sciendo ACC JOURNAL 2025, 31(1) DOI: 10.2478/acc-2025-0001

AN AUGMENTED REALITY APPLICATION FOR AN IMMERSIVE LABORATORY EXPERIENCE: THE ZITTAU FLOW TRAY

Juan A. González Morales[1]; **Jorge Valle García**[2]; **Fabian Lindner**[3]; **Frank Zacharias**[4]; **André Seeliger**[5]

[1, 2] Instituto Tecnológico y de Estudios Superiores de Monterrey, Engineering and Science, Av. Eugenio Garza Sada 2501 Sur, Tecnológico, 64849 Monterrey, N.L., Mexico

[3] Zittau/Görlitz University of Applied Sciences, Faculty of Business Administration and Engineering, SCO-TTi Labs, Schliebenstraße 21, 02763 Zittau, Germany

[4, 5] Zittau/Görlitz University of Applied Sciences, Institute for Process Technology, Process Automation and Measurement Technology (IPM), Nuclear Technology/Soft Computing Department, Theodor-Körner-Allee 8, 02763 Zittau, Germany

e-mail: [1]a01252106@tec.mx; [2]a00571775@tec.mx; [3]fabian.lindner@hszg.de; [4]f.zacharias@hszg.de; [5]a.seeliger@hszg.de

Abstract

Integrating augmented reality (AR) into engineering education can enhance the learning experience for complex concepts. This study presents an AR application's engineering process and prototype for the Zittau Flow Tray using (ZFT) Microsoft HoloLens 2 and Unity 3D. The application provides information on sump recirculation operations after a loss-of-coolant-accident in pressurized water reactors. Key features include interactive 3D models, flow simulations, and dynamic information overlays. Initial testing validated the application's core functionalities, though challenges such as user positioning accuracy and real-time data integration remain. Future enhancements will focus on refining these aspects and broadening the application's usability across various AR platforms.

Keywords

Industry 5.0; Human-computer interaction; Engineering education; Nuclear safety; Loss-of-coolant accident; Pressurized water reactor.

Introduction

Nuclear energy was still involved in power generation in Germany until 2023. Plant and reactor safety had to be guaranteed for the remaining service life of the nuclear reactors. This was one of the research focuses of the department "Nuclear Technology/Soft Computing" of the Institute of Process Technology, Process Automation and Measurement Technology (IPM), a research institute of the Zittau/Görlitz University of Applied Sciences (HSZG). For more than 20 years, this department has been working on nuclear safety research projects, focusing on the controllability of loss-of-coolant accidents (LOCA). The according experimental and methodological work has been carried out in close cooperation with the Helmholtz-Zentrum Dresden-Rossendorf and the Gesellschaft für Anlagen- und

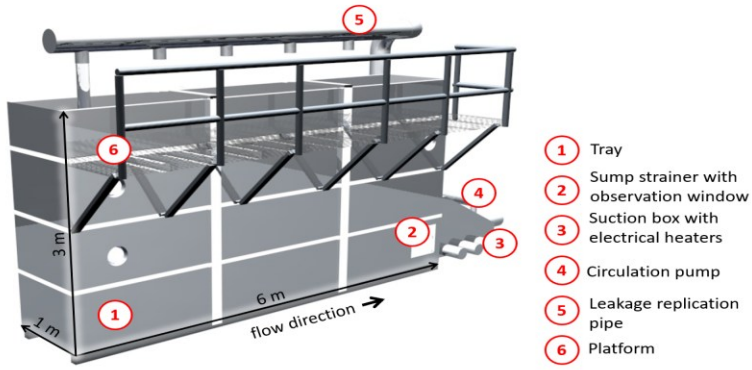
Reaktorsicherheit gGmbH on the following main topics. In the event of a LOCA in the reactor, insulation can be removed from surrounding pipelines when a feedwater line breaks. Investigations included the behavior of these insulation particles in the stationary and flowing coolant, the build-up of filter cakes on retention devices in the containment sump, and the accumulation behavior in the reactor core (Krepper et al., 2008). In a LOCA in PWR, zinc can be released in ionic form due to the corrosion of galvanized internals in the borated coolant (Harm et al., 2023). These zinc ions have the potential to reach the reactor core and transform into solid corrosion products (zinc borates) in hot channels (Kryk et al., 2014; Renger et al., 2018). At the HSZG, zinc corrosion was simulated under near-accident conditions (Kästner et al., 2020; Harm et al., 2022; Kästner et al., 2023). Accidents of this kind can result in complex thermohydraulic and physicochemical effects from the containment to the reactor core. The design of the test rigs used to analyze these processes in detail is correspondingly complex: components of the nuclear facility, such as the reactor sump and geometries of the reactor core, are represented on a semi-technical or even original scale (Renger et al., 2018). Two interconnectable test rigs have played a unique role in the investigations of recent years: the ZFT (Fig. 1) and the core simulator THETIS or Twofold HEaTIng rod configuration for core Simulation. Both systems are fully operational to carry out nuclear safety research. The performance of the system and many measured values can be seen through a dashboard on a local computer, which shows the metrics at runtime as well as some digital actuators (human-machine interface). This work focuses on the first system, the ZFT, which allows the simulation of a sump recirculation operation after a LOCA in a PWR. It is designed to investigate the thermohydraulic effects resulting from corrosion and precipitation processes in the structures of a PWR (Renger et al., 2018) and has the following features:

