table 2, all extracted subcategories and identified main categories are displayed; moreover, the number of subcategory occurrences and the number of respondents per subcategory are shown in absolute numbers and percentages. It is also specified, in brackets, whether the respondents were majorly astronauts, denoted as 'astro', or support engineers/developers denoted as 'dev'.

Aspects concerning user satisfaction received the most mentions (32 % of 139 quotes) during the interviews. Both astronauts and support engineers argued that an AR tool could be "*easier and faster*" (R04) to use than the EFB on a tablet. Hands-free operations were of paramount importance for most of the interviewees. Scepticism remains on the potential of this tool in aiding the crew during complex activities. Astronauts argued that the systems should be simple, easy to use, and capable of guiding step by step, for instance, through procedural work. Step-by-step procedures in AR were mentioned as a potential solution. One of the support engineers underlined the restrictions on the head movement due to the spacesuit helmet

Table 2
Number of main category occurrences and subcategory occurrences, percentage of subcategories occurrences and respective main category occurrences, number of respondents ('astro' stands for astronaut and 'dev' for support engineers) per subcategory, and the percentage of respondents with respect to all respondents ($N = 4$).

Category and corresponding subcategories	Number of occurrences	% of occurrences w.r.t. all subcategories	Number of respondents	% w.r.t. all respondents
1. User satisfaction	**45**	**32%**		
annoying	6	4%	2 (2 astro)	50%
complex	3	2%	2 (2 astro)	50%
easy usage	4	3%	3 (1 astro, 2 dev)	75%
helpful	7	5%	3 (2 astro, 1 dev)	75%
information in the field of view	4	3%	3 (1 astro, 2 dev)	75%
integration of different systems	7	5%	3 (1 astro, 2 dev)	75%
simple	8	6%	2 (1 astro, 1 dev)	50%
useful	6	4%	3 (1 astro, 2 dev)	75%
2. Effectiveness	**2**	**1%**		
effective	2	1%	2 (1 astro, 1 dev)	50%
3. Efficiency	**5**	**4%**		
time consuming	5	4%	2 (2 astro)	50%
4. Workload	**3**	**2%**		
hard task	3	2%	3 (2 astro, 1 dev)	75%
5. Situational awareness	**4**	**3%**		
situational awareness	4	3%	2 (1 astro, 1 dev)	50%
6. Training	**4**	**3%**		
training	4	3%	3 (2 astro, 1 dev)	75%
7. User interaction	**33**	**24%**		
button/clicker	9	6%	4 (2 astro, 2 dev)	100%
double confirmation	3	2%	2 (1 astro, 1 dev)	50%
hands-free	5	4%	2 (2 astro)	50%
interaction	3	2%	2 (2 astro)	50%
voice	13	9%	2 (2 astro)	50%
8. Implementation aspects	**29**	**21%**		
adaptation of technology rather than human	3	2%	2 (2 astro)	50%
AR integrated in the helmet	9	6%	3 (1 astro, 2 dev)	75%
easy data transfer	2	1%	2 (1 astro, 1 dev)	50%
operationally feasible	2	1%	2 (2 dev)	50%
remote support	7	5%	2 (2 astro)	50%
work automation and/or sharing work with off-site scientists	6	4%	2 (1 astro, 1 dev)	50%
9. Concepts of operations	**14**	**10%**	3 (1 astro, 2 dev)	75%
Sum	**139**	100%	4 (2 astro, 2 dev)	–

and hence the importance of placing information in the user's field of view. One astronaut emphasized the importance of showing solely relevant data to avoid cluttering the user's view, hence impairing situational awareness, and affecting safety: *"you don't want to clutter your view, you don't want to clutter all your awareness with information that is not relevant to you*" (R02).

Aspects related to user interaction received the second-highest number of mentions in the interviews (24 % of 139 quotes). While voice input received the most attention (9 % of 139 quotes) from the two astronauts, the use of the button/clicker was addressed by all respondents (6 % of 139 quotes). Interview but also questionnaire data show that most experts believe that voice is the most intuitive and trustworthy means of interaction. Experts confirmed that as long as the voice commands are simple and straightforward to remember, those inputs should be considered primary user inputs. The experts also agreed that having a backup option (e.g., a mechanical interface such as a button) is a good solution. The novel process of *"double confirmation*" was regarded as a good process, as it ensures error-free operations and gives the user more control and freedom over their actions. Opinions seem divided regarding the most effective and efficient type and combination of user inputs needed to complete an action. While some experts valued the current *"few gaze-clicks*" (R06) process, others, especially astronauts, underlined the effectiveness and lower user effort when using voice.

Both support engineers and astronauts mentioned that *"a tool capable of easy data transfer*" (R03) between different systems, such as the developed AR-IoT tool, is especially necessary for geological fieldwork (5 % of 139 quotes). It was argued that gathering and integrating data from the different instruments used in the field could increase the understanding of the performed fieldwork by the scientists and enhance the system's active use by astronauts. One of the astronauts particularly appreciated the cooperation aspect and the integration of different systems and underlined the helpfulness of the tool in simplifying operations while guaranteeing efficiency by saying: *"it is* *absolutely mandatory that clever tools and I think your HoloLens approach is really really nice to come and help the astronaut in simplifying and being way more efficient*" (R02).

