SNM Operator Training Using Digital Twin and Extended Reality – 24008

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ABSTRACT

Training personnel is essential in keeping systems and sites operational and is even more important to keeping personnel safe. However, existing training methods are often ineffective and expose workers to worksite hazards before they are educated on the hazards that may be present. This presentation will focus on training using mixed reality (MR) platforms in a process called familiarization. Familiarization is where already qualified operators are made to understand a new system and its unique characteristics. Physical mockups can reduce problems by providing a method of familiarization outside of the worksite. However, these mockups are expensive, are not truly representative of the work to be done, and are built near the end of an engineering effort after the design has been finished. Combining the tools of digital twin (DT) and extended reality (XR) could provide a solution to these training limitations. The Beartooth testbed project at Idaho National Laboratory (INL) used DT and XR throughout the design process, discovering errors and potential operational constraints due to inadequate design. This testbed is entering the fabrication stage, and the digital engineering team is working to adapt the MR representations for the use of training operators at the Fuel Conditioning Facility. Of the numerous unique challenges facing this testbed, one of the most prominent is that this will be a research and development (R&D) testbed handling fissile material and will be housed in a HAZCAT 2 production facility. The testbed operators will be unfamiliar with operating an R&D asset. Additionally, the testbed is reconfigurable, further complicating the demand on the operators. INL is working with Brigham Young University (BYU) to produce a novel training process to enable operators to be prepared for a readiness assessment on this complex situation. BYU is working with operators and aqueous separations researchers to integrate traditional training performed with piping and instrumentation diagrams with onsite walkthroughs of operations into narrative-driven, interactive trainings that will use MR and DT. Because the MR model is built using the engineering accurate design model, the training will provide trainees with an experience that is truly representative unlike a mockup. Trainees are traditionally walked through unit operations onsite on the fabricated and installed equipment shortly before a readiness assessment. The MR training will enable performing the bulk of the training and familiarization during the fabrication stage instead of after. Additionally, trainees will be able to highlight and search for tag numbers and instrumentation on the MR model and various systems flow, which is colored to help trainees understand various processes in a way that an onsite training would be unable to provide. After the training presentation, the trainees will have an understanding of the technology being used and the process being developed for the training, the challenges of transforming traditional trainings into MR trainings, and INL's roadmap to produce trainings sufficient for preparing operators for readiness review.

INTRODUCTION

Idaho National Laboratory (INL) is fabricating a one-of-a-kind special nuclear material testbed glovebox called Beartooth (Figure 1). Beartooth is a highly configurable research and development (R&D) testbed capability that houses the major unit operations pertaining to aqueous reprocessing, namely fuel dissolution, chemical separations, and calcining/solidification. Beartooth will incorporate real-time data collection, using advanced sensors and monitoring equipment to enable digital twin (DT), artificial intelligence, and machine learning capabilities for nonproliferation R&D.



Figure 1. Beartooth testbed.

In addition to its unique abilities for nuclear R&D, Beartooth will be the first-of-a-kind project to use digital engineering from design to operation. The efforts of using models-based systems engineering and DT with mixed reality (MR) to accelerate the design phase were presented previously at WM 2022 and WM 2023. This system is out of the design phase and is entering the fabrication phase. The next opportunity for digital engineering to accelerate the Beartooth project is through training. Training largely depends on printed documents, PowerPoints, and on-the-job (OTJ) training. The printed documents and PowerPoints produce meager training outcomes, and the physical methods require either an expensive physical mockup or the final system to be installed and ready for use. The digital engineering team is bridging the gap between these two methods by using the DT and MR system previously used for design to translate these traditional methods into interactive scenarios. The aim of the scenarios is to familiarize operators with this unique testbed in a way that allows for a quicker route to a readiness assessment. Familiarization is the process of training experienced operators on the specific form and functions of a new system. Beyond accelerating the schedule, this method will reduce project risk. This R&D testbed is being installed in a HAZCAT 2 operational facility, where issues that arise in an R&D setting could produce situations that are consequential in an operational facility. Finally, the same system developed for training will enable operations. It is important that reconfigurations are done correctly to prevent spills in the glovebox and that the use of the training simulator system will allow operators to practice an operation before performing it.

