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Honors Thesis

EXPLORING EXTENDED REALITY IN AN AQUEOUS PROCESSING TEST BED FOR NUCLEAR MATERIAL

by
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Submitted to Brigham Young University in partial fulfillment of
graduation requirements for University Honors

Department of Electrical & Computer Engineering
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ABSTRACT

EXPLORING EXTENDED REALITY IN AN AQUEOUS PROCESSING TEST BED FOR NUCLEAR MATERIAL

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Bachelor of Science in Information Technology

This research aided in the ongoing creation of an extended reality training experience for Beartooth, an aqueous processing test bed for nuclear material, by exploring what will be comfortable and effective for users of the experience. Participants consisted of staff members from Idaho National Laboratory (INL) and authorized members of the Augmented Learning Lab at BYU. We conducted usability testing with participants who were given extended reality (XR) equipment to explore the Beartooth virtual training system. We also performed a heuristic evaluation on the system using an augmented reality evaluation checklist. Findings were discussed with the INL team and recommendations were iteratively developed. Insights for XR training systems related to complex machinery are also discussed.

Due to the sensitive nature of the Beartooth system, some specifics are omitted.

Keywords: extended reality, augmented reality, nuclear material handling, heuristic evaluation, training

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Derek Hansen, Jason McDonald, Jon Balzotti, Steve Francis, Ezra Bradley, Tyler Westerberg, and other BYU Augmented Learning lab members.

Derek Hansen, Jason McDonald, and Amanda Hughes as thesis committee members.

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CHAPTER 1

Introduction

The Beartooth system is an aqueous research test bed for handling nuclear materials currently under construction at Idaho National Laboratory (INL). A team from INL approached BYU to request aid in creating an augmented reality (AR) training environment, which overlays a virtual model onto the real world. The goal of this virtual system is twofold: First, it will be capable of training operators before the completion of the physical system. This will help improve training efficacy, reduce costs, increase efficiency, prevent exposure to radiation, and reduce errors. Second, it will eventually act as a digital twin to the Beartooth physical system, allowing users to interact with real-time information that maps to and from the virtual version. The work for this thesis was focused primarily on the first goal, training. As part of my role on the BYU team, I aided in carrying out, recording, and analyzing both a usability test and a heuristic evaluation on the Beartooth virtual training system, which allowed us to give generalized and specific feedback to the INL team. Many of the findings have already been discussed with the INL team and were subsequently implemented, greatly improving and guiding the project.

Extended Reality (XR), which includes technology like virtual reality (VR) and AR, is a new field of technology enabling novel types of training with complex machinery. Because of this, the user experience has not been settled, leaving open many questions to be answered, e.g., if controllers should be used, what type of headsets to use, and how to spotlight different components. The answers to these questions have a larger impact on health and safety in settings involving nuclear or other dangerous materials.

Therefore, our goal was to explore the challenges and opportunities for trainings developed in an extended reality setting for the Beartooth virtual system.

Statement of Purpose

Our purpose was to help INL design a Beartooth virtual training system which is user-friendly, familiarizes users with the Beartooth physical system, and trains users for common procedures. Many design choices can affect these aspects, and there are no specific guidelines listed for the creation of an extended reality experience such as Beartooth. Throughout our work, we were sensitive to the confidential nature of the system and the dangers inherent with handling nuclear material.

Research Questions or Research Hypotheses

The questions we aim to address in this work relate specifically to the design of the Beartooth virtual training system. They include:

1. What affordances does an XR environment provide for training on an aqueous processing test bed for nuclear material (e.g., making part of the system transparent and moving inside of virtual objects would provide perspectives that wouldn’t be possible in the real-world system)?
2. What challenges (e.g., usability issues) exist in a complex collaborative XR training environment such as Beartooth?
3. What specific and generalized design recommendations would help improve the user experience for Beartooth?

CHAPTER 2

Review of Literature

This review will first describe what the Beartooth system is and what it aims to do. Next, we will look at what Extended Reality (XR) is and what it encompasses, as well as why it can be helpful in familiarization and training exercises. Finally, we will discuss what a Heuristic evaluation is, how it applies to XR, and why we choose the specific Heuristic guideline we did.

Beartooth Virtual System Overview

The Beartooth System is an Aqueous Processing Test Bed for Nuclear Material. The physical system is still currently under development but has been digitally designed and modeled. Jay Hix describes Beartooth as:

> *[a] testbed to advance research into nuclear material solvent extraction process. This testbed will give researchers the opportunity to develop novel solvent extraction processes and train early career scientist on known nuclear extraction processes for knowledge transfer. Beartooth extraction operations will include the use of centrifugal contactors designed for the recovery and purification of special nuclear materials from irradiated fuel. This new testbed will provide researchers with the opportunity to study innovative technologies in addition to solvent extraction techniques.* (2022)

In addition to the nuclear and chemical engineering system, Beartooth will also include digital components. Kaleb Houck, head of the digital engineering team, described this as:

> *Beartooth is a cutting-edge research and development testbed for processing*

> *novel special nuclear material (SNM) feedstocks that will integrate INL's latest efforts in artificial intelligence (AI), machine learning (ML), and digital twins. In addition to its nuclear material processing capabilities, the testbed will incorporate digital engineering concepts and cyber-physical systems to gain new insights into SNM accounting and proliferation detection.* (2022)

The virtual model used in the trainings discussed in this thesis includes tanks, piping, centrifugal contactors, and other equipment used for research (see Fig. 1 for an example of an aqueous system like Beartooth, though this one is not set up to handle nuclear material). This equipment is physically reconfigurable, which adds extra difficulty in the creation of a virtual model and the trainings for it. Instead of a static model and training, developers will need to design something that is flexible enough to accommodate the new layouts and procedures.

Figure 1: Example of solvent extraction equipment, like that used in the Beartooth physical system, though without a glovebox. Image from https://inl.gov/integrated-fuel-cycle-solutions/

Because the physical system will handle nuclear material, operators and researchers are separated from the system by a glovebox, which is a protective layer of radiation-shielded glass and gloves. An early conceptual rendering of the glass shielding with holes for gloves can be seen in Figure 2. The system and glovebox combined are about 8 ft tall, 15ft wide, and 30ft long. It is a large system with many integrated parts and potential configurations, modifiable to match whatever process is required.

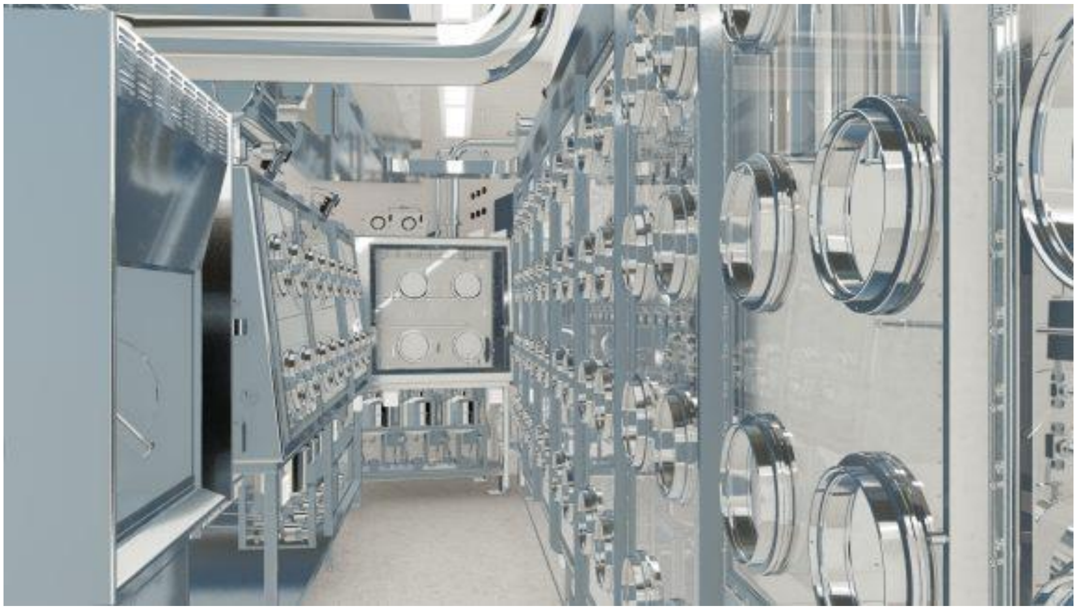

Figure 2: Conceptual rendering of the Beartooth test bed glovebox.