Source: Own

Fig. 1: *Photo of the ZFT representing the containment sump of a PWR*

- It is a **downscaled German PWR sump model**, modularly designed and constructed as a flow circuit for liquid media like coolant, with a large tray as storage (Fig. 2). The system circulates coolant by transporting it from the tray via a suction box into a horizontal pipe above the tray, from where it returns to the tray through outlets in free fall. Important measured variables, in addition to the tray fill level, are recorded along the flow path, e.g., the coolant's temperature, conduc-tivity, and volumetric flow.
- The stainless-steel **tray** represents the containment sump, downscaled to geometric dimensions of 6 m × 1 m × 3 m (L × W × H). Up to 15.6 m^3 of coolant can be stored in the tray. Particle suspensions can be added here to create a solid-liquid multiphase flow.
- **Sump strainer** (optional): Mounted in front of the suction box's inlet, the strainer (metal grid) ensures quantitative statements regarding the retention of released particles via the retention device in the PWR containment sump. An observation window allows for determining the thickness of the filter cake created from retained particles.

- **Suction box**: The circulating coolant inventory can be heated to a maximum of 80 °C. Three electric heating elements are installed for this purpose.
- **Circulation pump**: This pump is located at the outlet of the suction box and circulates the coolant inside the ZFT test rig. The flow rates in the components and upstream of the sump strainer are set by coarse adjustment of the pump flaps and fine adjustment of the pump's frequency converter.
- **Leakage replication pipe**: A horizontal pipe is installed above the open tray to replicate the leakage jet. This pipe has five downward outlets at different intervals representing different leaking positions (free fall section). Volume flows and spray patterns can be varied. Zinc-coated sources can be placed inside this section to provoke corrosion effects.



Source: Own

Fig. 2: *The main components of the ZFT*

During a lab tour, it can be challenging to communicate the project content and objectives to interested students and scientists. A complicating factor is that many parts of the test facility are not directly visible. Therefore, the references to the parts of the nuclear facility, which are modeled here on a semi-technical scale, are therefore difficult to identify. Here, AR can be a welcome tool for conveying this information clearly and interactively within a short time or remotely, i.e., off-site. AR, as a means of interactive, immersive visualization possibility, poses a promising opportunity to convey hidden and/or complex engineering concepts engagingly. It enhances the real world with holographic digital objects and information in real-time and allows users to interact with these objects (Porter & Heppelmann, 2017). AR and Virtual Reality (VR) are promising tools for training, maintenance, quality and safety management in nuclear power plants in general (Popov et al., 2021; Yim & Seong, 2010). However, there is no one-size-fits-all solution due to the variety of possible AR technologies, applications, and constant advancements. Therefore, each individual task still requires individual solutions. Also, to the authors' knowledge, research on AR in nuclear power plants has not yet included attempts to visualize hidden flows, such as using X-ray vision. However, such efforts are helpful to educate and make transparent the fundamental mechanisms in nuclear power plants to raise awareness and promote safety considerations. Therefore, it was proposed that AR technology be used to further enhance the experience of both tutors and students, with the possibility of extending its use to external people (from schools and energy research communities). The goal was to develop an interactive and immersive AR experience in the Thermal-Hydraulics Facilities for all stakeholders using the Microsoft HoloLens 2 head-mounted display (HMD).