METHODS

Current State of Training

The complexity and versatility of the testbed demands the use of state-of-the-art modeling capabilities to assist in the design of equipment and piping layouts within the glovebox and serves as a training tool to educate personnel on key design features incorporated into each unit operation. Traditional training consists of laboratory instructions and OTJ, which are typically developed after the construction of the testbed. These traditional training platforms often require personnel to read substantial amounts of documentation prior to performing any hands-on work. Reviewing two-dimensional documentation for equipment designs and piping and instrumentation diagrams to prepare for operations does not translate well to the three-dimensional aspects of the system. In addition, aspects, such as equipment familiarization and troubleshooting, are learned only after the testbed has been in operation. Current training does not allow for personnel to explore and interact with the testbed's design concepts in a hands-on manner, which creates problems for knowledge retention and difficulties prior to any physical equipment startup.

To address the issues that current training practices create, the Beartooth testbed will employ a stratified approach to training that consists of equipment layout acclimation, operations familiarization sequence, and exercises centered around equipment reconfigurability to allow personnel to apply their knowledge in complex systems. For future R&D endeavors, researchers will also have the capability to explore various test configurations even after the testbed is constructed in a controlled, hazard-free environment.

Transforming Traditional Training into a Digital Environment

BYU collaborated with INL on developing prototypes of different phases of the training program; the phases are meant to build on each other. First, the interactive model introduces learners to the basic components and structures that make up the Beartooth system. Completing the model will ensure learners can identify relevant components and explain how they contribute to the system's functioning. Second, the task walkthroughs allow learners to rehearse the individual functions associated with running the Beartooth system, leading to the outcome that they can execute each function without assistance. Finally, the training scenarios allow learners to practice real-world activities using the Beartooth system. Completing the training scenarios demonstrates that learners can operate the system as they will need to OTJ.

To create the training content for the training program, the BYU team first interviewed operators, researchers, trainers, and supervisors regarding current training and operations. The interviewees shared critical features and content related to the Beartooth training. The BYU team also examined system materials to understand system processes and procedures. Based on subject matter expert interviews, a minimum-viable framework was established for training modules, each with a distinct learning objective. The content interviews provided a substantial list of requirements and objectives for the training framework. Based on these considerations, the BYU team ideated various training activities. Using the most promising approaches, low-fidelity presentations were created. These were then used to communicate the premises of the approach to request specific feedback from INL stakeholders. Many iterations, each one presented and modified according to the feedback of content experts, potential users, and stakeholders, gradually produced the training as it currently stands.

To create the content outline that would port with the training modules, BYU met with a INL content expert who reviewed and replaced initial content with correct and relevant information. The content included a collection of activity prompts, which instructed the user on how to locate components in the virtual space. To assist the MR software engineers in scripting the 3D model, tag numbers for system components were added and correlated to the content. The tag numbers were copied from the written document to a spreadsheet used by the software engineers.

As the training interfaces became more clearly defined, a style guide was incorporated into a requirements document. Figure 2 demonstrates one of the style guides used to create a user-friendly experience. The requirements document outlined best practices, provided a wireframe for implementing the in-training interface, and demonstrated how the 3D model would respond to user interaction. After the MR software engineers implemented the specifications of the training according to the requirements document and incorporated the written content, BYU observed and interviewed operators while they used the XR training system to understand their experiences with the system and to get feedback resulting in changes for later system iterations. Once the interfaces were defined, a style guide was incorporated into a requirements document, outlining best practices and providing a wireframe for implementing the in-training interface and demonstrating how the 3D model would respond to user interaction.