The category *implementation aspects* also received a high number of mentions (21 % of 139 quotes). Ideally, AR should be integrated into the astronaut's suit; this was mentioned (6 % of 139 quotes) by both astronauts and support engineers. Nonetheless, one of the main issues is the use of electronics in a 100 % oxygen environment which can lead to fire hazards. Astronauts suggested that such an AR-IoT tool should be "*follow me*" (R01), thus adapting to and seconding the astronaut instead of the other way around. Finally, enabling remote support, in the form of "*virtual colleagues*" (R02) for instance, was mentioned as a useful feature that could increase the mission's scientific outcome. One astronaut said that it is "*especially useful*" when "*you have somebody remote seeing exactly what you are seeing and being able to project things for you in real life or pointing out things for you*" (R01).

A list of illustrative quotes from the semi-structured interviews, selected for each subcategory, can be found in Appendix D.

5. Discussion

Human factors design principles, standards, and guidelines, specifically for displays, have already been well established in the space sector for decades (NASA, 2001, 2010). However, with the rise of modern immersive technologies, precise standards and guidelines have yet to be determined. This research investigates which usability, user interaction, and implementation aspects are important for astronauts with respect to new technologies as well as for the specific use case of geological field activities. Additionally, it explores which of these pre-established design standards are transferable to the design of immersive technologies in general.

It should be noted that the sample size in this study is small (which appears to be often the case in space-related AR studies, see Table A1). However, the results can still be considered representative, thanks to the fact that all participants were experts in the field of astronautics and geological field activities. Future evaluations with large sample sizes would be beneficial.

5.1. User interface

The AR-IoT prototype fulfils most requirements outlined in Table 1. Overall opinions concerning the developed proof of concept were positive; experts commented that the application is "*promising*" and that, in terms of design and development, it is "*a good start*" and "*on a good track*". Experts commented that the application is "*easier and faster*" to use compared to conventional media (e.g., tablets). This is aligned with the common perception of users that hands-free displays are preferable over handheld devices due to the user's freedom to use both hands for a task while having the required information (Alarcon et al., 2020; Furuya et al., 2018). Further details on different aspects of the user interface are listed below.

5.1.1. Layout

For AR interfaces, displaying solely necessary information in the user's field of view is a very important aspect, with both astronauts and support engineers mentioning that one needs to avoid cluttering the user's view, hence impairing situational awareness and affecting safety, similarly to what has been studied in Anandapadmanaban et al. (2018), Furuya et al. (2018), Karasinski et al. (2017). The participants suggested optimizing the amount and type of information displayed by the AR-IoT tool. For instance, minimizing the amount of obstructing user interface elements by bringing irrelevant information to the background and adjusting the size of elements depending on their distance from the user (as reported in Furuya et al., 2018) could play a major role in the AR-IoT tool optimization process. The use of colour coding to increase salience and compatibility of information (Lee et al., 2018) was addressed by choosing vivid blue for the user interface elements and bright white for the text; this was also proposed by Anandapadmanaban et al. (2018) to achieve optimal outdoors visibility. Suggestions for future iterations include testing the interface colours under representative environmental conditions, e.g., simulated lunar conditions.

5.1.2. Capabilities

According to the user evaluations, the tool's interface manages to focus solely on important data for the accomplishment of astronaut geological site evaluation tasks, and the user interface design is task-based. Experts reported that integration and access to a map are essential to increase the usefulness of the tool in the field, as reported in Anandapadmanaban et al. (2018) and Beaton et al. (2019b). In addition, one expert stated that it would be very useful to have the AR tool display distances between sites of interest because it is particularly difficult for humans to estimate distances in terrains with sparse landmarks like the Moon and Mars without any aiding tools (Anandapadmanaban et al., 2018). Moreover, displaying horizon features' names and the location of important vital assets (e.g., lander position, rover position, EVA buddy position in AR) have been listed as desirable capabilities. Finally, having a calculated time allowance to reach a safe haven based on remaining suit consumables and distance to cover was suggested and considered essential data as well; this is in line with recommendations by Apollo astronauts in Scheuring et al. (2008), Schmitt et al. (2011), and was explored in the study by Johnson et al. (2010). The capability of the tool to show consumable levels has been successfully integrated into the AR-IoT tool prototype I. However, it could not be evaluated with user tests due to COVID-19 restrictions at the time.

5.1.3. Usability

The user evaluation results show that only certain usability aspects have been fulfilled, and improvements can be made. In this context, aspects concerning user satisfaction received the most mentions (32 % of 139 quotes) during the interviews. Both astronauts and support engineers argued that an AR tool could be easier and faster to use than the EFB on a tablet as it allows for hands-free operations, which is a paramount aspect for most interviewees.

Both support engineers and astronauts stated that a tool, such as the developed AR-IoT tool, capable of easy data transfer between different systems, is especially necessary for geological fieldwork. It was argued that gathering and integrating data from the different instruments used in the field could increase the scientists' understanding of the performed fieldwork and enhance the system's active use by astronauts. One of the astronauts particularly appreciated the cooperation aspect of the AR-IoT tool and the fact that different systems can be integrated and underlined the helpfulness of the tool in simplifying operations while guaranteeing efficiency.

