The Design of an HCC Based Mixed Reality User Interface to Support Astronauts in Lunar Activities

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NASA’s Artemis Mission will land our astronauts on the Moon by 2024. A next generation spacesuit for astronaut use is needed based on cutting edge cyber technologies and interfaces that are human centric, efficient and effective. NASA refers to such a space suit as the Exploration Extravehicular Activity Mobility Unit (xEMU). In this paper, the focus is on the process to design and develop an innovative user interface for the xEMU based on a 3D Head Mounted Device (running on the HoloLens 2 platform). This User Interface (UI) uses MR technology to assist astronauts with various Extra Vehicular Activities (EVA) in an intuitive, efficient and effective manner. This design is generated based on Human Centered Computing (HCC) principles, including affordance and cognitive load. The design process, the design outcomes and the results of the field tests is discussed in this paper.

I. Introduction

The next-generation lunar spacesuit, the exploration extravehicular mobile unit, defines the requirements for the visual display system. In future missions, the dynamic visual display system optimizes the effectiveness of astronauts’ ground operations [1]. Displays such as mixed reality (MR) are tools that can interface with lunar payloads, support scientific work, visualize consumables, simplify communication between crew members, support interaction methods of the mission control center (MCC) and navigate the terrain. The development of a visual information display system enables NASA to improve and innovate optical solutions in the emerging MR field, making the future EVA mission more efficient and effective.

This paper discusses the process and results of creating the user interface for the NASA Suit project. The overall goal of the SUITS project is to design an innovative user interface (UI) to support the autonomous operation of the gateway and related modules proposed by NASA. The design of these interfaces considers the main functions they need to support, enabling the unit to perform various operational functions, including access control.

The main goal of SUITS is to develop a user interface, use HMD devices in mixed reality or hybrid reality, and assist the crew in undertaking EVA responsibilities and tasks in a non-abrupt way through programs and EVA system status information [2]. This may also include peripherals (i.e., hand controls, unique positioning/navigation sensors, secondary indicators, virtual reality components, applications, cameras, etc.). The test scenario provides a specific lunar environment and resources for the design evaluator to test the student design in the test week, enabling the team to design the lunar exploration mission defined in this mission description. MR device should consider the following main functions:
1. Navigation: MR devices must guide users accurately in real-time and help navigate between multiple EVA assets and designated geological excavation sites. Students use their HMD internal sensors (local device coordinates), standard navigation algorithms, appropriate images (for identification/camera visual needs), and any other external data/information to help users navigate in the lunar environment.

2. EVA system status:
   - MR equipment must interact with protective clothing ports to perform airlock activities (i.e., UIA, DCU, in-cabin spacesuit preparation)
   - MR devices must interact with the specified telemetry suite to present vital signs unobtrusively.

3. Geological sampling: MR equipment must facilitate scientific sampling, scientific camera/image needs, and geological field recording at the designated lunar simulated geological excavation site.

4. Supplementary consideration:
   - Lighting conditions - the user interface must adapt to high contrast areas, between bright and dark areas, as it does on the moon's South Pole.
   - Control method - the control method component (which can be the only implementation or standard of the selected MR device) allows users to perform EVA tasks efficiently.
   - System tutorial - the user interface must include a short training or welcome video that provides users with instructions on using the features and browsing the user interface design. In this year's full remote test scenario, there is an urgent need for new users and subject matter experts to understand the UI environment of each team.

The overall user interface design based on MR emphasizes user-centered design, next-generation mixed reality technology, system engineering, and software engineering principles.

As part of the course project activities of the Department of computer science at Oklahoma State University, the project activities are completed within one semester. They are part of the curriculum project activities, involving a multidisciplinary group of undergraduate and graduate students from computer science, electrical engineering, and computer engineering.

The planned activities are completed using the system engineering (SE) method, emphasizing the design concept based on the principles of software engineering. The design of the target user interface is based on the human-centered principle (formerly known as HCI). It explores the adoption of next-generation virtual reality technologies and technologies to facilitate immersive verification of the proposed design.