Image from https://inl.gov/integrated-fuel-cycle-solutions/

Because of the size and complexity of the system, it is difficult to obtain an understanding of the system without seeing it in-person. Even if one were to see it in person (once constructed), the glovebox would obfuscate their view of some of the components.

The INL team started their development of the virtual model of the Beartooth system by importing the computer-aided design (CAD) files for the Beartooth physical system into the Unity game engine. This allowed them to create a virtual version of the system, which could be accessed through a VR or AR headset. Users could then walk around the model, draw using a virtual marker, and filter out the glovebox components. The system worked on the HoloLens 2 augmented reality headset and the Varjo XR-3 virtual reality headset. This version of the virtual system was used in design reviews but had no training content.

Augmented Reality/Extended Reality Training

Extended Reality (XR) is used as an umbrella term encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) (Çöltekin et al., 2020; Morimoto et al., 2022). See Figure 3 for a visual representation of how these terms compare. These technologies all involve the use of a device, typically a headset, which displays an altered, or entirely different, environment to the user. Headsets use sensors to detect movement by the user which in turn updates the display to reflect the user's movement. VR creates a more immersive experience for the user by excluding their vision of the real world, whereas AR is "a technology that overlays virtual content (i.e., 2D graphics, 3D graphics, sound, and video) onto the real world, with real-time interaction" (De Paiva Guimaraes & Martins, 2014).

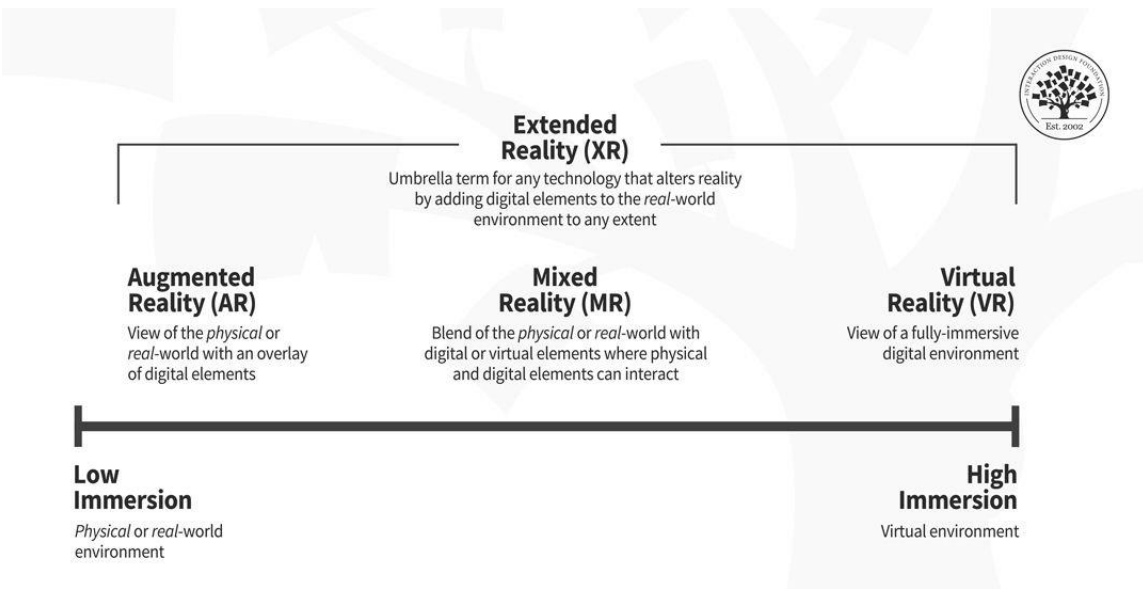

Figure 3: Comparison of AR/MR/VR/XR terminology (Tremosa, 2023).

A literature review on AR use in the manufacturing industry found that training/learning showed "great potential" but that research is mainly conducted on experimental prototypes, not production systems (Bottani & Vignali, 2019). Another literature review found that AR use in nuclear facilities would be interesting, but that the term ‘nuclear power plants’ was only mentioned in a small number of studies (Palmarini et al., 2018). There are some studies that explore VR/AR use in training. For example, Radoeva et al. provide a theoretical framework for the elements of VR training systems such as the logic of the training system and the system requirements (2021). Other examples of papers on VR training include research on training in a cockpit (A. Caputo et al., 2020), for automotive service and maintenance (Palmarini et al., 2018), and in the medical field (Ruthenbeck & Reynolds, 2015).

Although there are papers which describe the application of VR use in Nuclear Power plants (Popov et al., 2021), there are only a few articles that have explored VR training in nuclear contexts. In a literature review exploring VR training solutions for nuclear power plant field operators, Satu et al. (2024) had difficulty finding relevant articles, identifying less than 20. They concluded that “VR training was found to offer, at its best, an inspiring and effective means for training Nuclear Power Plant field operator work” (Satu et al., 2024).

The research performed for this thesis is unique in that it not only adds to the field of XR training in a nuclear production system under construction, but that it also explores the heuristic and usability in that training while the physical system is under development.

Heuristic evaluation

A heuristic evaluation is a common usability testing technique performed by “a small set of evaluators” who “examine the interface and judge its compliance with recognized usability principles” (Nielsen, 1995). It reveals usability problems in a user interface design so they can be addressed. These heuristics allow evaluators to perform "rapid and low cost usability evaluations" (Endsley et al., 2017).

There are different heuristics (i.e., guidelines) for different user interfaces, such as Websites, mobile apps, and mixed reality devices. While there are several heuristics for augmented reality (Labrie & Cheng, 2020; Novita Sari et al., 2020), these were not suitable for our purposes as our use of AR technology utilizes a dedicated headset, not a mobile device.

Two papers that provide heuristics for an augmented reality headset are most pertinent to our research. Endsley et al. (2017) created a set of heuristics based on other checklists, coupled with feedback from designers, developers, and evaluator experts. These heuristics are intended to be used by developers during the design process. De Paiva Guimaraes & Martins (2014) created a heuristic checklist specifically to test AR applications. Their work focused less on guidelines for developers and more on specific items for experts to check against. This thesis used the checklist created by De Paiva Guimaraes & Martins (2014) as described in the methods section.

CHAPTER 3

Methods

First, we discuss the design process that BYU and INL used to develop the Beartooth virtual training system. Then, we give an overview of the training itself. Finally, we put forth how we performed our 2 evaluations: Usability and Heuristic. The participants, locations, and details of how each evaluation was conducted will be discussed. As this study is focused on the improvement of the Beartooth virtual system itself, rather than the users of the system, IRB approval was deemed unnecessary.

Beartooth Virtual Training Design Process

In May of 2023, I and other members of the BYU Augmented Learning Lab travelled to Idaho for a project kickoff meeting. While there, we were introduced to the Beartooth virtual system, using the Microsoft HoloLens 2. This version had little functionality but provided a starting point for us to understand the goals of the Beartooth physical system, and how the Beartooth virtual training system could help in achieving those goals. Researchers, acting as content experts, gave us a short demonstration of centrifugal contactors, which make up part of the Beartooth physical system. We discussed ideas, goals, and challenges for the project, and then made plans for the next few months.