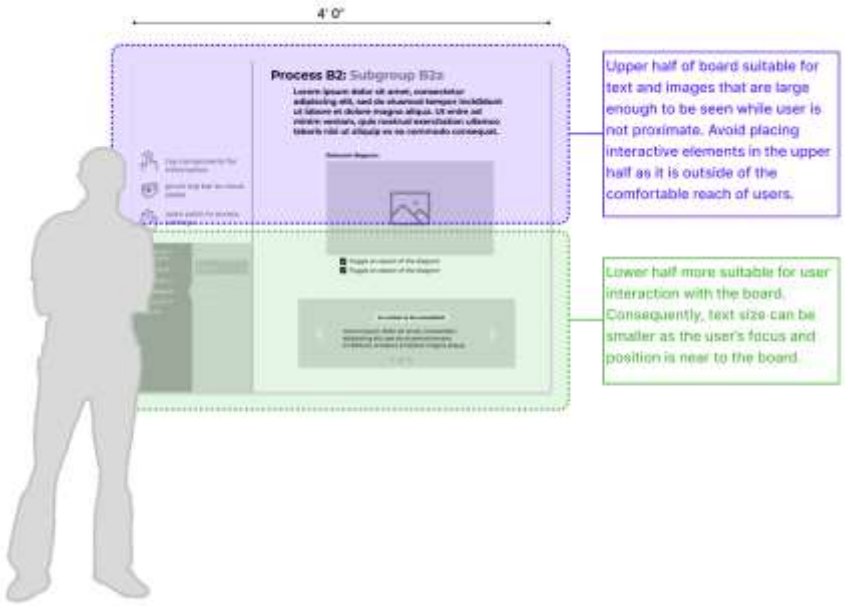


Figure 2. Style guide and design considerations.

Translating Interactive Narratives into an Ontology

Natural language is often ambiguous and can be interpreted in multiple ways. These ambiguities can create uncertainty for people who are trying to follow instructions when performing a task. Additionally, this same limitation also hinders machines and algorithms from completing or in aiding a task. An important step of translating traditional training into digital training is removing these ambiguities. BYU is undertaking the process of removing this ambiguity and adapting the training to an interactive narrative. An example of their efforts is shown in Figure 3. The narrative is composed of activity prompts with a call to action, the text provided to the student, verification cases to validate the student's actions, and finally there may be remediation steps that help the student correct any mistakes that they make.

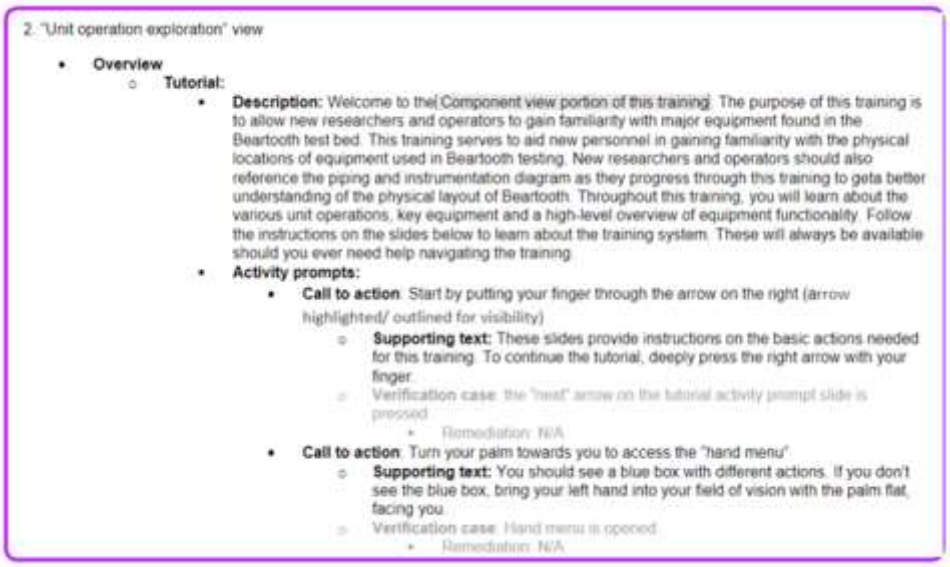


Figure 3. Interactive narrative.

These interactive narratives are an explicit set of sequenced steps, which removes the ambiguities that a traditional training may have. Once ambiguities are removed, the next step is to structure it in a way that the training is composed of reusable structures. This allows for assumptions that can be used by software programs to automate the generation of scenarios. The structure used by the team was an ontology, which is "a specification of a conceptualization" [1]. The key ontological classes used were that of plan, actor, instruction, history, function, and a non-temporal entity. The ontology defines both the types of entities and their relationships. Figure 4 demonstrates the core entities, which allow the narrative authors to express an interactive narrative in an unambiguous structure, are still written in language a human can understand easily but are meant for computer consumption also.

