Technical

Abstract

The Collaborative Lab for Advancing Work in Space (CLAWS) proposes the *Immersive Reality Interplanetary System* (IRIS). IRIS is an interactive augmented reality interface that supports astronauts in EVA operations on Mars by helping crewmates perform UIA egress, navigate to and from locations of interest, assess geological samples, direct a rover, perform airlock and ingress procedure, and manage equipment and diagnosis repair.

IRIS's design aims to be seamless, intuitive, visually lightweight, and as automated as possible. To support this, IRIS provides astronauts with AR screens and audio feedback to help astronauts complete each operation. Astronauts may interact with IRIS's interfaces using voice commands or tactile inputs for maximum flexibility and usability. Tasks each trigger a unique *mode*, in which the layout of screens will change to aid the astronaut in the specific operation they are performing. Each *mode* will show only the most relevant screens to the astronaut for their current task.

With IRIS, CLAWS' goal is to provide a fully functional and realistic simulation of an AR head-mounted display (HMD) in Mars EVA conditions as it interacts with the Local Mission Control Console, peripheral hardware systems, a rover, and other astronauts. IRIS supports and enables seamless, effective teamwork between all parties involved in an EVA. Features like the task list, map, and vitals monitoring have been designed to allow astronauts to monitor the status of other astronauts. Throughout the entirety of the EVA, there will be two-way communication between astronauts and the Local Mission Control Console (LMCC) controlled by the IVA operator. The geological sampling, rover commanding, and navigation procedures have also been designed realistically, incorporating NASA's expectations and concerns in their Mars EVA CONOPS.

The LMCC is a mission control center designed for local activities based on Mars, which allows for planned autonomy. In the case of unexpected situations like broken equipment, loss of communication (LOC), or an incapacitated crewmember (ICM), IRIS is proactive, helping astronauts to mitigate potential issues in advance and respond quickly to issues when they arise. LMCC is built to be powerful, enabling the IV to send astronauts informational messages, images, and drawings; generate navigational routes; highlight screens on the astronaut's UI; and take control of astronaut suit settings.

IRIS will allow CLAWS to comprehensively simulate astronaut operations and mission control operations on a Martian EVA. In this proposal, we will describe the system we plan to build and our motivations behind those choices.

Software and Hardware Design Description

Design Concept

IRIS's augmented reality information display will seamlessly adapt to astronauts' current needs. Through past anonymous astronaut interviews and research, CLAWS has determined astronauts prioritize having their hands free during EVAs (Anonymous Informant #1, personal communication, Oct. 20, 2022). Thus, the system will be primarily controlled through voice commands, and direct touch interaction will serve as a fallback input medium. The interface will be designed around a navigation bar containing key features and the ability to launch focused *modes* for specific tasks (Figure A). These *modes* will reduce visual overload by hiding less relevant information during tasks. IRIS's design will be

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visually lightweight, with subtle animations and restrained color use. Feature-rich, simple, and consistent flows will put the astronaut in control, enabling true autonomy with ease. The system will automate as much as possible, automatically changing suit controls to remedy issues and classifying geological samples' shape and color. Multiplayer capabilities will be integrated throughout IRIS, allowing astronauts to communicate with and monitor one another. Information between AR and the LMCC will be directly synchronized, with the LMCC being able to control all aspects of an astronaut's HMD. These design choices have been derived from the NASA CONOPS document in consideration of Mars EVAs potential concerns and points of failure as well as design heuristics intended for effective use of AR technologies [1, 2].

Task List

The task list will allow the user to see all mission tasks and subtasks that have been assigned to the user, as well as the name and description of each subtask (Figure M). A progress bar will show the overall EVA status and, throughout the entire EVA, the user will be able to see their current task by looking down at a screen placed near their stomach. This screen will be placed outside the user's normal FOV, but will be easily accessible by looking down. In the case a user shares a task with their companion astronaut, the task list will show the names of each astronaut working on the task and whether they are ready to begin the shared task. The LMCC will show all tasks for all astronauts in the EVA. At any time during an EVA, the IVA operator can create a new task or edit an existing one. These changes will be relayed to each astronaut with the new or edited task via a pop-up message, and the astronaut's task list will update accordingly.