After that kickoff meeting, but before our evaluations, work in the BYU Augmented Learning Lab included researching XR system best practices, interviewing INL content experts, and meeting weekly with INL to discuss both their progress on functionality as well as our suggestions from research and testing. The BYU Augmented Learning Lab based this feedback on several minor versions of the Beartooth virtual system which were given to us over this time period. The combined effort from both the BYU and INL team culminated in version 1 of the Beartooth virtual training system.

Beartooth Virtual Training Overview

The primary goal of the Beartooth virtual training system is to orient operators and researchers to the system, increase safety by reducing exposure to nuclear materials, and accelerate efficiency by training staff before the Beartooth physical system is fully operational.

The following sections are based on the Requirements Document which was collaboratively authored by the BYU Augmented Learning Lab.

Beartooth trainings are made available via a large Training Board that appears in the Beartooth virtual environment. See Figure 4 for an early conceptual layout of the Training Board. A main board was chosen as the primary interface because (a) it is easily noticeable to those starting the training and (b) multiple people can view it at the same time, which will be important in future trainings which allow for multiple participants.

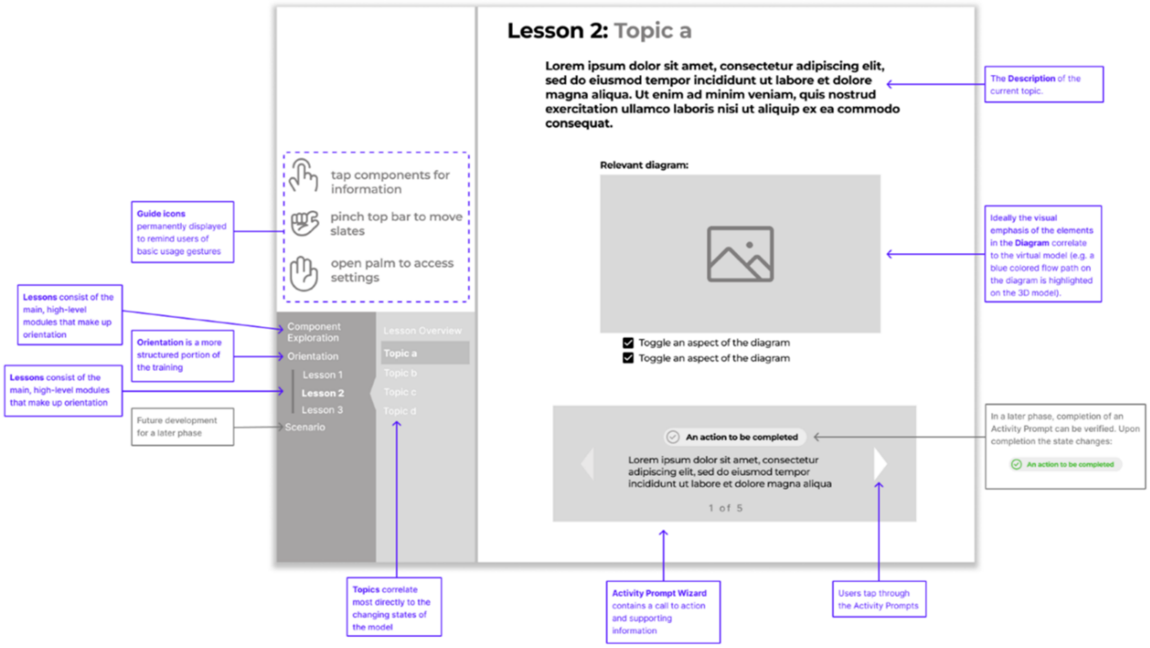

Figure 4: Training Board Conceptual Layout.

Training Frameworks

The Beartooth Training Framework includes three key components, each of which is designed to support different learning objectives for the users. The **Component Exploration** component orients new users to the complex Beartooth system by helping learners identify the primary units of operations, their functions, and how they relate to one another. The **Unit Operation Exploration** component allows learners to explore the equipment relating to the key unit operations (e.g., dissolution, solvent extraction, calcification). This framework will include visual interactions with the components and demonstrations of flow through the system. Users will receive specific activity prompts that invite them to interact with the model and allow users to demonstrate their understanding of how the different units of operation function. The **Walkthrough** component provides sequential tasks designed to test learners' ability to complete a series of tasks related to a specific unit operation (e.g., prepare the Beartooth system for dissolution, run lines according to a Block Flow Diagram).

1. **Component Exploration.**

   The component exploration is the first training module the user is encouraged to take. It provides an unstructured exploratory experience for the user, in which information relating to components can be found by touching the component itself. Component Exploration is used for "design reviews," group discussions, and initial orientation. It primarily provides non-structured exploration of individual components and includes simple training on how to interact with the system, such as using hand gestures.

2. **Unit Operation Exploration.**

   The Unit Operations Exploration training module shows users how the different components map to the unit operations. This builds on knowledge gained in the Component Exploration training, in which users became familiar with individual components. This portion shows how these individual components map to specific Unit Operations that Beartooth supports. This section does not offer direct instruction regarding the performance of Unit Operations, that is done in the Operational Walkthrough component.

3. **Operational Walkthroughs.**

   The Operational Walkthroughs are used to educate system operators and researchers about procedures through a step-by-step process of selected operations.

Users also have access to a Hand Menu, which helps them place and orient the Beartooth virtual system in their real world "play space." See Figure 5 for an early rendition of the Hand Menu. This menu will also have control options, such as hiding the glovebox and muting audio prompts. Controls specific to the user are accessible on this Hand Menu, which can be accessed at any time and location.

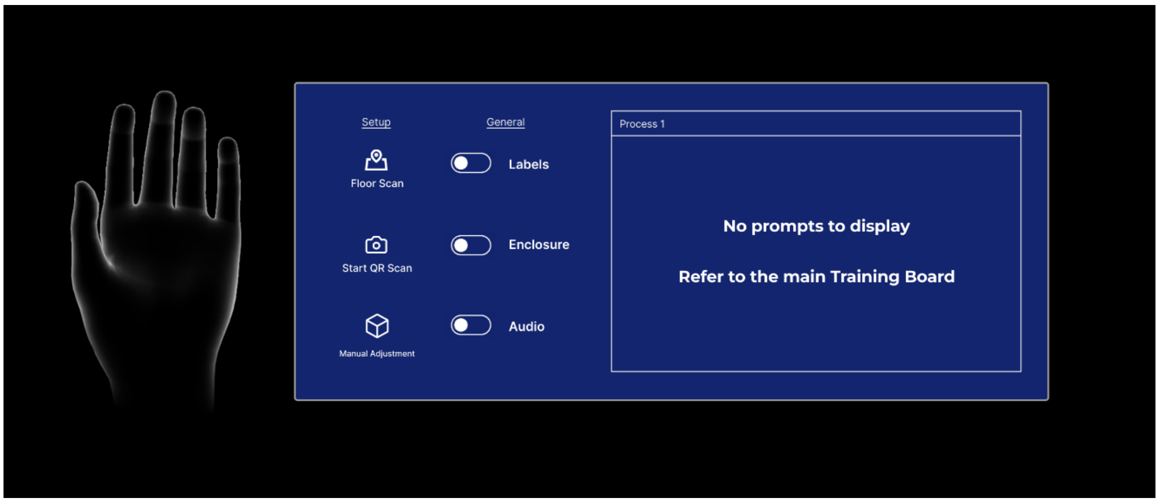

Figure 5: Hand Menu early rendition.

Controls and content related to the trainings, which may be conducted with multiple users, are found on the Training Board, as they will necessarily be interactable by other users. See Figure 6 for an early rendition of the Training Board with an example.