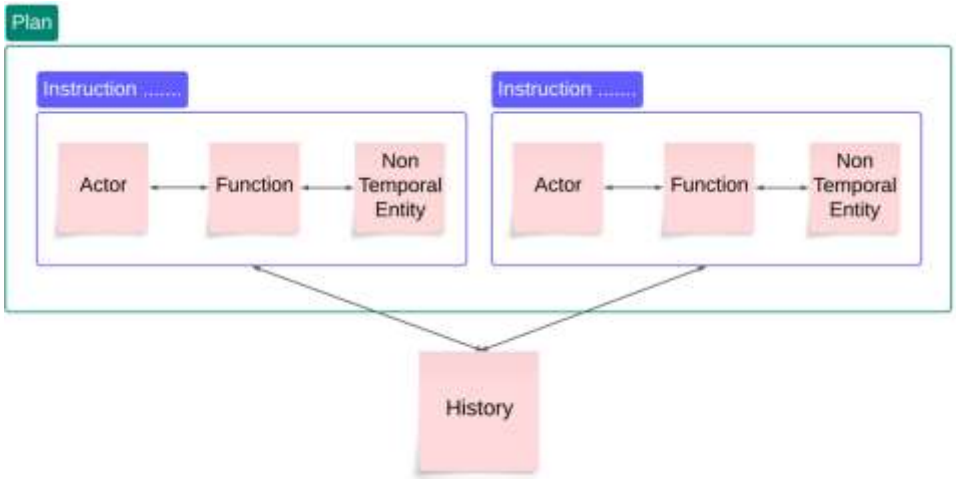


Figure 4. Ontology of a training.

A plan is composed of a sequence of instructions, which require an actor that has a function that is performed on a non-temporal entity. The results of these instructions are captured in a history (a type of temporal entity). These elements are either currently part of or are an upcoming addition to the general entity model (GEM) ontology [2]. This ontological breakdown of training leads to object-oriented programming. The INL team is storing this ontological representation in an open-source graph database called DeepLynx. DeepLynx allows INL to store relational data represented in Figure 5 such as time-series data that comes from sensors and 3D models representing computer-aided design (CAD) that represents the system to be trained on.

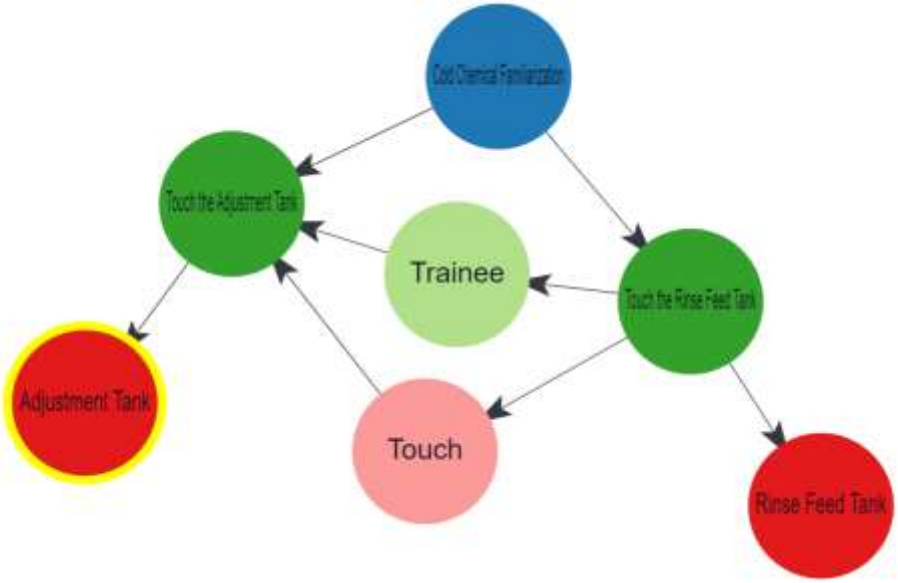


Figure 5. Ontological breakdown of a test plan with two instructions.

This approach allows for the ability for a training translated into the ontology to then be translated automatically into a scenario simulated into a game engine. The process is accomplished through the elements in Figure 6.