5.1.4. User interaction

From the interviews and the questionnaire data, it can be concluded that the novel process of "double confirmation" is a good process, as it ensures error-free operations and gives the user more control and freedom over their actions. Multimodal user interaction, such as the double confirmation process, is considered best, especially for AR systems (Billinghurst et al., 2009; Spillers and Mortensen, 2019). The advantage in terms of error-free operations for human–machine communication, in general, has been corroborated by Cohen and Oviatt (1995). Opinions seem divided regarding the most effective and efficient type and combination of user inputs needed to complete an action. While some experts value the present "few gaze-clicks" process, others, especially astronauts, underline the effectiveness and lower user effort when using voice.

In the past, the use of voice and thus speech recognition expressed concerns by Apollo astronauts (Connors et al., 1994), especially because of interferences in noisy environments such as a space station or spacesuit. Especially when astronauts may need to communicate with other crewmembers while interacting with an AR application via voice commands, interferences may become an issue. While the use of voice is still being debated, interviews and questionnaire data showed that most experts believe that voice is the most intuitive and trustworthy means of interaction, which is consistent with the findings of Anandapadmanaban et al. (2018), Byrne et al. (2019), Cardano et al. (2009), and Ravagnolo et al. (2019a, 2019b). The experts confirmed that as long as voice commands are simple and straightforward to remember, those inputs should be considered primary user inputs, as reported in Helin et al. (2019a). According to Microsoft (2022c), voice input for AR applications, particularly the HoloLens, can reduce time, minimize user effort as tasks are supposed to be more fluid, and reduce cognitive demand as it is intuitive. However, the experts agreed that having a mechanical interface, such as a button, as a backup option is a good solution.

The concerns around the use of a button greatly depend upon the integration within the spacesuit. The idea is to integrate the button in the spacesuit's gloves such that the crew would only have to move their fingers, guaranteeing hands-free operations, which is a crucial aspect for EVAs (Anandapadmanaban et al., 2018; Johnson et al., 2010; Scheuring et al., 2008).

Finally, no conclusions can be drawn on the most suitable combination of inputs as a means of interaction for the double confirmation process. Some experts were satisfied with gazing and clicking on a button; others suggested voice as primary input and clicking on a button as backup, whereas others suggested gaze and voice, voice and hand gestures, or eye blinking and tongue clicking. Notably, heuristic evaluators, who had the opportunity to actually wear the HoloLens and try the application, rated the gaze input as effective, clear, and user-friendly.

5.2. Applications of the AR-IoT tool

The developed AR-IoT tool is a promising asset for analogue training missions that involve the simulation of extra-terrestrial geological fieldwork and, in the future, for lunar geological fieldwork. The tool features several desirable and recommended capabilities identified during BASALT-2 analogue missions (Beaton et al., 2019a, 2019b). Furthermore, it is not only supposed to support astronauts in performing geological site inspections more autonomously but also aid monitoring scientists that are off-site in keeping track of the operations performed. Scientists could see what the astronaut is seeing and have immediate access to the data being generated and stored by the astronaut.

This AR-IoT proof of concept, being one of the first of its kind applications, paves the way and represents an incentive for the development of further AR applications for lunar and planetary EVA training in terms of both software and hardware. Several technological constraints are still present in the AR-IoT proof of concept and need to be handled when planning the implementation of AR technologies into operations. Ideally, AR should be integrated into the astronaut's suit; nonetheless, one of the main issues is the use of electronics in a 100 % oxygen environment. A solution for integrating AR glasses or even head-up displays (HUD) within the suit has not been found yet. Moreover, the HoloLens has been designed for indoor use; finding custom-made hardware solutions with a physically more robust design, more powerful sensors, and application-specific hardware will play a major role (Anandapadmanaban et al., 2018).

6. Conclusion

This study aimed to develop and investigate the usability of an AR user interface coupled with an IoT sensors' architecture for future human lunar and planetary surface exploration EVAs as well as astronaut analogue missions. The tool studied has been specifically tailored for site evaluation activities to enhance crew autonomy in the absence of real-time communication with ground control.

Following a user-centred design methodology, which involved questionnaires and in-depth interviews with astronauts and astronaut training experts at the European Astronaut Centre (EAC), relevant design principles for AR were established and compared with other AR space-related studies. Important aspects for AR interfaces, particularly for lunar and planetary EVAs, included displaying only strictly necessary information in the astronaut's field of view, ensuring situational awareness and thus safety, and adjusting interface elements to the user's visual acuity by adapting their distance and size. Astronauts underlined that AR interfaces should be simple and easy to use. AR tools should follow or even second the astronaut instead of the other way around and enable remote support capabilities. Additionally, an AR-IoT tool like the one developed is helpful if it offers integration possibilities with external tools, e.g., analytical tools and/or navigational tools, including easy data transfer.

Astronauts and support engineers perceived the AR-IoT tool as helpful, useful, and operationally relevant. The tool was considered potentially easier and faster than the currently used tools on a tablet because it enables hands-free operations. Its operational feasibility has yet to be tested in the field, but the current results are encouraging. In conclusion, this research highlighted important factors to determine the usability and operational feasibility of such an AR tool for analogue training missions. The results presented provide a firm foundation for future development iterations and an eventual integration of AR into a spacesuit's visor.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Space-related AR studies

(See Table A1).