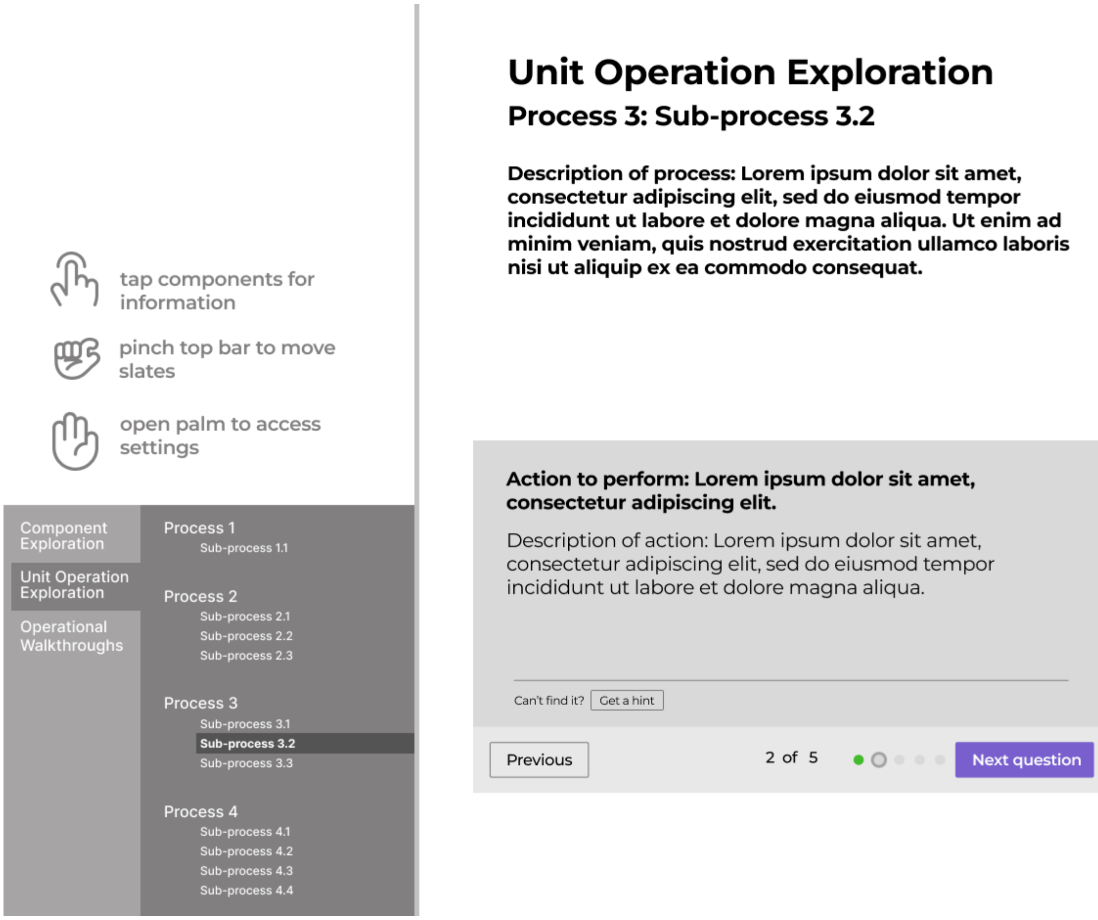

Figure 6: Training Board with example.

Usability Evaluations

With version 1 of the Beartooth virtual system created, we could perform more formal evaluations to assess how to improve the virtual trainings. Our approach consisted of performing two main evaluations: The first evaluation focused on how the system was seen by non-experts, and the second evaluation focused on how the system held up to expert established guidelines. Non-expert feedback is designed to find elements that are confusing to non-experts and represent a typical user's perspective, while expert feedback is designed to refine the system based on expert guidelines and suggest resolutions to issues. Some of the heuristic guidelines found in our chosen checklist did not apply fully to the Beartooth virtual training system specifically and were thus adjusted, as explained in the Expert Heuristic Evaluation section. The results, gathered from both evaluations over time, were frequently discussed with INL during our weekly meetings. In our final report to INL, and this thesis, we have integrated the findings from both evaluations into specific issues and recommendations organized according to the nine sections of the heuristic checklist. This approach helped reduce redundancies. We also include some general principles intended to help guide future development.

User Testing Evaluation

In October of 2023, I and other members of the BYU Augmented Learning Lab travelled to Idaho for a second time to meet with the INL team. While there, we conducted a usability evaluation of the Beartooth virtual system at INL's Collaborative Computing Center. This evaluation focused on how the system was perceived by those unfamiliar with XR technology. We looked to determine the user's initial perception of the system, how the system expected users to interact with it, and if the system led users towards intended goals without issue. Participants in the usability evaluation consisted of researchers, operators, and other members of INL staff. The evaluation was set up by INL developers with BYU team members recording audio and taking notes. Most participants had little to no prior experience with XR, which is ideal, as the finished system is intended to accommodate those who are unfamiliar with XR technology.

INL staff set up the Beartooth virtual system on a variety of devices: The Microsoft HoloLens 2, Varjo XR-3, and the Magic Leap 2. Participants were encouraged to test the Beartooth virtual system on multiple devices and note any differences.

Researchers followed and asked informal questions centered around how participants were interacting with and perceiving the system, as well as any issues related to discomfort or confusion. After their experience, participants were asked for any final thoughts, what they did and did not like, which platform they preferred, and to what extent they thought the system would be helpful as a training platform. The information from these non-expert participants was especially valuable, as many would likely use the completed virtual system once it is fully operational.

Expert Heuristic Evaluation

From October 2023 through the first half of January 2024, I led the efforts surrounding our Expert Heuristic Evaluation, with input from a graduate Instructional Psychology & Technology student and an undergraduate user experience designer. Our focus was comparing the Beartooth virtual system against specific heuristic guidelines. We evaluated the Beartooth virtual system using the Microsoft HoloLens 2, as that had been deemed the primary focus for current development efforts.

Of the two heuristic guidelines mentioned in the above literature review, we decided to base our evaluations on the one created by De Paiva Guimaraes & Martins (2014). We initially started our assessment with the guidelines created by Endsley et al. (2017), but found they were difficult to apply to the Beartooth virtual system. This may be because the guidelines were intended more for the development/design process, rather than a summative evaluation of a system. The heuristic guidelines created by De Paiva Guimaraes & Martins (2014) allowed us to evaluate the system by focusing on one or two of the checklist items as we viewed and interacted with the system.

CHAPTER 4

Results

In our usability testing and heuristic evaluation, we searched for ways to improve the Beartooth virtual system and discussed those findings with the INL team. We were looking for answers to our original questions:

1. What affordances does an XR environment provide for training on an aqueous processing test bed for nuclear material (e.g., making part of the system transparent and moving inside of virtual objects would provide perspectives that wouldn't be possible in the real-world system)?
2. What challenges (e.g., usability issues) exist in a complex collaborative XR training environment such as Beartooth?
3. What specific and generalized design recommendations would help improve the user experience for Beartooth?

At the end of the project, the BYU team summarized the work done and presented it to INL as a record and for future reference. What follows is the bulk of the usability report, with minor changes for formatting. I was the primary author of this report. The report is organized into the nine sections of the Heuristic checklist, with the changes noted in the Methods section above. Each section begins with a description of the relevant heuristic from the original checklist (De Paiva Guimaraes & Martins, 2014). We then list one or more questions we derived from the checklist which were applicable to the Beartooth virtual system. After that, we list each question and note our findings relevant to the question, including any issues found. Finally, each issue has one or more recommendations, which, along with the general guidelines and principles of the sections, are the main takeaways for the INL team. The report references a "System Requirements Document," which is a document given to the INL team, and is not included with this thesis.