There were 2 primary objectives of the SUITS Project, which include:
1) The creation of MR based UIs to support the astronauts in EVA tasks during lunar mission.
2) The assessment of impact of HCC based criteria such as affordance and visual density during the user interactions with the MR based UIs.

II. Design of the MR Based Simulators

The overall design method emphasizes the system engineering (SE) process and emphasizes the HCI and software engineering principles.

A. Role of Systems Engineering and IDEF-0 based function modeling

In general, systems engineering (SE) emphasizes an interdisciplinary process to ensure that the needs of customers and stakeholders are met in a high-quality and timely manner throughout the life cycle of the system. SE also focuses on the formulation, analysis, and interpretation of each phase of the system life cycle [3]. SE can be applied to any system, complex or other system using the system thinking method. SE is also used to verify the system and interactions within the system. SE method can be top-down, bottom-up, or middle out. In the top-down approach, the top-level process is decomposed into layers from abstraction to implementation [4]. The SE approach is tailored to the scope and complexity of the SUITS project. The SE principles adopted include:
1) Meet the needs of customers, let customers participate in the design process.
2) A multidisciplinary team of computer science, electrical engineering, and mechanical engineering students participated in the project. Se thinking helps to integrate planned activities.
3) It emphasizes the generation of user interface requirements and adopts the requirement-driven design method.

4) Create use case diagrams or models that represent a process or functional scenarios to use these tools (associated with individual modules) and the Requirements Driven Design of the system.

IDEF-0 modeling method is used to emphasize the adoption of system engineering principles and describe the functional processes of various activities [5]. IDEF stands for integrated definition, which is an information modeling industry standard and supports the adoption of system engineering principles.

The creation of the function model of the target process has been used as the basis for building the software environment in different fields; This functional model is the basis of developing automatic fixture design method and system for manufacturing application [6, 7, 15-19] and space system application [20-22]. An information centric orthopedic surgery process model is established, and a medical training IoT framework is designed based on this model [8-10, 23-27]. The framework is designed and implemented based on the information centric system engineering method. The framework adopts the principle of participatory design, and designs a simulation environment based on tactile and immersive virtual reality. Expert surgeons play a key role in creating information centric process models (iCPM). Then, based on the iCPM, a simulation training environment based on touch and virtual reality is designed and constructed.

Generally, IDEF-0 model can model a variety of software development, manufacturing and other processes graphically at the required level of detail (or abstraction). IDEF-0 model consists of a series of cross-referenced graphs, texts and vocabularies. In this proposal, the Suit project activities (completed by students) appear in the form of functions (verb phrases in rectangular boxes); The related data and objects related to these functions are represented by arrows and divided into four categories, which are called ICOM (input I, control C, mechanism m and output o). The direction of the arrows (relationships) entering or leaving each activity box is shown in the illustration in Figure 1. Control attribute refers to the concept or data (e.g. plan, task target, and input) that controls the performance of a given activity. Input refers to the physical or data / information input required to perform the activity (requirement, etc.). Output refers to the result of the activity (it can be the completion of the design, etc.). Mechanisms are the resources (software, personnel, equipment, etc.) needed to perform a given function. Using IDEF-0 method, the SUITS project plan is shown in Figure 1.

The design and construction of user interface module follow the principle of software engineering (based on the unified process), including four stages: initial stage, refinement stage, construction stage and transition stage.

The key activities shown in IDEF 0 model (Figure 1) are carried out by students as part of the course project activities, including:

- Activity 1 (A1): Problem and Domain Understanding
- Activity 2 (A2): Define Requirements and Systems Design
- Activity 3 (A3): Build the UIs
- Activity 4 (A4): Perform Functional and Field Tests
- Activity 5 (A5): Perform HCI Tests
- Activity 6 (A6): Submit the Reports
B. Role of Software Engineering Design Diagrams

UML-based sequence diagrams and activity diagrams model the time interaction and function calls between software objects used to build UI [11, 12]. Generally, UML-based diagrams are design diagrams for dynamic modeling. They focus on identifying the behavior of entities in the system. Create activity and sequence diagrams to understand the interaction of navigation activities. UML-based activity diagrams are also used as project operational concepts (CONOPS). For brevity, this paper only provided an activity diagram and a sequence diagram (Fig. 2 and Fig. 3).
Fig 2. An UML based Activity Diagram showing the science sampling task.