Appendix B. Expert requirements compliance questionnaire results

In total, seven of the experts that have been contacted provided the completed questionnaire. Hereafter, the frequencies and percentages for each response are described together with the central tendency (Median, Mdn) and the variation (Interquartile range, IQR).

B.1 Interface layout

The interface elements are perceived as consistent (Mdn = 5, IQR = 1), clear and relevant (Mdn = 5, IQR = 1.5), as well as logically grouped (Mdn = 4, IQR = 0.5). Only important data required is displayed (Mdn = 4, IQR = 0.75), and information is easily accessible (Mdn = 4, IQR = 1). The application features, as well as the integration of the different media, are mostly understandable (Mdn = 4, IQR = 1). Experts had different opinions regarding the information density (Mdn = 3, IQR = 1.5). From the associated comments, it became clear that some experts suggested to including additional information for a more complete set of tasks for geological activities, whereas others suggested only including important data in the field of view and adjust the latter to the user's visual acuity.

B.2 Interface capabilities

The design of the interface was rated as task-based (Mdn = 4, IQR = 0). While the necessary capabilities for the geological site inspection tasks are considered present, experts mentioned the following missing capabilities: mapping and navigation, displaying distance between sites and highlighting landmarks, displaying vital assets (e.g., lander, rover, EVA buddy), displaying time allowance, and providing geological sampling support.

B.3 Usability

Experts rated the interface as useful and helpful (Mdn = 4, IQR = 1), as well as operationally feasible (Mdn = 4, IQR = 0.5). Moreover, the provided feedback was rated appropriate (Mdn = 4, IQR = 0.75), and navigation through the interface as clear and intuitive (Mdn = 4, IQR = 0.75). Finally, according to experts, the AR tool has the potential to become flight-proven (Mdn = 4, IQR = 0.5). Experts' opinions seemed to be divided on whether the tool allows for task completion with the minimum number of actions (Mdn = 3, IQR = 1.5) and whether the number of user inputs is minimized (Mdn = 4, IQR = 2). In the added comments, experts suggested different means of interaction and combinations: voice input only, gazing and clicking, voice and clicking, eye blinking, and tongue clicking. Finally, no conclusions can be drawn on whether the tool reduces the user's mental effort (Mdn = 3.5, IQR = 1.75), is designed for efficient use (Mdn = 3, IQR = 1), or is astronaut-friendly (Mdn = 3.5, IQR = 1.25). The latter depends on which the most reliable and intuitive means of user interaction is; for that actual user, testing is required.

Appendix C. Expert requirements compliance questionnaire

1 The application is useful and helpful for future astronaut geology field training and geology field exploration activities on the Moon.
2 The application is operationally feasible for future astronaut geology field training and geology field exploration activities on the Moon.
3 Only data that is important to mission success and significant in terms of crew interface is provided (SSP 50313).
4 The overall display design is based on the geological site inspection tasks that will be performed with the display (SSP 50313).
(i) Specific data shown, the display layout and groupings, and the choice of display elements are driven by operational requirements.
(ii) Information is logically grouped according to purpose, function, or sequence of use (e.g., either a left-to-right or top-to-bottom orientation).
(iii) The display follows operational flows and allows task completion with the minimum number of actions.
5 The display is consistent when grouping/ordering display elements (SSP 50313).
6 The interface elements, colours, and provided feedback are consistent.
7 The interface elements (e.g., text, icons, labels, objects) are clear and relevant.
8 Information density is held to a minimum in displays used for critical geological site inspection tasks (SSP 50313).
9 Primary information required for performing a geological site inspection task is on a summary display (SSP 50313).
10 Information layering, via secondary displays or dialog boxes, is implemented to provide supplemental information in support of the primary display (e.g., specify options available to the crewmember or to provide details) (SSP 50313).
11 The interface is designed for efficient use of crew time and to minimize crew and flight controller training time (SSP 50313).
12 The number of user inputs e.g., gestures/voice/gaze needed to perform simple or routine functions is minimized (SSP 50313).
13 A help function is accessible to the crewmembers (SSP 50313).
14 The display design facilitates error-free operations (SSP 50313).
15 Data is protected from inadvertent errors and hardware failures e.g., frequent saves (SSP 50313).
16 When a process is initiated or completed, crewmember feedback is provided (SSP 50313).
17 When an input is required, an indication is provided to the crewmember, e.g., a cursor change (SSP50313).
18 If the completed command implies the need for further crewmember action, the need for action is indicated (SSP 50313).
19 The application responds to crewmember interaction with appropriate feedback (SSP 50313).
20 Navigation through the interface is clear and intuitive.
21 The application minimizes the user's mental workload.
22 The interface is satisfying for crewmembers and training members.
23 The required information is easily found and accessed.
24 It is possible to understand what the features of the application represent and to realize the integration of the different media.
25 The application is "astronaut crew-friendly".

Table A1
Summary of space-related AR studies and projects.