Visibility of the system status

> *"Evaluate how the system is seen by the user. Users must receive feedback about what is occurring in the system. AR applications utilize tracking systems to determine the virtual content position in a real scene, which must be fast and reliable otherwise users will become lost while interacting with the application;" (De Paiva Guimaraes & Martins, 2014, p. 43)*

Application for the Beartooth Virtual System

The main questions related to this heuristic applicable to the Beartooth Virtual System are as follows:

- How is the system seen by the user?
- Does the user receive feedback about what is occurring in the system?
- Does the system utilize tracking systems (hardware sensors) to determine the virtual content position in a real scene in a fast and reliable way?

How is the system seen by the user?

When a user utilizes the HoloLens to view the Beartooth virtual system, it is important to consider how they view it and what changes could occur from user to user, in various locations, and if the experience is pleasant enough to avoid distraction from the main objectives.

Issue #1**:** Bright lighting can impede the user's use of the HoloLens.

HoloLens AR offers much better clarity and lower eye strain when the environment is darker and users can freely adjust the HoloLens brightness.

Recommendations:

- Users should be advised to avoid large windows or other potential bright sources of light. They should also be informed about the brightness controls on the HoloLens itself.

Issue #2: Users are disoriented after completing the setup process.

The final step of the setup process is to scan a QR code tied to a part of the Beartooth virtual system. This results in the system being placed such that the user will find themselves inside the system, potentially leading to disorientation and discomfort.

Recommendations:

- Adjust the starting point/QR code scan, such that a user can scan it during the final setup step while remaining outside the virtual system, preferably near the main menu board.

Issue #3: Default Layer appearance leads to overwhelming info and FPS loss.

When the system first appears, the enclosure layer is shown by default, showing the glass walls of the glovebox over the system. Those unfamiliar with XR could be overwhelmed with information (see Heuristic *Aesthetic and Minimalist Design*). On the other hand, this provides a view that is more realistic to what would be seen in the real world (see Heuristic *Match Between the System and the Real World*).

Recommendations:

- Change the default Layer appearance. Set the default option to have the enclosure layer hidden, while allowing the option to be toggled by users.
- Consider activating the enclosure layer as a mandatory setting in future training when a user has already become accustomed to the system and greater accuracy to the Beartooth Physical system is desired.
- Prioritize System Performance. To avoid user discomfort and dislike for using the system, high FPS should be a priority throughout the project. This could be achieved through using more powerful hardware, reducing fidelity on non-critical rendered objects, and other means.

Does the user receive feedback about what is occurring in the system?

It is important for users to feel their actions matter and that they see the result of those actions. Feedback should be quick, clear, and aid in recognition (See section *Recognition Rather than Recall*). This section will become more relevant as the Beartooth Virtual System training exercises become more developed.

Issue #4: System lacks specific feedback.

As the system is further developed, care should be taken to incorporate different types of feedback that indicate successes, failures, and system status.

Recommendations:

- Add audio prompts and visual cues to indicate successes and failures. Turning a valve, attaching a pipe, completing a task, etc., would benefit from audio to clarify user actions and state.
- Simplify and reorganize the main board to match the System Requirements document. See System Requirements document.

Does the system utilize tracking systems (hardware sensors) to determine the virtual content position in a real scene in a fast and reliable way?

When setting up the Beartooth Virtual System, the user must first scan their real-world surroundings and place a virtual floor marker. This enables the model and main instruction board to be placed in an accurate and usable way with relation to the real world. Potential problems with this setup process can range from minor, such as the system appearing to float an inch or two above the ground, to major, such as the system appearing outside the usable space or skewed at a severe angle.

<u>Issue #5:</u> When placing the system in the real world, the placement of the virtual model is inconsistent.

The HoloLens scans the user's environment to determine where things are, and thus, usable space. This scanning process appeared to be affected by patterns in the carpet and other objects.

Recommendations:

- Implement a more robust scanning process that identifies more than one location (e.g., scanning multiple QR codes at key locations).

<u>Issue #6:</u> Add improved manual adjustment features for system placement.

The Beartooth system currently allows manual adjustment (up, down, left, right, and rotations), however, it does not handle large or small adjustments well. Currently, changes are limited to increments of about a foot. This means large changes take a frustratingly long time to apply and require a large amount of button pressing. More granular changes, such as moving the system an inch down to match the ground, are impossible. In addition, manual adjustment moves the Beartooth system, but not the main board.

Recommendations:

- Implement pinch and drag features for manual adjustment of the system location, similar to other HoloLens adjustment features.
- Allow users to fine-tune the scale of manual system location adjustment controls.

- Ensure manual adjustment is tied to all aspects of the Beartooth virtual System, including the main board.

Match between the system and the real world

The system design should follow real-world conventions, thereby making information appear in a natural and logical order. Users must interact with the virtual content in the same way as they would in the real world. The object scale and animation must be coherent with the scene;

Application for the Beartooth Virtual System

The main questions related to this heuristic applicable to the Beartooth Virtual System are as follows:

- ❖ Does the system design follow real-world conventions such that information appears in a natural and logical order?
- ❖ Are users expected to interact with virtual content in the same way as the real world?
- ❖ Do the animations and scale of virtual objects match the real world?

Does the system design follow real-world conventions such that information appears in a natural and logical order?

The current system follows a natural and logical order, so long as it follows recommendations found in the *System Requirements* document.

Are users expected to interact with virtual content in the same way as the real world?

For the Beartooth virtual system, the importance of *Match between system and the real world* is higher than normal, as the goal for this system is to eventually become a Digital Twin to the Beartooth Physical system – complete with real-time data from the physical system fed to this virtual system. In addition, operators, researchers, and other personnel are required to follow very strict instructions that match object names perfectly. Even object names (Using P&ID's) will be important.

<u>Issue #7:</u> User movement through virtual objects can trigger unintentional actions.

Currently users can walk through the virtual model, which can be disorienting and could trigger unintentional actions such as touching objects they walk through. Since users must travel back and forth from the main board to the model, they are tempted to take shortcuts through the model.

Recommendations:

- Add a warning at the beginning of the training that users walking through the model may trigger actions unintentionally.
- Reduce the need to walk through the model by adding access to menus and content through the Hand Menu. See the System Requirements Document for Hand Menu designs.

Issue #8: Mapping of real-world interactions to virtual gestures can cause usability problems or misunderstandings.

To create, attach, detach, and delete pipes, users simply touch virtual objects to interact with them. This can be helpful for new users learning the system but does not represent the actual process of changing pipes. Other walkthrough actions such as *Open dissolver vessel flange* or *Load dissolver basket*, may not map directly to the Beartooth physical system.

Recommendations:

- Compare ease of use with matching real-world system interactions when creating virtual interactions for users.
- We do not believe all mapping to be identical to real-world actions is wise. Review actions that are part of the walkthroughs with content experts to make the most informed decision. Focus on the goal of the user action. For example, requiring users to connect piping in realistic ways would require unnecessary effort on the part of developers to create that level of fidelity, as well as for users to complete that task, when the learning outcome is to merely know where the pipes connect, not how to attach a pipe. In such cases, using a touch-based system improves usability and is unlikely to transfer problems for users who will ultimately pipe the real system. However, some actions may not be as obvious and should map more directly to real-world actions. For example, turning a valve off should require rotating to the OFF position, rather than simply touching the valve.
- Add constraints on object interaction to prevent actions not physically possible. If it is impossible to realistically reproduce real-world controls in XR, consider having a menu or other abstract control mechanism. This will ensure users will not be misled into inaccurate mental models of component function.

Do the animations and scale of virtual objects match the real world?

As most objects in the Beartooth virtual system are imported from the same files used for constructing the Beartooth physical system, the scale of virtual objects matches real-world objects. However, there are still some potential issues of note.

Issue #9: Future changes to the Beartooth physical system may not be captured in the virtual system.