Fig 3. An elided view of sequence diagram.
C. Functional Requirements and Cyber-Human design principles

Functional requirements describe the characteristics of system behavior. The response of the system is based on the designed function. The simulator must meet the functional requirements of astronauts to perform the scheduled mission. After discussion with the NASA project manager, a set of functional requirements was identified, as shown in Table 1.

Table 1. Functional Requirements for the MR based simulators

<table>
<thead>
<tr>
<th>No</th>
<th>Description</th>
<th>Rationale</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>The UI needs to support navigation to guide the user between EVA assets and designated excavation sites, using data from HMD, navigation algorithms, other external data</td>
<td>These are the primary functions that the UIs need to support; the UIs design based on HCI principles is necessary to ensure successful completion of various tasks.</td>
</tr>
<tr>
<td>2</td>
<td>The UI needs to assist the astronaut in the science activities (picking up rock samples)</td>
<td>The UI needs to be user friendly and efficient in ensuring helping astronauts complete these rock sampling tasks.</td>
</tr>
<tr>
<td>3</td>
<td>The UI needs to provide the ability to communicate with the Mission Control Center (MCC)</td>
<td>Safety and control is important; the ability to contact MCC at all times ensures continuous monitoring including task progress, report of any emergency situation, etc.</td>
</tr>
<tr>
<td>4</td>
<td>The UI needs to communicate the EVA System State and space suit vital information (ex. heart rate, EVA time, O2 levels) continuously to the astronaut</td>
<td>The astronaut needs to be cognizant of such data to ensure their safety and respond accordingly to ensure their own safety.</td>
</tr>
<tr>
<td>5</td>
<td>The UI needs to be controllable under various lighting conditions</td>
<td>The astronaut should always able to perform various tasks, retrieve needed data/information throughout their lunar activities to ensure safety and success of activities.</td>
</tr>
<tr>
<td>6</td>
<td>The UI needs to be user friendly, with adoption of Human-Computer Interaction [HCI] and Cyber-Human Design principles</td>
<td>User friendly interfaces enhance the effectiveness of the training process. EVA missions can be potentially more efficient with an intuitive user interface and accessible functions.</td>
</tr>
<tr>
<td>7</td>
<td>Outreach Requirement: The software prototype will be basis to support K-12 STEM activities Report and Publication Requirements:</td>
<td>Outreach: Encouraging K-12 students toward K-12 careers is important to NASA and our nation Report and Paper publications is important for dissemination to the public and engineering community</td>
</tr>
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</table>

The design of the 3D user interface includes the layout design of the user interface based on the HCI design principle and the software design represented by sequence diagram and activity diagram. The iterative design method is adopted; The initial design layout includes several menu-based alternatives and layouts optimized based on user-friendliness and cognitive load. During PDR and CDR, as part of the agile process, 3D models of some design alternatives were created; Feedback from project managers and student users is used to modify and refine these menus and user interfaces. The design diagram is based on UML sequence diagram (Figure 3) and activity diagram (Figure 2). The project team follows the top-level decomposition of key tasks in the idef-0-based model, promoting the adoption of system engineering principles.

III. Building the MR Environments

The goal of NASA’s University program is to design a user interface that enables astronauts to have virtual access to telemetry data and other information and ways to perform scientific sampling tasks during lunar missions. The student team studied the physical and virtual aspects of the design and studied the human-computer interaction involved in the design process. On this basis, the student team developed a pair of UI that meets all the standards.