Study/Project	Topic	Focus	Data type	AR device used	Alternative method	Study design	Dependent measures	User rating scales	Participants
Braly et al. (2019)	Procedural work on ISS	User	O + S	MS HoloLens	Paper manuals	Between-subjects	Task completion time, number of errors, perceived mental workload	NASA TLX, SUS, questionnaires	20 (35 % female, 65 % male)
Markov-Vetter and Staadt (2013)	Procedural work on ISS	User	O + S	Vuzix WRAP920	PDF	Within-subjects	Task completion time, perceived mental workload	NASA RTLX	10 (30 % female, 70 % male)
Furuya et al. (2018)	Stowage operations on ISS	User	O + S	MS HoloLens	Apple iPad	Between-subjects (pilot study), Within-subjects (user study)	Task completion time, number of errors, perceived mental workload	NASA TLX	25 (pilot study), 9 (user study)
Karasinski et al. (2017)	Just-in-time training	User	O + S	MS HoloLens	N/A	N/A	N/A	Direct observations, user feedback	5
MOON (Serván et al., 2012)	Assembly	N/A	N/A	Handheld device	N/A	N/A	Task completion time	N/A	N/A
OnSight (Ramsey, 2015)	Rover operations	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
EdcAR (Helin et al., 2018; Tedone et al., 2017)	Procedural work	User/ Technology	S	Epson Moverio BT-2000	N/A	N/A	N/A	Direct observations, user feedback	14
WEKIT (Helin et al., 2018; Ravagnolo et al., 2019b)	Procedural work	User	S	MS HoloLens	N/A	N/A	N/A	SGUS, SUS, QUIS, interviews, TAMARA, SPINE	39 & 147
MobiPV (Boyd et al., 2016)	Procedural work on ISS	User	S	iPad/Google Glass/ HoloLens	N/A	N/A	N/A	Direct observations, user feedback	At least 4 astronauts
WEAR (Arguello, 2009; Cardano et al., 2009)	Procedural work on ISS	User	S	Custom-built HMD	N/A	N/A	N/A	Direct observations, user feedback	At least 1 astronaut
ARAMIS (Lentini and Afelli, 2020)	Maintenance, Inventory, Stowage	N/A	N/A	iPad	N/A	N/A	N/A	Direct observations, user feedback	1 astronaut
Sidekick (Ramsey, 2015)	Procedural work on ISS	User	S	MS HoloLens	N/A	N/A	N/A	Direct observations, user feedback	At least 1 astronaut
T2 Augmented Reality (Byrne et al., 2019)	Procedural work for maintenance	User	S	MS HoloLens	N/A	N/A	N/A	Direct observations, user feedback	Around 8
ARPASS (Alarcon et al., 2020)	Product Assurance and Safety	User/ Technology	N/A	MS HoloLens	N/A	N/A	N/A	Surveys, interviews	56
Holo-SEXTANT						(Anandapadmanaban et al., 2018)	Planetary EVA Navigation Interface	User/Technology	N/A
MS HoloLens	N/A	N/A	N/A	User interviews and feedback (after field tests)	3				

Note. O: objective; S: subjective; N/A: Not applicable to the study/project, or information not available.

Advances in Space Research 70 (2022) 2145–2166

26 The application has the potential to become "flight proven" assuming that Augmented Reality technology will be an integral part of the astronauts' EVA helmet.

Appendix D. Semi-structured interview quotes

Category I: User satisfaction

Subcategory: Annoying

Two respondents, both astronauts, addressed this subcategory, highlighting what aspects of an AR application they would find annoying, leading to poor user satisfaction. One of them described previous experiences during analogue missions, in this case, NASA's Extreme Environment Mission Operations (NEEMO), where the crew was asked to test different types of applications for maintenance and medical-related tasks with the Microsoft HoloLens:

"it was annoying, it would get stuck, or you know when you finally were able to change the step it would actually change two of them and then it would get stuck and then it wouldn't go back and then I mean it was just... so I was like if I just had a piece of paper in my hands." (R01).

The other respondent referred to the AR-IoT tool developed for this project. Based on the video demonstration, the astronaut mentioned that it is annoying when an application used for fieldwork provides too many options, namely fields to fill in:

"longitude, latitude, modify... honestly I would not need it in the field, and it is just annoying to have too many options." (R02).

Subcategory: Complex

Two respondents, both astronauts, mentioned this subcategory, highlighting what operational technology- and task-related aspects they find complex, hence leading to poor user satisfaction. One of them described previous experiences during analogue missions, in this case, NEEMO, where crew tested an AR application for logistics involving the use of the Microsoft HoloLens:

"I thought OK, I just want to have my single white bag; usually I fire the computer, I punch in a number and I get the stowage location and here with the HoloLens I need to walk through a completely over-lengthened procedure that is way too complex, takes way too long to get me there." (R02).

The other astronaut addressed the fact that maintenance tasks are often complex and that, just as humans have a hard time dealing with these, technology has a difficult time as well:

"but the real pieces of equipment where you really would need help right?! Because they are complex, because they have maybe a bunch of cables and they are very close to each other and maybe they are all tangled and that's where you as a human have a difficult time, but that's also where the technology has a difficult time." (R01).

Subcategory: Easy usage

Three respondents referred to this subcategory, the two CAVES & PANGAEA experts, with the role of support engineers, and one of the astronauts. All gave suggestions on features that would make the developed AR-IoT tool easy to use. One of the support engineers referred to the interaction component and the double confirmation process used for the developed application:

"if you make that piece like very easy to use in a suit and during the operations, that's gonna add a lot of value and I think it is a very good idea to have like this double accepting." (R04).

