Abstract— In future long-duration exploration missions (LDEMs), communication with mission control will be significantly delayed. Crews will often need to react to time-sensitive issues or hazards without relying on mission control for assistance. The need for a higher degree of crew autonomy without direct oversight from mission control introduces the implementation of virtual assistants (VAs) to aid the crew; however, we must first create standards and guidelines for VAs in this context. For this purpose, we have developed a VA called Daphne-AT (Anomaly Treatment) to investigate the interaction between astronauts and virtual assistants in the context of anomaly resolution related to the Environmental Control and Life Support System (ECLSS).

A series of experiments will be conducted in a laboratory environment and at the Human Exploration Research Analog (HERA) at NASA Johnson Space Center (JSC) to study user’s performance, situational awareness, cognitive workload, and trust in Daphne-AT. Subjects in a simulated LDEM will be given several ECLSS anomalies to identify and solve with and without the support of Daphne-AT. We based the scenarios we developed on existing ECLSS hardware and pre-existing anomaly resolution procedures from the HERA environment. Solving an anomaly requires the subject to complete the correct anomaly resolution procedure(s) for the appropriate anomaly, which could include various tasks such as swapping out component parts and activating or deactivating ECLSS systems. In experiment sessions without Daphne-AT, subjects will rely on telemetry feeds as well as background knowledge and training to solve anomalies. However, during experiment sessions with Daphne-AT, the VA will also assist subjects in detecting and diagnosing these anomalies.

We conducted an initial set of experiments at Texas A&M University (TAMU) prior to those at HERA. However, the subject must complete anomaly resolution procedures during an experiment that require access to hardware and components not available at the TAMU location. To emulate the HERA ECLSS hardware elements in our laboratory at TAMU, we recreated a virtual 3D representation of HERA and its ECLSS systems using the game engine Unreal Engine 4 (UE4). This virtual model will act as an analog for subjects who are tested on TAMU’s campus to complete relevant ECLSS procedures. All subsystems featured in the UE4 model are interactive and allow the user to perform steps in an anomaly resolution procedure similar to how the user would do it in HERA. The UE4 model allows the user to complete more than 20 anomaly resolution procedures, thus increasing the TAMU experiment’s fidelity compared to those conducted at HERA. This paper describes the development of the UE4 model and how we used it to validate the experimental protocol implemented at HERA. The results of these experiments will inform future guidelines for VAs deployed on LDEMs.

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1. Introduction

Recent years have found a reinvigorated interest in space exploration from both NASA and private companies, and NASA is laying down the groundwork to send humans to Mars through the Artemis missions [1]. The length of a Mars mission or other long-duration missions will be unprecedented and provide new unique challenges to solve. Increasingly complex space systems coupled with long
communication delays and communication constraints make immediate oversight and support from mission control impractical [2]. Crews will increasingly have to use their knowledge and judgment to react to potential hazards and anomalies since sending and receiving messages from ground control is not an effective means of discussion for time-sensitive issues. These communication delays along with elements of isolation and distance between the crew and ground control will require increased crew autonomy when compared to current space missions [3]–[4].

For future Mars missions, round-trip communication delays will range from 6.5 to 44 minutes [5], which would disrupt potential communications and significantly reduce the quality of communication between the crew and mission control [6]–[9]. For example, in a study of crew performance under simulated communication delays of 50 seconds between the ISS and mission control, researchers found that while latency did not affect the completion rate of tasks, it did pose performance and mood-related challenges [10]. Artificial intelligence will play a key role in helping to mitigate the issues that arise with long-duration space flight [11].

Intellectual Agents Used in Spaceflight

While there are many aspects of spaceflight that artificial intelligence could assist with such as navigation or robotic exploration, this paper is primarily interested in virtual assistants. VAs could support crew members by supplementing knowledge, quickly retrieving and processing relevant information from various sources, enhancing performance, and decreasing workload. Intelligent agents such as the Crew INteractive Mobile Companion (CIMON) have already been developed and deployed on the ISS as astronaut assistants, helping in routine tasks such as taking inventory [12]. While the initial CIMON required active human oversight, its successor, CIMON-2, already shows a 30% increase in autonomy [13]. The CIMON projects aim to investigate how the support of an intelligent agent affects stress levels in astronauts as well as study if CIMON could reduce the stress associated with isolation present in space missions.