If changes are made to the Beartooth physical system, but are not reflected in the Beartooth virtual system, this could lead to issues if not caught and applied.

Recommendations:

- Develop a workflow for updating the virtual model after changes to the CAD model are made. This workflow should consider the need to remove unnecessary detail (e.g., screws) and optimize images for computer rendering. Where possible, this simplification should be done to reduce unnecessary information (see section *Aesthetic and minimalist design*) and to improve FPS (see section *Visibility of the system status*).

Issue #10: The Beartooth virtual system requires a large physical space, which may not be available for all use cases.

The Beartooth system is large and has a unique shape, and many real-world locations or objects in those locations may obstruct freedom of movement to parts of the virtual Beartooth system. For example, if trainees want to practice on the system from their office, they will not have sufficient space to do so.

Recommendations:

- Inform users of spatial requirements needed for the Beartooth model (e.g., dimensions of the model).
- Develop a virtual reality version of the Beartooth virtual trainings that allows users to move positions via controller. This should only be prioritized once the HoloLens version of the system is complete and the use case is needed.

Consistency and Standards

The application interface layout and the user interaction must be consistent. Users must interact in the same way with all virtual objects. Each marker must be associated with a specific action or virtual object to avoid mistakes;

Application for the Beartooth Virtual System

The main question related to this heuristic that is applicable to the Beartooth Virtual System is as follows:

- ❖ Is the application interface layout consistent such that user interaction remains the same throughout their experience?

Is the application interface layout consistent such that user interaction remains the same throughout their experience?

When a user is navigating through menus or obtaining information on objects, their experience should remain consistent throughout all sections of the Beartooth virtual system.

Issue #11: Touching an object triggers different responses depending on what part of the training users are in.

When users are in Component Exploration view, touching objects brings up additional information. However, when users are in Unit Operations view, touching objects indicates the completion of a prompt. This can confuse users due to the inconsistency.

Recommendations:

- Show additional information when a user touches the hovering P&ID card instead of the object itself. Make this consistent throughout all training views. Reserve touching of objects to training activities (e.g., finishing a prompt; connecting a pipe).

Error Prevention; Help Users Recognize, Diagnose, and Recover from Errors

The application must be designed to avoid mistakes and to prevent undesired actions. If this occurs, it is essential that users receive readily understandable messages.
The system must indicate problems precisely and make suggestions in a constructive manner. For example, if an unacceptable marker is detected, the system must provide guidance to solve the mistake.

Application for the Beartooth Virtual System

The main questions related to the combined heuristics applicable to the Beartooth Virtual System are as follows:

- Is the system designed to prevent undesired actions?
- Does the system alert users to mistakes while providing a simple way to correct those mistakes?

Is the system designed to prevent undesired actions?

While this system is meant to train users and will thus have users fail in some actions such as piping incorrectly, those failures in the training module should be seen as separate from failures in using the Beartooth system itself. The latter being focused on reduced as much as possible. We did not identify any major issues in this area with the current version. As more complicated interactions are added, this should be re-evaluated.

Does the system alert users to mistakes while providing a simple way to correct those mistakes?

The current version of the Beartooth virtual system does not know if a piping configuration is correct, and thus this section was not evaluated as in-depth. These heuristics should be noted for future versions.

Issue #12: The system does not inform users of mistakes in the Unit Operation view.

The current setup for Unit Operations remains in the same state waiting for the user to touch the correct object. The system does not inform the user if they attempt to touch an incorrect object, or if a significant amount of time has passed without touching the correct object.

Recommendations:

- Provide visual or audio feedback for users who make a mistake. Re-play audio if a desired action does not occur within a set amount of time. Incorrect piping, or even attempted piping that is not physically possible could be given a red glow or text box pop-up to inform users. Care should be taken to determine if this feedback should be given at time of user attempt, or if users should attempt a full piping set, then ask the system to check their work.

Issues #13: Pipe removal mode is cumbersome and unintuitive.

In the initial piping mode, a user wishing to undo or change a pipe must open the Hand Menu, select ‘Remove Pipes’ to enter pipe removal mode, select the pipe they wish to remove, return to the Hand Menu, deselect ‘Remove Pipes’ to exit pipe removal mode, then touch the correct endpoints to create the desired pipe.

Recommendations:

- Simplify piping removal by allowing the user to re-select a placed pipe endpoint to remove it. See designs in System Requirement document.

User Control and Freedom

The application must provide freedom so the user can perform actions and undo incorrect actions. If a user presents the wrong marker to the camera, the system must support simple marker replacement and, if possible, alert the user about the mistake. Actions such as undo and redo must be simple.

Application for the Beartooth Virtual System

The main points found in this heuristic applicable to the Beartooth Virtual System are:

- ❖ Does the system allow users to perform actions and obtain information when desired?

Does the system allow users to perform actions and obtain information when desired?

Most objects have a P&ID and other information specific to each individual object. This information should be accessible to the user throughout their use of the Beartooth virtual system.

<u>Issue #14:</u> Additional information in P&ID card is limited to Component Exploration mode.

Objects in the Component Exploration mode have a P&ID card floating above them. These cards can be interacted with to display or hide information specific to their associated object. This is a good design, however this feature is not available in other modes.

Recommendations:

- Ensure interactable information cards on objects are available to users throughout the entire Beartooth virtual system.

Recognition rather than recall

This establishes whether a user can run the application in an intuitive way. The marker functionalities and positioning in the scene must be easy to memorize;

Application for the Beartooth Virtual System

The main points found in this heuristic applicable to the Beartooth Virtual System is:

- Can users interact with the system intuitively, without additional instructions?
- Are users asked to remember information which could instead be recognized?

Can users interact with the system intuitively, without additional instructions?

It is best to assume a user is unfamiliar with XR systems, the Beartooth system itself, and does not have an expert on-hand to guide them through the experience. To that end, the Beartooth virtual system should focus on ease-of-use, intuitive controls, and a logical flow of information.

<u>Issue #15:</u> Colors of objects have no assigned meaning.

When first introduced to the system, nearly all objects are gray, while some are red or blue. Users typically associate these colors to mean the objects are different in some way, such as a warning to avoid an object. However, it is not clear what the colors mean or if they have any significance in the current system.

Recommendations:

- Assign meaning to colors, then apply those colors to the appropriate objects in a consistent manner (e.g., yellow highlighting around an object indicates it should be interacted with).

<u>Issue #16:</u> The Beartooth virtual system lacks glow, pulsing, and other visual effects.

Visual effects quickly convey information to the user, and effects that appear through other objects aid greatly when trying to locate a specific object obscured by other objects. The current system has implemented some highlighting in the Unit Operations and piping views. As new activities are added, additional visual cues should be added.

Recommendations:

- Apply appropriate visual effects to important objects as new functionality is added.

Are users asked to remember information which could instead be recognized?

Unless information should be memorized, such as certain training material, the system should try and help users recognize that information. For example, menu locations, gestures, and other ways of interacting with the training should be recognized, not recalled.

Issue #17: Navigation controls do not clearly indicate where users currently are in the menu.

There is no indication of where a user currently is in the menu, requiring them to recall their place from memory instead of recognizing it through a visual cue.

Recommendation:

- Add highlighting on the menu to indicate current selected section. See System Requirements Document for interface recommendations.

Issue #18: First time users struggled interacting with the Beartooth virtual system.

First time users need some source of information (preferably easily understood graphics) to inform them of navigation gestures and controls that are available to them. These graphics should be immediately available and easily referenced to prevent user frustration over lack of knowledge and control.

Recommendations:

- Add onboarding graphics to main board and unit operations section. See the System Requirement and Activity Prompt Content documents.