While describing a complex experiment involving lengthy procedures, as a pdf-file on a computer, which had to be carried out during a NEEMO mission, the astronaut mentioned that an application, potentially an AR application that could guide the astronaut step by step, would ease them while using procedures:

"a program logic guiding you step by step, I think that would be helpful to avoid steps that you easily get stuck or get lost in the text or to ease us." (R02).

Subcategory: Helpful

Three respondents addressed this subcategory, two astronauts and one support engineer. One of the astronauts expresses the difficulties related to operations encountered during PANGAEA analogue missions, namely the cooperation between different instruments, by saying:

"this cooperation part of your instruments, that is really difficult currently using the EVA gloves you cannot use small buttons and you don't wanna go on the small screen like on a GoPro on the bag and then touch stuff, so there it is absolutely mandatory that clever tools and I think your HoloLens approach is really really nice to come and help the astronaut in simplifying and being way more efficient." (R02).

On a different note, one of the support engineers stressed the importance of starting with the development of technology now, despite the current constraints:

"if you think that will be helpful in that case [geological field exploration] it would also be sort of helpful now given the technology constraints. So right now, you have to face with these constraints, in the future you won't, but still if it will be useful for that objective, you have any way to start now to develop it." (R03).

Subcategory: Information in the field of view

This subcategory was mentioned by three respondents, one astronaut and both support engineers. One of the support engineers underlined the importance of information being in the field of view (FOV), particularly in suitable locations for the astronaut doing fieldwork, explaining:

"you know the helmet itself doesn't turn so even if they move their head, they are gonna like see inside of the helmet, so it would be best if it's in that field of view." (R04).

On the other hand, one of the astronauts stressed the importance of only having necessary information in the FOV, saying:

"I mean, you don't want to clutter your view, you don't wanna clutter all your awareness with information that is not relevant to you." (R02).

Subcategory: Integration of different systems

Three respondents addressed this subcategory, two support engineers and one astronaut. Both support engineers, based on their experience with CAVES & PANGAEA, highlighted that, in the future, it would be crucial to integrate external tools, systems and subsystems in the AR-IoT tool; this way the usefulness of the tool can be further increased:

"if you want them to use it actively of course it must be at some point capable of integration with for example the EFB or whatever other system for data transmission, ground anyway has to interact with that in a proper way." (R03).

Similarly, the astronaut mentioned that:

"once you are on the Moon, I also believe that we will have additional tools like the spectrometers and also tools like the camera system or like some measuring devices for distance or whatever, I mean like different types of instruments that all need to be connected, the data needs to flow into the system, so that people later on understand exactly what we did." (R02).

Subcategory: Simple

Two respondents, one astronaut and one support engineer, mentioned the importance of a technology or interface meant for astronauts to be simple. One of the support engineers, who develops technologies for EVAs, while narrating experiences in the development of a cart for astronaut crew for EVAs, said:

"of course, because it was so small and simple, they really liked it." (R04).

When the astronaut was asked what is necessary for an application to be astronaut-friendly, the response was:

"it needs to be simple!" (R02).

Subcategory: Useful

Three respondents mentioned this subcategory, one astronaut and two support engineers. The astronaut argued that only in case an AR tool is essential for the task it is useful; else, it is annoying:

"I have tried the HoloLens, which is obviously one of the professional systems that is out there, and even that was annoying, I mean, of course it is useful if you don't have something else and I think some applications that are especially useful of course is when you have somebody remote seeing exactly what you are seeing and being able to project things for you in real life or pointing out things for you, I mean, those are all things that you cannot do in any other way." (R01).

One of the support engineers, on the other hand, made a suggestion on how to increase the value of an AR application by enhancing its usefulness. More specifically, the support engineer explained how, during Pangaea missions, crew was given zoom cameras on a long stick (as bending to reach the ground is very difficult in a spacesuit) to inspect samples:

"if they had a tool that could like give them a close up and that they could kind of already display in that system and I think that would be very useful as well, I mean I know it's an external tool, but I am just saying that a link to those additional tools would increase the value as well." (R04).

Category II: Effectiveness

Two respondents mentioned this subcategory, one astronaut and one support engineer. Both stressed the importance of technology leading to effective operations. Referring to the developed AR-IoT tool, the astronaut said:

"that's exactly what we are looking for, tools that give us more autonomy and lead us to efficient and effective operations." (R02).

The support engineer said:

"the final goal is still of course improved exploration, so improve technology to support effective sampling, scientific experiments and operations on the field." (R03).

Category III: Efficiency

Subcategory: Time consuming

This subcategory was mentioned by two respondents, both astronauts. These narrated their experiences during analogue missions, Pangaea and NEEMO, respectively, and explained their concerns regarding tasks/operations being time-consuming with the technology at hand:

"the EFB had too many steps, they are all interlinked, so it was time-consuming, as, to go to one action, one had to go through all the prior steps." (R02).

"that was a little bit of rickety type of instrument, and it was quite a complicated calibration and setup procedure, so that was a little bit challenging and time-consuming and we were, we had this procedure on the iPad; however, we didn't really have a good solution to like hold the iPad while we were reading; we also didn't want this iPad to be on the seafloor because if you had like sand going into the seal of its case it might just damage it and then it might have leaks and you now not have an iPad the next day." (R01).