2. AN INTRODUCTION TO DAPHNE-AT

As with any new technology, governing bodies require extensive testing and validation before it is considered mission-ready [14]. The goal of this project is to identify standards and guidelines that will help NASA develop VAs in the future. For this reason, we must investigate human interaction with virtual assistants in the context of space flight and LDEMs. The virtual assistant Daphne-AT is being developed for the Human Capabilities Assessments for Autonomous Missions (HCAAM) project as a part of NASA’s Human Research Program (HRP) [15]. Daphne-AT will assist users in resolving Environmental Control and Life Support System (ECLSS) anomalies, including different aspects such as anomaly detection, diagnosis, and recommendation of an appropriate course of action.

Figure 1 shows the Daphne-AT user interface, which has four main windows: Anomaly Detection (1), Sensor Data (2), Anomaly Diagnosis (3), and Anomaly Response (4). The Anomaly Detection window is anchored to the top of the screen and is always visible to the user. It reports any parameter readings that are outside of nominal ranges. For example, the Anomaly Detection window in Figure 1 shows the trace contaminants parameters Dichloromethane, n-Butanol, and Acetaldehyde are above their upper warning limits and the auxiliary cabin fan parameters are below the lower warning limit.

The Sensor Data window displays the current telemetry feed from the ECLSS simulator. This simulator contains the values of all ECLSS parameters such as partial pressure of O₂ and trace contaminants. This feature is particularly helpful for viewing parameter trends over time. Once a user has selected a set of abnormal parameters to investigate from the Anomaly Detection window, they will appear in the Anomaly Diagnosis window (we will define this group of parameters as an anomaly signature). Here, the user can ask Daphne-AT to give a list of possible causes for the selected anomaly signature. The user may then select a potential cause, and Daphne-AT will display the procedures required to resolve that anomaly in the Anomaly Response tab. Alternatively, the user may directly use the Anomaly Response tab to select an anomaly resolution procedure manually to follow if desired.

Additionally, Daphne-AT also has a chat window, shown in Figure 2, where the user can ask Daphne-AT questions of specific categories such as “What is the signature of anomaly X?” or “What are the thresholds for measurement X?” Daphne-AT also has a voice interface that possesses the same capabilities as the chat window, which can be particularly useful if the user is completing a task that requires both of their hands to be free while interacting with Daphne-AT.

We will investigate the effect of Daphne-AT on a user’s performance, cognitive workload, situational awareness, and trust in a series of human experiments in our laboratory at TAMU. The results from these experiments will shape future standards and guidelines for virtual assistants for spaceflight applications. For the upcoming experiments, we are investigating an initial version of Daphne-AT. Daphne-AT will only engage reactively when asked a question by the user and cannot proactively initiate a conversation. For future experiments, Daphne-AT will also be able to initiate interaction with the user as well as provide explanations about its recommendations and user’s questions, thus increasing the user’s understanding of Daphne-AT.

Notably, user understanding of a system decreases as the complexity of the autonomous system increases. Decrement in the user’s understanding could then decrease their trust in the system and lead to a reduction in usage [16]. On the other hand, exceedingly high levels of trust in automation can lead
to over-reliance [17]. For this reason, it is important to also study a user’s level of trust in virtual assistants.

Daphne-AT will also be deployed at the Human Exploration Research Analog (HERA), an analog environment located at NASA Johnson Space Center (JSC), used to simulate isolated and confined space habitats to investigate relevant topics such as communication, autonomy, and behavioral health [18]. During their simulated spaceflight mission, crew members will use Daphne-AT to resolve anomalies related to the ECLSS. Resolving anomalies requires crew members to interact with HERA ECLSS hardware and execute pre-existing ECLSS anomaly resolution procedures.

To reproduce similar anomaly scenarios at TAMU, we designed our laboratory experiments based on HERA’s ECLSS hardware and anomaly resolution procedures [19]. To replicate the same ECLSS components present at the HERA facility, we developed a 3D virtual environment that includes all the necessary ECLSS hardware to resolve the anomaly scenarios. Users can interact with each of these ECLSS components and follow the anomaly resolution procedures as if they were interacting with the real hardware present at the HERA facility. The following sections describe the current status of the development of this virtual environment and the planned future work.