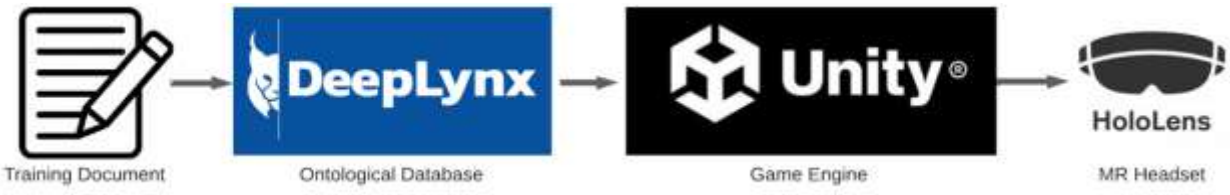


Figure 6. Digitized training architecture.

Deciding on the Right Extended Reality Tools for Training

Extended reality (XR) is a device's ability to allow a user to view digital content overlayed with the real-world environment and give the user a natural form of interaction in the form of hand tracking or controllers. There are numerous devices in the market today, all with differing capabilities and approaches. INL's design phase efforts in MR included the Microsoft HoloLens 2 and Varjo XR3. HoloLens 2 is a holographic MR headset with built-in spatial and hand-tracking features that enable users to view digital models while retaining complete cognizance of their environment. The hand tracking allows the natural touch interaction with digital content. The Varjo XR3 is a pass-through MR headset that uses cameras mounted externally on the device to pass-through a high-quality color image of the real world and is displayed in front of the users' eyes. Digital content is then blended with this color pass-through, and high-resolution digital content can be viewed and interacted with by either hand tracking or controllers.

The ultimate deciding factor in INL's choice of hardware was the preference of the primary users. Overall, MR offered the most comfortable and intuitive visualization experience. The necessity for a physical controller in a purely virtual reality environment required additional acclimation for users as opposed to the more intuitive hand gestures and direct interaction of MR. Pass-through MR generally requires heavier and more cumbersome equipment as opposed to overlay style MR, though newer headsets are addressing this issue. The headset weight and necessity to adjust the headset to each user's unique eye profile created further discomfort and aversion to the technology than a headset that simply superimposed images into the user's field of view.

During testing, it was also clear that the most familiar and convenient method to regularly view digital models was in a workstation environment. To accommodate this, a WebGL-based platform was developed to allow users to view the model from any personal computer while also coordinating with users using head-mounted display's (HMD) by implementing avatars that indicate any user's current relative position in the digital environment to other connected users in the same environment (Figure 7). This platform ultimately complements but does not replace the MR platform as it lacks representation of real-world perspective and direct interaction.

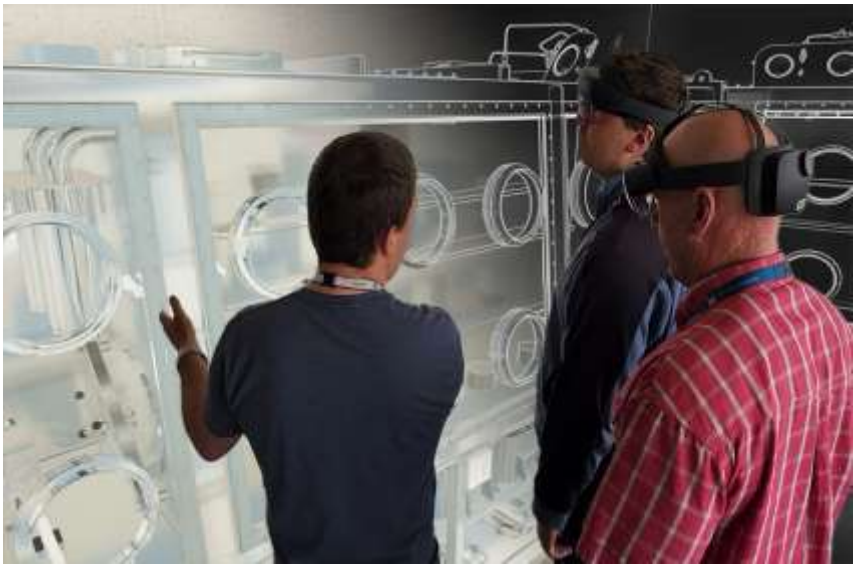


Figure 7. Collaborative viewing of the digital asset.