Flexibility and efficiency of use

Users must be able to interact with the application in a fast and flexible manner. Novice users must be able to interact easily with the AR application and interactions with expert users must be facilitated, e.g., they are not required to watch the video instructions whenever the application is started. Furthermore, the user and the marker must be positioned easily in the environment;

Application for the Beartooth Virtual System

The main point found in the combined heuristics applicable to the Beartooth Virtual System is:

- Can users interact with the system quickly, and obtain needed information from the system, rather than an expert?

Can users interact with the system quickly, and obtain needed information from the system, rather than an expert?

Users should be able to easily use the system without needing help from an expert.

<u>Issue #19:</u> Users are unable to obtain additional info about nearby objects during Unit Operation mode.

During Unit Operation mode, users were able to obtain information on certain objects, but when they attempted to obtain information on nearby objects, they were unable to. This is because information on all objects was only available to users when in the Component Exploration training. However, during the Unit Operation training, users wanted to have the flexibility to learn the name and information about nearby components of the model.

Recommendations:

- Allow users to see additional information on any object in the model by selecting the P&ID of that object (See issue #10).

<u>Issue #20:</u> Users were not comfortable with controllers.

During testing on October 3rd, many users expressed frustration with some of the controllers. VR/AR controls were unfamiliar to many of those completing the training and it was not clear which buttons did what. Furthermore, the grabbing motion, while possible on some controllers, was not mapped directly to a person's physical hand, causing a disorienting experience. Nearly every user we spoke with recommended using hand gestures without any controllers. This has the added benefit of removing another potential point of failure (e.g., controllers that aren't charged).

Recommendations:

- In the short term, focus on the HoloLens system. If a VR version is implemented later, use hand gestures instead of controllers where possible. However, if the user has limited play space, a controller may be necessary to control location within the virtual space (see issue #9).

<u>Issue #21:</u> Instructions displayed on the main board are difficult to read and understand.

Extra care should be taken to ensure users can read text found throughout the Beartooth virtual system. Some users may have challenges such as poor eyesight or colorblindness, which can add difficulty.

Recommendations:

- Follow guidelines for clear, understandable text. Ensure text is large enough to be seen easily, and that the colors used for the background of the text and the text itself contrast enough while avoiding colorblind issues. See the System Requirements document.

Aesthetic and minimalist design

> *The system should not provide irrelevant information during the dialogue with the user. Irrelevant information competes with relevant information and eventually the user's attention is focused on unimportant aspects. The presence of many virtual objects or markers in the same application can lead to an overload of information;*

Application for the Beartooth Virtual System

The main points found in this heuristic applicable to the Beartooth Virtual System are:

- Is relevant information presented to the user while avoiding distractions? Is the user overwhelmed with objects that are not relevant?

Is relevant information presented to the user, free from distractions? Is the user overwhelmed with objects that are not relevant?

While it is important to maintain the fidelity of the Beartooth virtual system to the Beartooth physical system (see section *Match between the system and the real world*), users can become lost in learning how they can interact with the system, as well as knowing what is expected of them. Removing or focusing their attention can be helpful in aiding their experience.

Issue #22: Irrelevant objects distract and mislead users.

There are many objects shown in the virtual Beartooth system which will likely never be interacted with directly by the user. While this is not a problem in and of itself, since it provides an authentic context, it can at times draw attention away from the immediate training activity, increasing cognitive load. Many objects which are interactable do not become so until specific parts of the training.

Recommendations:

- Consider using a pre-determined color, such as grey, for objects that are not critical to the current task. See issue #14 for a related issue.
- Assign objects to layers that can be hidden by the user. Some objects could be

kept for orientation and fidelity, but removing other objects could help both in the user experience as well as hardware rendering. See issue #3

Help and Documentation

It is better if a system can be used without documentation, but the provision of a good procedure and documentation is helpful. Information should be easy to find and should be focused on the user's task in a concise manner. For example, the system must explain how each marker works. Explanatory videos for AR users are interesting solutions.

Application for the Beartooth Virtual System

The main points found in the combined heuristics applicable to the Beartooth Virtual System are:

- Where can a user go for additional information and help?

Where can a user go for additional information and help?

It should be noted that this section was not focused on as much due to the Beartooth virtual system being in development. Help and documentation should be added later once there is a lower chance of that documentation requiring updates to match the changes made in the system.

Issue #23: There is no place for users to obtain additional information.

Users need an obvious place to go for help in understanding how to use the training. Currently, there are onboarding experiences tied to the various individual trainings, but as the system develops in complexity there will likely need to be a help section that includes things like a Frequently Asked Question (FAQ) section.

Recommendations:

- Add a help button to the main menu and have it link to FAQs.

CHAPTER 5

Discussion

Our purpose was to help INL design a Beartooth virtual training system which is user-friendly, familiarizes users with the Beartooth physical system, and trains users for common procedures. Our usability and heuristic evaluations showed many areas which could be improved, and other general principles for INL developers to follow in their future development. They can reference our recommendations not only for the rest of the Beartooth virtual training project, but other similar projects in the future.

Affordances of AR training

Our experiences with the Beartooth virtual training system helped us address our first research question focused on identifying the affordances of AR in training systems.

One key affordance was the ability to walk around and interact with a realistic representation of the physical model. This helps users to gain a more comprehensive understanding of the system, especially as the size and shape of the virtual model would exactly match the size and shape of the system. They could see where objects were in relation to other objects, and thus start to connect locations and form habits as if they were using with the physical system.

Another affordance found is the ability to modify the digital model in ways that would be difficult or impossible to do on the real model. We found that hiding certain noncritical objects, such as the glovebox, greatly helped users to avoid becoming overwhelmed with a large system comprised of many objects. Because it’s digital, we can also provide more information to the users than what would normally be available. For example, showing the flow of chemicals from one part of the system to another, or showing contextual information about specific parts. This can be very helpful to users, as normally their training with the system piping relies heavily on a Piping & Instrument Diagram (P&ID), where pipes and tanks that are represented close on paper could actually be separated by large distances on the physical system, and vice versa. Now, they can check the P&ID, see where a tank is located in the system, and trace the piping from it to the next one with ease.

One more noteworthy affordance of AR training is the virtual nature and remote accessibility of the model. Because it is virtual, there is no danger of radiation or other hazardous materials to users. Users can learn and even practice situations that would otherwise be extremely dangerous in a physical setting, without risk to themselves or the system. Users can also utilize the trainings in remote locations, reducing travel time greatly. The trainings can even begin before the physical system is built, greatly enhancing the timeline of a given project.

Reflections on Results

While the findings are noted in the results section and have already been given to the team at INL, the following findings may be of particular interest to readers for use in other XR training projects.

Initial Setup and Physical Location

While many of the findings focus on what users would experience using the Beartooth virtual training system, there were a few critical issues that had the potential to prevent users from even beginning their experience. These initial set-up issues could arguably be more important than the rest, as a flawed experience is still better than no experience at all.

While testing at INL, the setup process was managed completely by expert INL developers before any users even started to go through the usability testing. While this was necessary to avoid complications with large numbers of users and limitations in time and hardware, this meant that these issues were not investigated more fully until later during researcher testing in the BYU Augmented Learning Lab.

Alongside setting up the system, developers can sometimes overlook the physical location. When meshing the physical and virtual world together, the physical spatial restraints are almost always the more constraining factor. The Beartooth system is large and uniquely shaped, the scope of which is difficult to grasp until one is experiencing it. Often, this new understanding is accompanied by the realization that the room one is attempting to use for the training is smaller than required. Another surprising issue found was that of bright ambient light (especially bright daylight) can affect the AR experience of the user.