The user interface developed by the team supports five different types of interaction.

1. Navigation allows astronauts to find the shortest path between the current position and the desired position.
2. Communications that allow astronauts to contact NASA headquarters.
3. Airlock tutorial, showing astronauts how to open, enter and close airlocks.
4. Scientific sampling, allowing astronauts to interact, collect and identify specimens.
5. Other settings allow astronauts to change user interface-specific settings, such as switching to the side where important information is displayed.

1. Navigation

Navigation solutions have a gap in capabilities to support and maintain future planetary surface operations. An ideal lunar navigation system can help astronauts to locate on the moon surface at any time, safely return to and from the lander, complete scientific objectives, understand the location of geological samples collection, cross the shadow area, and cross the scene that may cause danger or threat (let users realize the mountain crater area, cross the bright lighting conditions, etc.). The student team uses data from NASA parameters provided (listed in the navigation targets below) or customize HMD internal sensors, local equipment coordinates, standard navigation algorithms, pre-planned waypoints, geotags, path planning, sensor networks, cameras, and any other available data/information to help users navigate in the simulated EVA. The teams used an A star algorithm based approach and data from the Hololens 2 to guide users around obstacles (as shown in Figure 4). The HoloLens 2’s spatial mapping recognized real-world surfaces in the environment which would help the user navigate and avoid obstacles in real time.

![Fig 4. Navigation Approach based on A-Star Algorithm](image)

2. Communications

In this use case, astronauts on the lunar surface interface with the display and control unit (DCU) and umbilical interface assembly (UIA) during EVA and spacesuit preparation. Important information about spacesuits is conveyed to astronauts, such as informing them when to return to a pressurized environment in case of abnormality. The MR based UI must display all the information related to these factors to ensure the safety of astronauts and the success of the mission. All data are communicated through the telemetry stream on the local network; therefore, the UI must receive this data from the stream and unobtrusively display key information. A view of the main menu of the MR based UI is shown in Figure 5.
3. Airlock Operation

The airlock tutorial demonstrates to astronauts how to operate the airlock of the lunar lander. The model of the airlock appears over the physical airlock through the HoloLens’s mixed reality environment. Astronauts can navigate the menu through a series of buttons that show them either the next or previous instructions (Figure 6). After watching all the instructions the astronaut can either return to the main menu or watch the tutorial again.

1. Science Sampling

Every lunar mission is an opportunity for astronauts to collect and bring back lunar samples for geological research. Geological sampling points are clearly marked and equipped with tools. Other data included scientific sampling checklists and cue cards, tool images, and coordinates of regions of interest. To collect specific scientific samples, the on-site design evaluator uses the MR based UI designed by the student team to navigate the following steps correctly:

- Display scientific sampling instructions.
- Interact with sample bags, pliers, rakes and various other lunar tools.
- Locate / navigate to the right site.
- Provide unique on-site recording methods (i.e. voice, video, photo / image, dictation, animation, other new and creative methods).
- Take excavation site and geological samples.
- Collect samples.
IV. User Assessment

Developing and evaluating our user interface is based on the principles of human-computer interaction (HCI). This includes computer science, cognitive science, and human factor engineering, whose goal is to create accessible and effective interfaces between computer systems and end-users. The team created a questionnaire using a modified version of the NASA mission load index (TLX) tool [13]. This tool is handy for measuring the psychological, physical, and time requirements of computer interaction, including the user interface. Additional issues focus on details, such as the usefulness of text-based and voice-based interaction and the ease of navigation in the UI. The UI was shown to 10 college students (who were not part of the project), and each participant was asked to complete various functions using a simulation environment. Then, participants were asked to rate perceived usefulness, clarity, and other important factors in the user interface. The results are shown in Table 2. On a scale of 1 to 10, the average score of intelligibility was 8.0, the average usefulness of voice-based interaction was 8.3, and the average score of ease of completing tasks was 8.9. The average frustration, mental, physical, and time needs were also low, with an average of 2.375.