Creating a Mixed Reality Training Environment

Using the Unity game engine and HoloLens 2, INL was able to create an initial proof-of-concept training for familiarity of the various unit operations of the testbed. The first step was to get the computer-aided design (CAD) model of the Beartooth testbed workable with Unity. CAD models are geometries that model the exact dimensions of what will be produced during fabrication. These geometries are difficult to render in a simulation due to the level of detail. Instead, geometries are "meshed" using a process of tessellation that approximates the shapes using triangles. Using the software product Pixyz, INL was able to translate the CAD geometry into Unity game mesh while preserving metadata. Pixyz was also used to perform preprocessing to reduce vertices to make the model easier to render. The model retains high fidelity even after this reduction. Once the model has been imported into Unity, INL builds out specific features. The most important features pertain to displaying the model correctly, ingesting data from DeepLynx, building out the training user interface panel, and hooking up specific XR interactions to be used during the training.

An important aspect of the training is to ensure that the model looks as realistic as possible and appears predictably within the user's environment. The user's position in a room is constantly being calculated and measured against where the virtual models are supposed to appear. The training's effectiveness is reduced if the model viewed is not being shown to scale, is not level, or has missing geometry. To solve this problem, we allow the user to scan the floor using the depth sensor, mark the floor as looking appropriate, and then scan a QR code that places the model on the virtual floor [3]. This allows for predictable placement of the Beartooth hologram to deliver a consistent experience to the user. For use in the intended facility, a QR code is placed in the facility and in a building information model at the same location. This allows for the precise location of the model in its intended location.

BYU and the chemical engineers worked together to provide the software development team with non-contrived real data in the form of csv files. These files specified the curated text that would be shown to the trainee as well as what actions the trainee would need to take to complete each training activity. These files were uploaded into DeepLynx. At runtime, the application is designed to pull the DeepLynx training data and build a training UI dynamically. This data-driven approach allows for aspects of the training to be redefined and changed without needing to rebuild the software platform that hosts the simulation without code changes. Many of the visual assets used to build the Training UI were based on the Microsoft Mixed Reality Toolkit (MRTK), which is an open-source toolset used for creating MR applications (Figure 8).

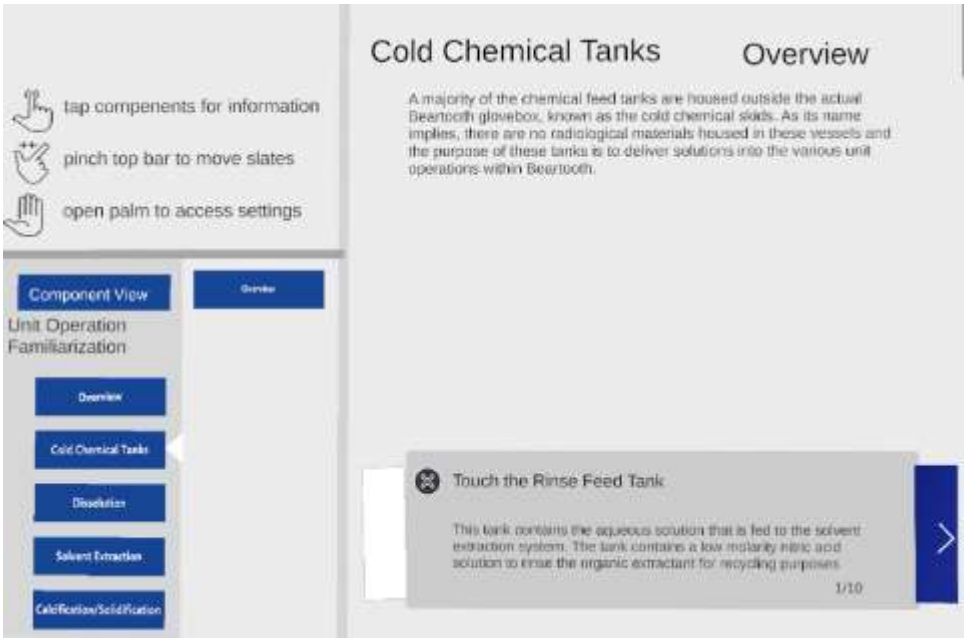


Figure 8. Snapshot of the training UI.