UIA Egress and Utility Air Lock

To support the astronaut during UIA Egress, IRIS will use a computer vision (CV) panel-tracking system to display a holographic arrow over the current UIA switch that the astronaut needs to toggle.When a switch is correctly toggled, the UI will update and a new arrow will appear over the next switch. In the case of CV failure, IRIS will send a pop-up with information on the name of the next switch and additional parameters that must be met (Figure C). IRIS will also provide warning messages to alert the astronaut if switches are moved incorrectly.

IRIS will also use CV to support astronauts during the Utility Air Lock procedure by displaying a holographic arrow over each air lock latch that the astronaut should pull. During this task, the IVA operator will select specific latches on the LMCC for the astronaut to pull while watching a live video feed of the HMD. IRIS will then show arrows over the corresponding latches and alert the user if they pull an incorrect switch.

Equipment Diagnosis and Repair

The LMCC enables robust equipment diagnosis and repair capabilities to assist astronauts during EVAs. The LMCC can guide the astronaut through repairs via voice instructions based on live video feed and conversation. To further aid in troubleshooting, the LMCC can send relevant information, such as cue cards, images, diagrams, and illustrations, directly to an astronaut's HMD (Figure M). For more precise guidance, the LMCC has the ability to visually highlight specific buttons on the astronaut's display. With this diverse set of assistive features, the LMCC allows for flexible, customized troubleshooting tailored to any form of equipment failure.

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Geological Sampling

When an astronaut enters an area they would like to investigate for geological sampling, they will enter *Geological Sampling Mode*. In this mode, the user will scan many samples within a geological sampling zone. The user will first take notes and pictures of the geological sampling zone. Then, the user will begin taking individual samples. During this process, IRIS will use CV to determine important metadata tags like the shape and color of samples. Geological sampling screens will be spatially anchored to the location of the sample and will contain information such as XRF data, location, shape, and color. The user can interact with these screens to check relevant data, record speech-to-text observations, and take pictures of the sample (Figure D). The user may also "recall" the sample screens to them to interact with them within a HUD rather than in space allowing for easier access.

Additionally, LMCC will receive all scanned sample data, sample zone data, and can indicate samples of interest. The corresponding sample screens will then be highlighted within IRIS. LMCC will also give the IVA operator the ability to search the database of samples using the metadata tags attached to each sample. This gives LMCC quick access to samples that may otherwise be hard to find. The AR UI will also have a geological sample database, which can be accessed through geological sampling zones folders (Figure E).

Map

IRIS will contain a 3D map, which can be opened via a voice command or button within the menu. This will place a 3D render of the local Martian surface in front of the user in space. When the 3D map is open, the user will be able to rotate the map on the y-axis, zoom in and out, and place pins at any location using touch input. This 3D render will also showcase all features related to navigation such as pins, dangerous terrain, navigational paths, rover location, and companion astronaut location (Figure L).

IRIS will also include a 2D miniature elevation map of the rock yard that is fixed at the user's location. This will serve to show all important information related to location and navigation at a glance. The map will show the user's current path in addition to pins, stations, and the companion astronaut's navigational path.

Navigation

IRIS will enable dynamic route-planning to any landmark, point of interest, or astronaut using Unity NavMesh on a 3D terrain map. In *Route Planning Mode* a user can walk around a 3D map anchored to world space and can select multiple pinned locations to navigate to. The most optimal navigational path would then be rendered on the 3D map and additional screens will show route details, like the distance, estimated time, and estimated resource consumption. When a route is confirmed, *Navigation Mode* will begin (Figure L).

In *Navigation Mode*, the UI will shift to a more focused layout to support navigation; screens that are normally positioned near the user's stomach will either disappear or shift to the side to allow the user to look down and avoid rocky terrain as they walk (Figure B). A trail of breadcrumbs will show a path that avoids terrain hazardous to the user. As the user walks, they will see a screen that shows navigation metrics, like the destination, elapsed time, remaining distance, and traversed distance. Additionally, waypoints will show up in space at the locations they are defined at within the map. Upon reaching a destination or manually ending navigation, *Navigation Mode* will end.

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LMCC can also play a vital role in navigation. The IVA operator can create a route plan for an EVA astronaut and send this to the astronaut anytime during the EVA. The user who receives this route may view it in *Route Planning Mode* and then begin navigation. During *Navigation Mode*, the LMCC operator will be able to see each astronaut's breadcrumb trail in the console's 2D map as well as each astronaut's navigation metrics. At the end of the mission, the user can start the ingress procedure by navigating back to the starting station (Figure H).