Table 2. Results of the modified NASA TLX study

<table>
<thead>
<tr>
<th>Criteria (Rating between 1-10)</th>
<th>Rating</th>
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<tbody>
<tr>
<td>1. Clarity of the instructions in the AR platform.</td>
<td>8.0</td>
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<tr>
<td>2. The degree of usefulness of the 3D avatar-based interactions.</td>
<td>7.1</td>
</tr>
<tr>
<td>3. The degree of usefulness of the voice-based interactions.</td>
<td>8.3</td>
</tr>
<tr>
<td>4. The degree of usefulness of the text-based interactions.</td>
<td>8.6</td>
</tr>
<tr>
<td>5. The ease of completing tasks while wearing the headset.</td>
<td>8.9</td>
</tr>
<tr>
<td>6. The ease of navigating through the simulation environment.</td>
<td>7.6</td>
</tr>
<tr>
<td>7. The overall usefulness of the AR environment.</td>
<td>7.9</td>
</tr>
<tr>
<td>8. Effort: How hard did you have to focus in order to complete the tasks? (1:Low, 10:High)</td>
<td>3.7</td>
</tr>
<tr>
<td>9. Frustration: How frustrated were you when trying to complete the tasks? (1:Low, 10:High)</td>
<td>2.0</td>
</tr>
<tr>
<td>10. Mental Demand: How mentally demanding were the tasks? (1:Low, 10:High)</td>
<td>2.9</td>
</tr>
<tr>
<td>11. Physical Demand: How physically demanding were the tasks? (1:Low, 10:High)</td>
<td>2.7</td>
</tr>
<tr>
<td>12. Temporal Demand: How hurried or rushed were you during the tasks? (1:Low, 10:High)</td>
<td>1.9</td>
</tr>
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</table>

Another HCI factor to consider is visual density, measured by the number of elements in the user's field of vision. This is closely related to affordability, another HCI principle describing the relationship between users and the systems that users interact with. The team designed different environments and studied the applicability of each design based on visual density and contrast. The design of a high and low visual density environment is shown in Figure 7. Two-color schemes are used in the design (Figure 8). A study involving 10 college students who did not participate in the project was conducted. Table 3 shows the average score of students for each design scheme. Students' evaluation of low visual density environment and blue and white color scheme is high. Integrating the principles of human-computer interaction into the development process can make the team make improvements and aesthetic changes to improve efficiency.

Fig. 7. Views of low visual density (left) and high visual density environment (right)
V. Discussion

This paper describes the six-month NASA SUITS project, in which students design, develop and evaluate MR-based training simulators for spacesuit-related activities. At the beginning of the project, students interact with NASA engineers to understand the domain and define requirements. After determining the requirements, the students used systems engineering and software engineering tools to carry out the preliminary and key design for the MR-based simulator. Subsequently, users began to use MR platform such as HoloLens 2 to develop the UIs. Finally, the user evaluation research is carried out, and the user scores the MR simulator under different standards. During the one-semester project, students are assessed through homework, mid-term and final exam project results. The results of students' summative evaluation are as follows.

1) Students' performance in homework and projects is better than in previous years
2) Students' participation (obtained through feedback/survey) is higher than in previous years
3) Through participating in the NASA SUITS project, students' model building skills, system engineering, and software engineering principles have been improved.
4) Students are keen to disseminate results at the 2021 AIAA virtual conference
5) Improve students' understanding and interest in space systems and NASA Related Occupations

VI. Conclusion

This paper discusses the creation of MR based UIs to support astronauts in various extravehicular activities. These activities are part of NASA's litigation challenge program, involving projects in the context of lunar missions. This paper summarizes the requirements, system design, methods, and system verification framework for the MR based UIs. The UIs were developed based on system engineering and HCC principles. Three student teams were involved in designing, implementing, and testing the MR based UIs. HCC based user studies were also conducted to understand the impact of affordance and visual density during the user interactions with the UIs.

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References