Figure 1: Daphne-AT Interface with (1) the Anomaly Detection window, (2) the Sensor Data window, (3) the Anomaly Diagnosis window, and (4) the Anomaly Response window
3. VIRTUAL HERA ENVIRONMENT

Description of the Virtual HERA Environment

The virtual HERA environment we developed uses the Unreal Engine 4 (UE4) and consists of a large circular room with ECLSS components placed around the room (Figure 3). We modeled the following ECLSS subsystem components in the virtual environment: the Common Cabin Air Assembly (CCAA) Fans and Vents, the Carbon Dioxide Removal Assembly (CDRA), the Fuel Cell System, the N\textsubscript{2} Ballast Tank and Tank Line, the Solid Polymer Electrolysis (SPE), the Trace Contaminant Control System (TCCS), and the Water Recovery System (WRS) and Water Tank.

Each subsystem is responsible for a different ECLSS operation. The CCAA maintains cabin temperature and humidity, the CDRA removes excess CO\textsubscript{2} from the air and maintains oxygen levels, the fuel cell system provides power to the other ECLSS subsystems, the N\textsubscript{2} tank supplies nitrogen gas to maintain the total pressure in the habitat, the TCCS removes trace contaminants from the air, and the WRS reclaims, filters, and processes wastewater to turn it into potable water.

User Interface with the Virtual HERA

The virtual HERA environment is accessible via an executable file created for use in experiments. Once the program is launched, the user is placed in the center of the HERA habitat and must use mouse and keyboard inputs to interact with the environment. From here, the user can approach any in-world object and attempt to interact with it by simply hovering the mouse over different subsystem components. An object that the user can interact with will then be highlighted in green once hovered over, and a button is presented.
menu will appear when the component is clicked. This menu will provide the user with a list of possible actions they can take that are related to the specific component selected, such as “Remove Filter” or “Switch to Standby”. These menu options were created using a User Interface component called a Widget. The widgets were customized for each component and provide the functionality to each button action.

Most of the procedures require the user to pick up and interact with an object, such as spare parts and tools or personal protective equipment (PPE). These procedure steps necessitate the use of an “inventory” system or a way to keep track of what objects the user has collected over the course of a procedure. When the user picks up an item, the UE4 code adds the item’s information to a data structure containing information about all objects that are on hand. When the user presses the “M” key and selects “Items on Hand” from the menu that appears, a widget will appear calling on this list and naming all the objects at the user’s disposal (Figure 4, left panel). Selecting one of these items from the left-hand side of the menu will provide a list of possible actions that the user can complete with this item (Figure 4, right panel).

Additionally, we added selected functionalities to prevent the user from having to switch between multiple applications when completing anomaly resolution procedures. One of these is the Habitat Simulation System (HSS) software that was recently implemented at HERA to monitor ECLSS readings and control certain subsystems. Some procedures require the use of the HSS screen to complete actions such as turning on and off fans. Other procedures also require users to record information such as serial numbers in an excel log. These functionalities were primitively recreated in UE4 for users to complete procedures that require interaction with the HSS display (Figure 5) or a spreadsheet.

Users will often need to gather spare parts and tools, which users can find in the airlock stowage (Figure 6). Once selected, the airlock stowage will display a menu similar to the “Items on Hand” menu, allowing the user to stow items or remove them from storage. This component uses the same type of data structure as the inventory to store information about items contained in stowage.
Backend Development

We modeled the ECLSS subsystems primarily using basic shapes to create a rough reconstruction of each component. We then added functionality to these components; however, the user can only access these functionalities if they are within a certain radius – illustrated by a collision sphere (Figure 7) – of the desired component. We used UE4’s native visual coding language called Blueprints to add functions and actions to each component (Figure 8). These different functionalities are accessible via custom popup widget menus that appear once the user has selected a component.