Rover Commanding

The LMCC provides robust capabilities for remotely commanding the rover and showcasing rover system state data. The rover adds an additional level of mobility to the team, providing storage and imaging capabilities, as well as acting as a safety resource [1]. The IVA operator can control the rover on the Martian surface by utilizing two live camera feeds on the vehicle alongside mouse and keyboard input. For navigation guidance, the LMCC displays a mapped path showcasing the optimal route the rover should take to a given destination. Once the rover arrives at a site, it can remotely pick up and drop geological samples under the LMCC's control. The rover logs location data for each sample collected, takes pictures, and allows the operator to append textual notes (Figure I).

Vitals and Suit Data

From astronaut interviews and test week feedback, CLAWS has learned that users typically only want to see vitals and suit data if the values are entering off-nominal ranges. Thus, IRIS shows only the EVA mission time persistently to the user. If more detailed vital and suit data is required, the user can expand a vitals screen, which will include biometric and suit data for both the user and their companion astronaut (Figure F). All this information will be forwarded to the LMCC, allowing the IVA operator to track the health and suit systems of the astronauts on the EVA.

In the event of EV suit or biometric data entering off-nominal ranges, IRIS's caution and warning response system will automatically engage. The application UI will alert the user of the issue. The user will have the capability to manually adjust suit controls (Figure G). IRIS can also automatically adjust the suit controls to fix certain issues with the EV suit. The user will be prompted to decide to either accept or reject these changes. In addition, IRIS will send a warning alert to LMCC and the companion astronaut. In the case of an ICM, the LMCC operator can directly take control of the endangered astronaut's suit controls.

VEGA

In previous testing, CLAWS has found that users greatly prefer voice commands over tactile or eye-gaze inputs, especially in the context of astronaut EVAs. IRIS is designed to be controlled primarily through verbal commands, with tactile inputs available as a fallback. Our Voiced Entity for Guiding Astronauts (VEGA), an AI voice assistant that classifies astronaut voice commands based on intent, will be expanded upon to increase flexibility and efficiency. Further development will improve VEGA's ability to break down multi-step commands into a sequence of actions. VEGA will act similarly to a human assistant, having the ability to quickly complete complex tasks after being prompted by an astronaut. These multi-step commands will more closely resemble natural speech, and are especially useful for making *geological sampling*, *navigation*, and *rover commanding* faster.

COR

Through research and previous experience with the NASA SUITS Challenge, CLAWS has found the HoloLens' field of vision to be a major obstacle in the usability of our application. The device's FOV is

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limited to only 52 degrees [3]. Last year CLAWS implemented a software fix to partially address this issue. This year, the team is utilizing software in tandem with a hardware solution to expand the HUD space of IRIS. COR (Cardiac and Orientation Reporter) is an orientation unit with an inertial measurement sensor that sends heading data to the HoloLens. COR will use this information to effectively expand the FOV of the HUD by orienting screens to the astronaut's body rather than their head. The intended functionality of this sensor can be seen in Figure J and Figure K. When the astronaut looks to either side, screens in the HUD will stay body-locked, matching the rotation of the user's chest. This functionality will allow HUD screens to be placed above, below, and to either side of the astronaut, rather than always appearing head-locked.

SCOUT

IRIS will require a high-fidelity 3D render of the Martian surface to enable its navigation features. To enable this, CLAWS will develop SCOUT (Space Companion for Observing Uncharted Terrains), a fully featured rover focused on improving the navigational abilities of our application. Utilizing lidar and RGBD cameras, SCOUT will map the Martian surface autonomously. This data and the coordinates of any dangerous terrain will be sent to LMCC and the HoloLens. With this information, we can create navigational paths that avoid obstacles and keep the astronaut safe.