The remainder of the paper is structured as follows. Section 1 reviews the theoretical backgrounds and presents a state-of-the-art overview of current industrial applications of AR, as well as its benefits and challenges. Section 2 describes the methods to design and implement the AR application. In the central part, we report the results concerning the various parts of the application. These include the basics, such as the 3D model scan, positioning and anchoring approach, runtime architecture, and user interface (Subsection 3.1); mandatory features of augmentation, such as info boxes, interaction with the ZFT model, and visualization of a simulated water flow (Subsection 3.2); and an ad hoc evaluation by ZFT domain experts (Subsection 3.3). Finally, we discuss the application of the prototype in practice, its limitations (Section 4), and venues for future research before we conclude.

1 Literature Review on Augmented Reality in Industry and Education

AR or Mixed Reality (MR) refers to augmenting of users' line of sight with digital information by using HMD, handheld devices like smartphones and tablets, or projectors on surfaces. These devices link the physical and digital worlds through immersive and interactive experiences for users. AR enhances the real world by overlaying digital objects in real-time and allowing users to interact with them (Milgram et al., 1995). Key tools for the development of AR and MR include computer vision (to understand and interpret the environment), spatial mapping (3D representation of the physical world), sensors and tracking technologies (Global Positioning System or GPS, localization, and mapping), and respective display technologies. Companies like Microsoft, Magic Leap, Apple, and others have developed state-of-the-art AR and MR devices, such as HoloLens and Apple Vision. These devices provide navigation, education, industry, healthcare, and training simulation applications. Development tools like Unity, ARCore, and Arkit allow programmers to design immersive applications for these devices. According to Porter and Heppelmann (2017), the benefits of AR in organizations are, first, the capability to visualize information in 3D and to allow an X-ray vision of otherwise hidden mechanisms in real-world objects. Second, instructing and guiding others location-independently by domain experts will greatly support knowledge transfers. Moreover, the different interaction possibilities based on gestures, eye gaze, and voice enhance the practicality of AR devices. In industry, AR, in general, is used for assembly, maintenance, logistics, and quality management, investigating benefits on time, error rate, or task load (Egger & Masood, 2020; Fang et al., 2025). With VR, AR has experienced increased attention as a means of visualization in operations management and as a way to support human workers (Lindner et al., 2025). However, ready-to-use AR solutions for operations are uncommon because each application requires software engineering due to individual information technology systems, the specific characteristics of equipment and processes, etc. Mühlan et al. (2021) proposed a framework for industrial AR implementation to assist with such implementation projects. For engineering education in specific, AR can leverage student engagement, make abstract concepts tangible, or improve students' spatial abilities (Tuli et al., 2022; Vásquez-Carbonell, 2022; Winkler et al., 2022). In education and training, the implementation of AR and VR takes advantage of the ability to immerse users in augmented or virtual worlds. This allows users to gain implicit knowledge through experience and interaction (Lindner et al., 2025). This paper attempts to leverage the benefits of AR by applying its principles to the ZFT. This AR engineering project is especially challenging due to several constraints, including limited time (approximately 15 weeks part-time), resources, and the fact that AR software engineers do not develop it but rather industrial engineers and domain experts for their purposes.

2 Methodology

The project was developed in four main phases to create an immersive AR prototype for the ZFT (Fig. 3). These phases were defined using common software engineering and project management principles and processes, including requirements definition, design, implementation, and testing (O'Regan, 2022). First, the familiarization with Unity and

Microsoft's Mixed Reality Toolkit (MRTK) packages to develop the AR application for the HoloLens 2 took place. Second, regular visits to the Thermal-Hydraulic Facilities were necessary to compile and assess all the necessary information on the ZFT, make a 3D scan of it, and define the AR application requirements. Third, the AR application was developed, including its logical flow, menus and actions, object positioning system, additional features, and a flow simulation, before it was finally evaluated. Sections 2 and 3 report the approaches and results regarding steps 2 to 4 in more detail.