Category IV: Workload

Subcategory: Hard task

Three respondents mentioned this subcategory, two astronauts and one support engineer, highlighting activities that are challenging during astronaut geological fieldwork:

"it's really hard for them to say if the sample is really interesting if they look at it from a distance, and, I mean, you know they are tall guys trying to look on the ground, the ground will anyway be really bright and not all samples are actually interesting for scientists." (R04).

"this cooperation part of your instruments, that is really difficult currently using the EVA gloves; you know you cannot

use small buttons and you don't wanna go on the small screen like on a GoPro on the bag and then touch stuff." (R02).

Category V: Situational awareness

This subcategory was mentioned by two respondents: one astronaut and one support engineer. The importance of the astronaut maintaining situational awareness during operations in the field was underlined by both the astronaut and the support engineer, who said, respectively:

"*the EFB on tablets during Pangaea-X was a good tool; a lot of interaction was required with the tablet which would make you lose awareness of the site around you. A tool like yours is definitely something we look forward to.*" (R02).

"*humans have to collaborate together with a tool capable of easy data transfer, for sampling, for operations and coordination and situational awareness.*" (R03).

Category VI: Training

Three respondents mentioned this subcategory, two astronauts and one support engineer. The importance of geological field training for more crew autonomy in connection with innovative support tools was mentioned by one astronaut:

"*we figured out that it is hugely important that the astronaut is much better trained to be autonomous for like even scientific decisions and indeed to have also the right tools obviously we are all or most of us are not the perfect scientist.*" (R02).

The other astronaut referred more specifically to potentially beneficial effects achieved through training with AR applications specifically. The astronaut mentioned that none of the applications tested led to a satisfying usage, with one of the reasons being short training times:

"*in neither one of those cases, I had the chance to like use it [Microsoft HoloLens] for a long time. So, the question is, is there a training effect if you use it for five hours, ten hours, twenty hours, fifty hours, does it then become second nature? And then you might say, oh my gosh, it's great; I never want to do anything without it; it's just that I think it takes time to verify that.*" (R01).

Category VII: User interaction

Subcategory: Hands-free

Two respondents addressed this subcategory, more specifically, the two astronauts. They both mentioned the astronaut's need to be able to work hands-free during EVAs; one of them referred to the general need to work hands-free when in the field:

"*I think every activity when you are out in the field where you need to work hands-free.*" (R02).

The other one referred specifically to a NEEMO analogue mission scenario, and, more generally, to EVAs on the International Space Station (ISS):

"*what seemed to work much better was to have the IV, like the person inside just reading the steps of the procedure to us so we could work hand-free just basically what people do in EVAs on the space station nowadays, I mean they have somebody read the next step to them, so they don't, you know, we don't carry any written reference.*" (R01).

Subcategory: Voice

This subcategory was addressed by the two astronauts. Both agree that voice, e.g., speech recognition, should be a primary means of interaction with modern interfaces such as the developed AR-IoT tool, explaining:

"*ideally of course it should be voice and maybe a button just as a backup for whatever reason voice is not working or for whatever reason there is a very noisy environment in the suit and it's interfering, but I think as a baseline it should be something that you don't need your hands.*" (R01).

"*voice*; *voice command and voice recording is definitely the solution!*" (R02).

Subcategory: Buttons/Clicker

All four interviewees addressed this subcategory. While one of the astronauts preferred a mechanical interface such as a button, the other expressed concern about the interaction being hands-free if the mechanical interface, e.g., a button or clicker, is not integrated such that it ensures hands-free interaction.

"*I actually prefer like a more old-style mechanical interface if that is absolutely robust so like there is one button on the EVA suit as an interaction that you mentioned that definitely is, I think the way that the engineers would decide.*" (R02).

"*if you are doing something with both of your hands, what do you do? Unless it's a button that is somehow integrated on your hand itself and you just need to move a finger or something like that.*" (R01).

One of the support engineers made a different suggestion, namely using a smartphone-like interface that could ease the interaction:

"*if, instead of using the "clicker" button, you connect it to a smartphone and you implement two buttons on the smartphone interface, because these are easy to press if they are big, you can, for example, have one button to "create a site" and the other one for, I don't know, something else, such that instead of having to go into the menu and waiting for the AR button to load and the flag to appear, when you press the button "create site" on your smartphone, the flag readily appears moving in front of your eyes.*" (R03).

Subcategory: Double confirmation

Two respondents addressed this subcategory: an astronaut and a support engineer. The support engineer mentioned that using a double confirmation process is correct, pointing out that different combinations of inputs could have a large impact:

"double confirmation, no but it's good, it's good, I think this is a very good idea, it should be done this way and but probably there are like many options it can be clicker I don't know what else it could be but like probably there are some other options and I think by varying those options you actually make it much much better or worse." (R04).

The astronaut suggested an alternative combination to gazing and clicking:

"instead of the clicker, the double confirmation: gazing plus audio [voice] should also be an option." (R02).

Subcategory: Interaction

Two respondents, both astronauts, addressed this subcategory, stressing the importance of keeping the user interaction with a tool, interface, or procedure to the minimum and simple to avoid critical consequences. One of them explained:

"in NEEMO, we had a procedure that had more than 50 pages, it had a lot of interactions, and so it was a complex experiment, and as soon as you made one error the entire experiment was doomed." (R02).