In this familiarity training, the main interaction is done by touching different components. As shown in Figure 9, a user is prompted to touch a specific component. The user can move around and find the highlighted component and physically reach out to touch it with their finger. The articulated hand tracking makes this process very intuitive. The training is composed of two modules. The first module is the "Component View," which allows the trainee to select items of interest with their hands and get additional information such as component ID, data from instrumentation and control (I&C), and metadata from engineering models. This module is unguided and is designed as a sandbox mode to allow users to gain a general understanding of components of their choosing. The second module is the "Unit Operation Familiarization," which guides the user through a set of basic activities. These activities involve equipment familiarization related to each unit operation: solvent extraction, dissolution, calcification, and solidification.

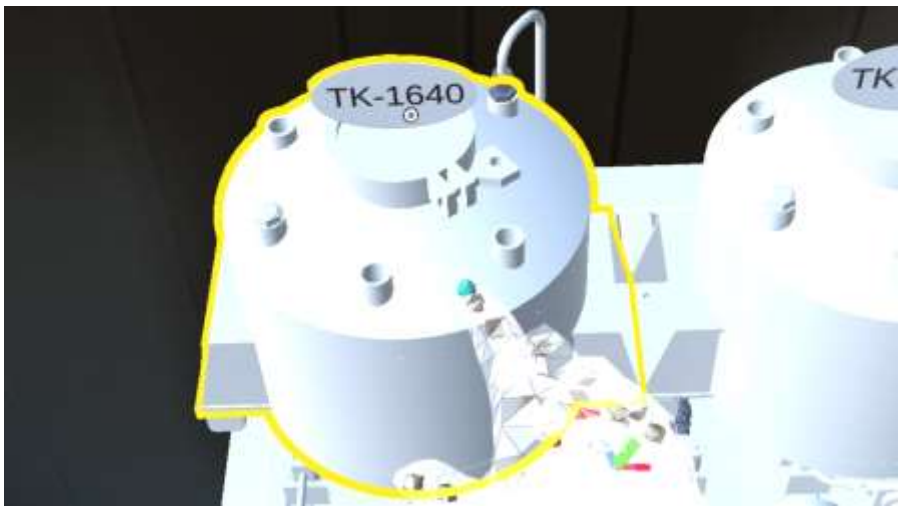


Figure 9. Highlighted tank with articulated hand tracking.

In future development, more immersive interactions will be developed that will improve the trainee's knowledge retention. While these initial training modules use simple touch-based interactions, users reported positive experiences while interacting with a complex system in this way. The benefits of viewing a full-scale model that accurately represents the designed system allow trainees to spatially orient themselves and gain an understanding of high-level processes that will be used.

Digital Twin Training Platform Aiding Operations

Once the Beartooth system is built and the training simulation is mature, it allows for many unique opportunities not present in conventional training. With the DT architecture, data about the system is collected and stored during design and operation. This data can be replayed within a training platform. For example, if the operators experienced an overfilling tank due to a hardware failure or operator oversight, it would be possible to replay the live data captured during the incident to a trainee using the MR training simulation. This would allow training on a problem likely to be experienced OTJ using data from the actual system the trainees are being trained to operate.

Digital displays, such as flow rates, conductivity, and heat, used to display I&C data to trainees would also be available to operators during operations. The MR headsets could be used without interfering with unit operations. This would allow operators to understand changes in a system without being required to go to the I&C's control system and its accompanying human machine interface. Additionally, the ability to display real-time data can be greatly enhanced with the increased variations of displays that a game engine can produce rather than an industrial control system. Finally, with a DT integrated into the testbed, the operator will be able to receive real-time predictions of the future state of the system.

CONCLUSIONS

The use of digital engineering and MR approaches for the purpose of training offers great potential value for future engineering efforts. The components needed to transition to MR training are largely commercial-off-the-shelf or open-source, making the adoption of this technology achievable by most engineering organizations. The approach demonstrated by INL and BYU offers a methodology that is ahead of the current artisanal approaches used by most organizations doing similar training in virtual reality. The integration of an engineering team and the MR team means that models will always match the actual engineering model held in CAD and produce accurate and realistic game models for the use of training. Producing a formal method that is applied to any training provides a pathway to consistently produce effective training. Finally, the use of MR training integrated with DT provides a critical bridge between the design phase and operations phase of an engineering effort that DT currently occupies most frequently.

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