Source: Own

Fig. 3: *Methodological approach*

2.1 Engineering Requirements for the Zittau Flow Tray Application

Three mandatory requirements of the to-be-developed application for the ZFT were identified, and two further optional features were defined.

Static but movable elements like texts and/or media should enable the augmentation of the ZFT. Furthermore, the display and interaction with the 3D model of the ZFT should be possible. The visualization of a flow simulation should be available within the 3D model. Real-time data integration and augmentation of the ZFT statuses through cloud services should be achieved, and the visualization of accurate system dynamics simulation based on real-time data resources should be possible (optional, extra-functional features).

To implement these requirements, the following resources were needed: a Microsoft HoloLens 2, a 3D Model of the ZFT, descriptions of each primary part of the ZFT, and a development environment, including the development engine (Unity) and its software dependencies, which are described more in detail in the next subsections.

2.2 Implementation on the Microsoft HoloLens 2

The HoloLens 2 is an MR headset developed by Microsoft, the successor to the original HoloLens. It is designed to blend digital content with the real world, creating interactive MR experiences. This device is a self-contained computer with a see-through holographic display equipped with various sensors, advanced optics, and a custom-built holographic processing unit. HoloLens 2 offers a more immersive and comfortable user experience than its predecessor. It has a more balanced center of gravity, a larger field of view, and hand and eye-tracking capabilities, allowing more natural hologram interactions.[1]

2.2.1 Microsoft's Mixed Reality Development Toolkit

The MRTK is a comprehensive, open-source development framework designed for building MR experiences on the Microsoft HoloLens and Windows MR headsets. It provides tools, components, and features that simplify the development process, making it accessible for developers of varying skill levels. The MRTK includes various functionalities such as spatial awareness, input simulation, hand tracking, and gesture recognition, which are integral to creating immersive and interactive mixed-reality applications. Additionally, it offers customizable templates and pre-built UI controls, enhancing the efficiency and user-friendliness of the design process. Developed primarily in C# and deployable in the Unity 3D

[1] https://www.microsoft.com/en-gb/hololens/

engine, the MRTK is celebrated for its ability to streamline complex aspects of MR development, allowing developers to focus on innovation and user experience. The version used for this project is MRTK 3, its most recent version.[2]

2.2.2 Unity 3D Engine

There are several reasons for choosing Unity 3D as the development engine for this application. The HoloLens 2 is designed to interact primarily with the C# programming language, which is also used within Unity 3D. The MRTK set is programmed in C#, ensuring an optimized and integrated workflow within the engine. Since the goal is to develop a MR application, and MRTK is specifically designed and optimized for integration with Unity 3D, the decision was made to use Unity 3D as the development environment and C# as the programming language.[3]

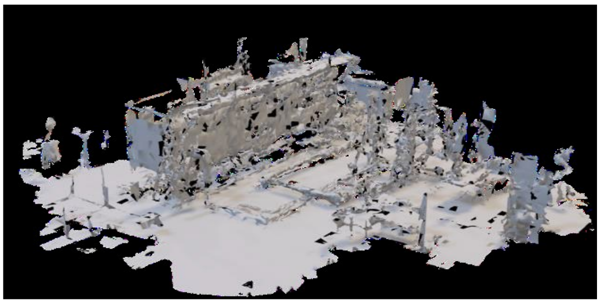
3 Results

In January 2024, the first functional prototype was tested and demonstrated at the ZFT. It includes all the pre-specified three mandatory requirements (Subsection 2.1): augmentation of the ZFT with texts, display, interaction with the 3D model, and simulation of a flow within the 3D model. In the following, the features of the prototype are described in detail.

3.1 Fundamentals

3.1.1 3D Model Scan

For the system's 3D scan, the sensors integrated within the HoloLens 2 were chosen due to their high precision and the ease of data extraction through the tool's interface. The scan took approximately ten minutes. A real-time scan could be viewed through the HoloLens's web interface. Once the scan was finished, the model was downloaded and saved locally (Fig. 4).