Category VIII: Implementation aspects

Subcategory: Adaptation of technology rather than human

Two respondents, both astronauts, mentioned this subcategory. They explained the importance of a tool that is meant for astronauts to adapt to the astronaut rather than the astronaut having to adapt to the tool. One astronaut explained:

"It should follow me, and I shouldn't be adapting to the tool, it's the tool that should be adapting to me." (R01).

Subcategory: AR integrated into the helmet

Three respondents mentioned this category, one astronaut and two support engineers; all agree that currently, there are technological constraints when it comes to the integration of AR in the spacesuit, such as current devices neither being certified for vacuum nor for spacesuits, which have 100 % oxygen, where the use of electronics can lead to fire hazards. The astronaut mentions:

"having this device inside the helmet would be preferred from a designer point of view so like a pilot, like a heads-up display, but currently NASA is trying to avoid this for the first Artemis missions because inside the spacesuit you have 100 % oxygen, you remember Apollo 1?" (R02).

Nevertheless, the technology development has to start now, as the support engineer pointed out:

"I think anyway that NASA is, how to say, already struggling in having a HUD, so I don't really think that for at least 5–6 years there will be a development on AR, or a usage of AR, its good anyway to have proof of concepts and proceed the development because at some point we have to be ready to embed them in the proper technology, yes totally." (R03).

Subcategory: Easy data transfer

This subcategory was mentioned by two respondents: one astronaut and one support engineer, both agreeing that easy data transfer is a crucial need of modern tools and interfaces meant to aid crew during EVAs:

"humans have to collaborate together with a tool capable of easy data transfer, for sampling, for operations and coordination, and situational awareness." (R03).

"to setup all the systems and to transfer data from instrument A to the EFB, that also needs to be easy." (R02).

Subcategory: Operationally feasible

This subcategory was mentioned by two respondents, both support engineers, who raised the importance of operational feasibility when designing tools and interfaces for EVAs:

"if you use everything together, you basically don't have enough hands. I mean, [the] astronaut would have to hold the tools but still click on the tablet and that just, you know, didn't work all the time, so he would have to put the tool away to check something in the electronic field book or like press few buttons, then take the tool back, then to take a picture with another tool they also had to click it on the tablet, and they were complaining that it's not like really feasible." (R04).

*"it must be also comfortable to bring on your head for prolonged sessions, for example hours, a traverse it will last at least two hours, it can be up to four hours, six hours, you have to be with power constraints; of course you can connect batteries et cetera but you can't connect, I don't know, six kg of power banks just to power the heads-up display otherwise, I mean, it's unfeasible."(*R03).

Subcategory: Enable remote support

The two astronauts addressed this subcategory. One of them referred to the importance of enabling remote support, in the form of "virtual colleagues" to increase the scientific outcome of the mission through future innovative interfaces:

"so, this is the main point: to increase the outcome of the mission, to get more scientific data without bringing actually the stones back and also to enable virtual colleagues to walk with you in the field so and all this needs to be integrated efficiently and shouldn't lead to an overload of the astronaut." (R02).

The other one mentioned that enabling real-time remote support through an interface, such as an AR application, would be an irreplaceable feature:

"I have tried the HoloLens, which is obviously one of the professional systems that is out there, and even that was annoying, I mean, of course it is useful if you don't have something else, and I think some applications that are especially useful of course is when you have somebody remote seeing exactly what you are seeing and being able to project things for you in real life or pointing out things for you, I mean, those are all things that you cannot do in any other way." (R01).

Subcategory: Work automation and/or sharing work with off-site scientists

This subcategory has been addressed by two respondents: one astronaut and one support engineer. Both addressed the importance of relieving the astronaut crew from work which is transferred to the monitoring scientists. The support engineer described an idea that emerged during one of the Pangaea missions:

"they also had an idea, what if the astronaut takes the picture, it being sent to the scientists and they give it a name, they create that folder for [the] sample and whatever, what if they just do the necessity and then either some system does it or just scientists that do it manually. So, I think your system could be like the dummy scientist who does like some of the work that is repetitive in some way." (R04).

The astronaut explained how some processes should be automated to a certain extent:

"if everyone starts calling and questioning me, and then I could easily get distracted and if they say like: enter this data, enter that data, so that should not be the case, so if they wanna have additional data, then it needs to be an easy work flow or it should also be maybe semi-automatic." (R02).

Category IX: Concepts of operations

This subcategory was mentioned by three respondents: two support engineers and one astronaut. They all addressed the new concepts of operations being currently tested during the Pangaea analogue missions enabled by modern tools:

"the electronic field book, for example, it allowed us to test an exploration scenario, where the two astronauts work in close vicinity but actually have two different tasks to do, then you say, astronaut 1 collects rock 1 and astronaut 2 collects rock 2, so those need to document, those need to describe what they see, the context to enter the data." (R02).

"what we tested is the response time of humans to certain tasks, the time to reach a point in the traverse and then maybe to split, to separate, and then sampling, each astronaut sampling its own spot and then coming back together everything of course with this data sharing." (R03).

Appendix E. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.asr.2022.07.045.

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