Data about the state of each subsystem is stored in an object base class called an Actor. Each subsystem’s Actor must communicate any changes related to that Actor, such as position or power status, with its assigned widget menu. For example, let’s consider the user wants to increase the power of the Fan Dampener Assembly. The user would open the Fan Dampener Assembly’s widget and select the button labeled “Turn On: High Speed” (Figure 9, panel 7). The widget component first communicates to the Actor which button has been selected. Once the user’s selection is relayed to the Actor, it then rotates the Power Dial clockwise to the “High Power” position to indicate to the user that they have successfully performed the action. The status of the power dial will also be stored in a variable in the Fan Dampener Assembly Actor. If the user later attempts to complete a different action that requires the Power Dial to be off, the Fan Dampener Assembly Actor will not allow the code to execute the new action until the Power Dial is off.

Functionalities and Currently Modeled Procedures

The components and functionalities chosen to model in UE4 were selected based on a set of preexisting HERA ECLSS anomaly resolution procedures. We used these documents to create a set of 18 unique anomaly scenarios. For any given anomaly scenario, the subject must complete the appropriate resolution procedure(s) to solve the anomaly successfully.

4. AN EXAMPLE OF ANOMALY RESOLUTION USING THE UE4 HERA ENVIRONMENT

In an experiment session with Daphne-AT, the subject monitors the Daphne-AT screen for parameters that are detected out of the nominal range. Figure 1 shows that some trace contaminants and auxiliary fan parameters are outside of the nominal ranges. The user can then select the anomalous readings and ask Daphne-AT to diagnose the problem. Daphne-AT suggests the user complete the Fan Dampener Assembly Rate Change procedure and lists the necessary steps (Figure 1).

The user will then follow the procedure steps in the separate UE4 application, as illustrated in Figure 9. Panels 1 and 2 show the user collecting and donning the necessary PPE from the airlock stowage. Next, the user must locate (panel 3) and remove Floor Panel 1D to access the Fan Dampener Assembly Pump (panel 4). The user places a caution next to the floor panel to warn other crew members that they are doing work in this area (panel 5). Panel 6 illustrates the user donning and attaching the static wrist tether. The user then changes the FDA Pump Power Dial from low to high (panels 7 and 8). Once the user adjusts the power dial, they will then replace the floor panel and stow all PPE and equipment gathered during the procedure.

5. CONCLUSION AND FUTURE WORK

The virtual 3D environment detailed in this paper will allow our research team at TAMU to conduct experiments more akin to the experiments conducted at HERA. We achieved this by modeling current HERA ECLSS hardware components and their associated interactions in UE4 so that subjects may complete anomaly resolution procedures in an analogous environment to HERA.
This project has two potential avenues for further immersion or integration with Daphne-AT. The first is implementing communication between the backend of Daphne-AT and UE4. Backend communication between Daphne-AT and UE4 would allow for seamless transfer of information between the two applications. The next step of the procedure...

Figure 9: Fan Dampener Assembly Rate Change procedure being completed in the UE4 HERA environment. Steps are as follows: 1) Collect PPE and static wrist tether; 2) Don PPE; 3) Locate Floor Panel 1D and select; 4) Remove Floor Panel 1D; 5) Place caution cone by Floor Panel 1D; 6) Don and attach static wrist tether; 7) Select Power Dial; 8) Turn FDA Pump Power Dial to high
would then be displayed in the UE4 environment for the user to complete and a checkmark would be placed next to the completed step in Daphne-AT. This additional automation feature would eliminate the need for the user to constantly reference the procedure steps listed in Daphne-AT when they are attempting to resolve an anomaly in UE4. It would also provide improved real-time feedback to the user in correspondence to their actions in UE4.

Virtual reality has been used previously as a tool in space applications and provides another avenue for improvement [20], [21]. Transitioning to virtual reality would allow users to reach out and physically mimic opening modules or picking up tools. Thus, the user can resolve ECLSS anomalies in a way that is a closer analog to HERA. However, trying to resolve anomalies in virtual reality might be more inconvenient and time consuming. The user would need to repeatedly don and doff the headset to read each procedure step and then complete it in virtual reality. We could remedy this inconvenience by implementing the communication between Daphne-AT and UE4 (as mentioned in the previous paragraph) or having the subject ask Daphne-AT to read each procedure step aloud via the voice interface.

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REFERENCES


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