Technical Implementation

AR

The AR team will use the Unity game engine and Microsoft's MRTK 2 toolkit to create UI and interactive components. MRTK contains many built-in features and UI that the team will modify to fit the outlined goals for IRIS. Our software architecture relies on a publisher-subscriber event system to decouple dependencies between features, allowing for modular development of multiple features simultaneously. To enable rapid, iterative testing by the UX team, we have made a CI/CD pipeline. Developers will push new changes to GitHub often, which will trigger an automatic WebGL build through GitHub Actions. Members of the UX team can view this WebGL deployment online and quickly give feedback. To ensure the Web, AI, and Hardware teams' deliverables can integrate with the AR component, we have already defined a detailed API and data flow diagram that describes how data will be sent and received through JSON (Appendix D). The WebGL deployment will also allow these teams to rapidly test integration to AR without requiring Unity or a HoloLens.

Web

The web team will utilize a React frontend to provide the LMCC interface. This frontend will be supplemented by a ExpressJS RESTful API, which will provide several endpoints that allow the frontend to interact with system data stored within a MongoDB database. Websockets will be responsible for transferring a majority of data relating to astronaut vitals, locations, and task progress. These connections will have fault tolerance to detect connection failures. The web team will utilize a CI/CD pipeline to allow AR and UX teams to fully utilize LMCC features during the development process.

AI

In order to perform command classification IRIS will utilize a speech-to-text service to transcribe astronaut speech. VEGA will then utilize an intent classifier built using RASA to determine the intent of a given command, which can either lead to an action (such as retrieving vitals) or could be a compound command that can be parsed utilizing an LLM (LLAMA2). Which will break down complex commands

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into a sequence of actions (chain-of-thought LLM prompt). To achieve the panel-tracking implementation for UIA Egress and Utility Airlock tasks, spherical markers will be affixed to items of interest, such that we can utilize a Haar Cascade Classifier to detect said markers within the astronaut's POV. AR ray-casting can determine depth, such that the orientation of the given panel can be determined in real time (Figure C). To perform AI sample detection, VEGA will utilize a YOLO5 object detection model, which will be trained to identify viable geological samples and estimate their makeup and type by their color and shape.

Hardware

The Hardware team will utilize resources from the university, Intel, and Nvidia to gather the materials and sensors needed to develop the heart rate sensor and SCOUT. The Hardware Team plans to use a Raspberry Pi programmed with Python to read information from a heart rate sensor and send it wirelessly to the HoloLens 2. Additionally, the team will use lidar and RGBD sensors aboard SCOUT to create a 3D map of the area SCOUT is in. SCOUT will use the Robot Operating System (ROS) running on a Nvidia Jetson board to process and send this data wirelessly to the HoloLens 2. The team will utilize 3D printing to design and develop the chassis of SCOUT. The Hardware team will also conduct in-depth research into the capabilities of each component and create a hardware and systems design for each.

UX

The User Experience Design team will craft a design system within Figma, utilizing standardized, reusable components. This foundation will enable rapid design iteration while preserving feature consistency. Design components will be flexible, allowing their implementation to be tailored to each feature's specific needs. The team will also use a comprehensive research process for deducing optimal design decisions, involving interviews with astronaut contacts and a design exploration procedure. Throughout all design stages, concepts will be subject to design reviews to review functionality and aesthetic considerations.

Research

Our design decisions are based on research into NASA's EVA procedures for Mars, Microsoft's design recommendations, astronaut interviews conducted by CLAWS, and user-testing feedback from our previous AR interfaces–HOSHI and NOVA. Last year, the team conducted research to examine the effects of varying luminescence and hand coverings on HoloLens functionality, published in the Journal of Human Factors and Ergonomics Society [4]. This year, our team plans to simulate the effects of background noises as heard in a real Mars EVA setting on the reliability of voice commands on the HoloLens 2, expanding on previous research that examines the effects of office background noises on the HoloLens 2 [5]. An alternate research topic is to simulate the red luminescence of the Martian environment and examine its effects on HoloLens 2 reliability. In addition to these experiments, the research team will facilitate HITL testing with test participants outside of CLAWS at the end of the year, and conduct outreach at events and conferences.

Concept of Operations (CONOPS)

IRIS is primarily controlled through voice commands, allowing the astronauts' hands to remain free during their EVA. A menu pane and mini-map persistently stay at the top of the HMD. As a backup to voice commands, IRIS also supports direct touch interaction. There will be constant two-way voice communication between LMCC and EVA astronauts. The following six scenarios showcase a detailed sequence of potential mission events, presenting IRIS's assistive capabilities in an EVA. The procedures

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