Balance Between Authenticity and Usability

As noted in the results section entitled, *Match Between the System and the Real World*, the Beartooth virtual system will have a high degree of authenticity due to the models being pulled from the same CAD files used in the manufacturing process. This will be extremely helpful, as procedures, sensors, and those who interact with the system will all require a high degree of authenticity, especially considering the care and attention needed to prevent issues when interacting with nuclear material. However, not every small detail needs to be replicated with perfect accuracy. Developers found that small screws were being rendered in the virtual system, which cost the headset hardware valuable processing power (slowing the system down) with no benefit to the users.

As part of the process to discover what is needed and what is not, there were questions regarding how to implement the simulation of a user attaching pipes from one part of the system to the other. Would a user need to ‘pick up’ a simulated flexible pipe and attach it just as if they would in the real world? That would indeed increase the authenticity of the user experience, however the actual work required to create the code would be high, so it must be determined if it would be worth that effort. After discussion, it was deemed that the system was intended to teach the user where the pipes would attach, not how the pipes would attach. Teaching users how to do this and other tasks which likely have already been mastered could instead be abstracted. So instead of an authentic and complicated process, the current iteration allows users to simply touch one end of a tank to another and have a pipe created between them.

Other Findings of Note

Readers may have seen references to other documents in the recommendations listed in the results section of this paper. These issues and recommendations were more specific to work performed by other BYU team members. These included text size and layout, the color of the text and the background it is on, and even organizational issues of the menu. Unlike website and mobile app designs which have largely standardized over time, AR/VR interfaces have fewer standards. This is likely to change as these systems become more ubiquitous.

Limitations

The biggest limitation of this work is the number of people allowed to interact with the system. Because of the sensitive nature of the project and the near replica of the virtual system to the physical system, INL did not grant BYU permission to allow anyone who was not on the BYU Augmented Learning Lab team and also a U.S. citizen to view the Beartooth virtual training system. This limited our research to members of INL staff and researchers in the BYU Augmented Learning Lab.

Implications for Future Research

Future user evaluations and heuristic evaluations could be conducted again as the development of the Beartooth virtual training system continues. While many of the general principles and guidelines will remain the same, it is always helpful to look for and receive real feedback from those who will be using the system. Once the system is completed, INL should perform another full evaluation with those who will use the system.

It would be helpful to have use cases for the system more fully defined, such as when and where the training will take place, and then to perform a test as if it were truly being used in one of those defined times and places. It would also be helpful if users testing the system were those who had not already gone through earlier versions of the system, and were given as little help as possible, to fully test how well the system can stand on its own.

Because the Beartooth virtual system can be utilized by multiple users at a time, it would be worth studying how a team of users interact with the system. It would also be worth studying how well an expert could use the system to test and certify those being trained on the system.

Conclusion

The usability test and heuristic evaluation conducted as part of this research have produced a large amount of feedback for the team at INL. Our work has produced specific and actionable items, as well as more generalized user experience guidelines that are more specific to the Beartooth virtual system. The INL team has already incorporated many of our recommendations, and those recommendations can be referenced even in future projects similar to Beartooth.

REFERENCES

A. Caputo, S. Jacota, S. Krayevskyy, M. Pesavento, F. Pellacini, & A. Giachetti. (2020). XR-Cockpit: A comparison of VR and AR solutions on an interactive training station. *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, *1*, 603–610. https://doi.org/10.1109/ETFA46521.2020.9212043

Bottani, E., & Vignali, G. (2019). Augmented reality technology in the manufacturing industry: A review of the last decade. *IISE Transactions*, *51*(3), 284–310. https://doi.org/10.1080/24725854.2018.1493244

Çöltekin, A., Lochhead, I., Madden, M., Christophe, S., Devaux, A., Pettit, C., Lock, O., Shukla, S., Herman, L., Stachoň, Z., Kubíček, P., Snopková, D., Bernardes, S., & Hedley, N. (2020). Extended Reality in Spatial Sciences: A Review of Research Challenges and Future Directions. *ISPRS International Journal of Geo-Information*, *9*(7), Article 7. https://doi.org/10.3390/ijgi9070439

De Paiva Guimaraes, M., & Martins, V. F. (2014). A Checklist to Evaluate Augmented Reality Applications. *2014 XVI Symposium on Virtual and Augmented Reality*, 45–52. https://doi.org/10.1109/SVR.2014.17

Endsley, T. C., Sprehn, K. A., Brill, R. M., Ryan, K. J., Vincent, E. C., & Martin, J. M. (2017). Augmented Reality Design Heuristics: Designing for Dynamic Interactions. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *61*(1), 2100–2104. https://doi.org/10.1177/1541931213602007

Hix, J. D. (2022). *Color Sensor Comparison for Solvent Extraction Processes* (INL/RPT-22-70395-Rev000). Idaho National Laboratory (INL), Idaho Falls, ID (United States). https://www.osti.gov/biblio/2203696

Houck, K., Ritter, C., Burnett, T., & Cavaluzzi, J. (2022). Beartooth: Nuclear material testbed with MBSE and digital twin. *INCOSE International Symposium*, *32*, 142–154.

Labrie, A., & Cheng, J. (2020). Adapting Usability Heuristics to the Context of Mobile Augmented Reality. *Adjunct Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, 4–6. https://doi.org/10.1145/3379350.3416167

Morimoto, T., Kobayashi, T., Hirata, H., Otani, K., Sugimoto, M., Tsukamoto, M., Yoshihara, T., Ueno, M., & Mawatari, M. (2022). XR (Extended Reality: Virtual Reality, Augmented Reality, Mixed Reality) Technology in Spine Medicine: Status Quo and Quo Vadis. *Journal of Clinical Medicine*, *11*(2), Article 2. https://doi.org/10.3390/jcm11020470

Nielsen, J. (1995). How to conduct a heuristic evaluation. *Nielsen Norman Group*, *1*(1), 8.

Novita Sari, R., Sri Hayati, R., Fujiati, & Lestari Rahayu, S. (2020). Heuristic Evaluation In Mobile Augmented Reality Applications In Designing Houses. *2020 8th International Conference on Cyber and IT Service Management (CITSM)*, 1–5. https://doi.org/10.1109/CITSM50537.2020.9268922

Palmarini, R., Erkoyuncu, J. A., Roy, R., & Torabmostaedi, H. (2018). A systematic review of augmented reality applications in maintenance. *Robotics and Computer-*

Integrated Manufacturing, *49*, 215–228. https://doi.org/10.1016/j.rcim.2017.06.002

Popov, O., Iatsyshyn, A., Sokolov, D., Dement, M., Neklonskyi, I., & Yelizarov, A. (2021). Application of Virtual and Augmented Reality at Nuclear Power Plants. In A. Zaporozhets & V. Artemchuk (Eds.), *Systems, Decision and Control in Energy II* (pp. 243–260). Springer International Publishing. https://doi.org/10.1007/978-3-030-69189-9_14

Radoeva, R., Petkov, E., Kalushkov, T., & Shipkovenski, G. (2021). An Approach to Development of Virtual Reality Training Systems. *2021 5th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, 87–92. https://doi.org/10.1109/ISMSIT52890.2021.9604576

Ruthenbeck, G. S., & Reynolds, K. J. (2015). Virtual reality for medical training: The state-of-the-art. *Journal of Simulation*, *9*(1), 16–26. https://doi.org/10.1057/jos.2014.14

Satu, P., Jari, L., Hanna, K., Tomi, P., Marja, L., & Tuisku-Tuuli, S. (2024). Virtual-Reality training solutions for nuclear power plant field operators: A scoping review. *Progress in Nuclear Energy*, *169*, 105104. https://doi.org/10.1016/j.pnucene.2024.105104

Tremosa, L. (2023, July 25). *Beyond AR vs. VR: What is the Difference between AR vs. MR vs. VR vs. XR?* The Interaction Design Foundation. https://www.interaction-design.org/literature/article/beyond-ar-vs-vr-what-is-the-difference-between-ar-vs-mr-vs-vr-vs-xr