Source: Own

Fig. 4: *3D Scan model of the complete ZFT*

The scan encountered some minor issues detecting fine details in certain areas of the system because the machine's material reflects light (Fig. 1), affecting the quality of the 3D scan.

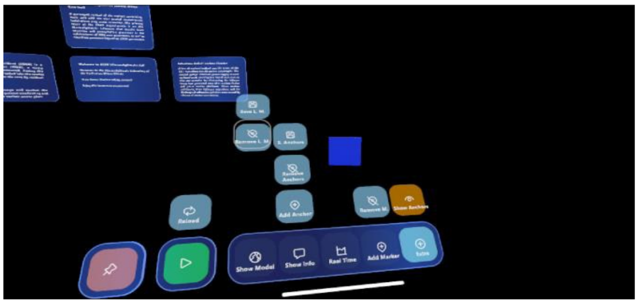
3.1.2 Positioning and Anchoring

The initial positioning of the AR application and the anchors of digital objects are locked to the user's position at startup. This gives laboratory staff and users more flexibility to arrange, scale, and adapt digital objects, such as info boxes and markers, before and during events like lab tours and training sessions for different audiences with varying levels of prior knowledge. Ideally, the anchoring system of the digital augmentations with the real world would be based

[2] https://learn.microsoft.com/en-gb/windows/mixed-reality/mrtk-unity/mrtk3-overview/

[3] https://unity.com/

on AzureSpatialAnchors, a cloud system from Microsoft Azure services that provides object anchoring for AI development purposes. However, due to the lack of documentation and the price of such services, it was decided to develop a local anchoring system. To set up an anchor, it must be created within the environment and made visible for its manipulation. This is done by interacting with the Add Anchors and Show Anchors interactable buttons under the "Extra" menu (Fig. 5).



Source: Own

Fig. 5: *Anchoring system*

As the anchors are positioned, one must be careful of the rotation as the anchoring system is rotation sensitive. Once the anchor game objects are correctly positioned, the Save Anchors method should be called, which can be done when interacting with the S. Anchors button (Subsection 3.2.2). Such a function takes the anchor's game objects' world positions and saves them to a local file. When the world is reloaded, the anchors should be automatically loaded (invisible mesh) and ready to be worked with.

3.1.3 Runtime Architecture

The logical runtime architecture consists of three central states (which inherently define the system's state): "idle" (no subprocesses running), "running" (system operational), and "error" (system halt, error found). The system state is updated based on a simple decision tree paradigm. When the program starts, no main subprocesses are running, meaning that the system state is "idle" and the user is just given one option to start the program. Starting the program changes the system state to "running". If an error is encountered during either state, the system state will be updated to "error", and a log line will be thrown to the console. Tab. 1 shows the system states as variable values.

Tab. 1: *System state definitions*

Variable	State	Value
_state	Error	-1
_state	Idle	0
_state	Running	1

Source: Own

3.1.4 User Interface

When the system state is defined as "Idle", the environment is loaded with static info boxes that introduce the system and are prompted by one interactable button with the play icon (Fig. 6).

At this point, the user can walk around and interact with the info boxes. Once the play button is pressed, then the main menu will become active, with a series of actions to choose from to either set some world settings or interact with the world objects (Fig. 7; Tab. 2). The system state is updated to "Running".

Source: Own

Fig. 6: *System state "Idle"*

Source: Own

Fig. 7: *Main menu with initial information boxes at startup*

Tab. 2: *The main menu action list*

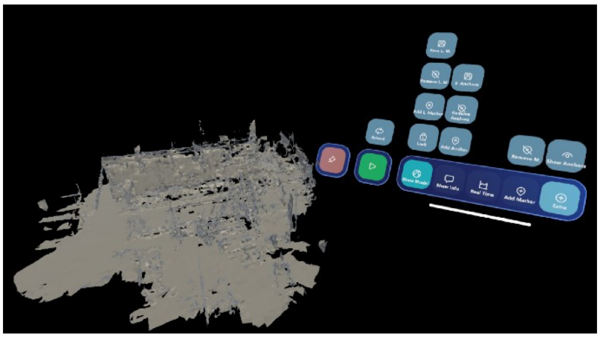
Name	Action
Pin	Fixes menu position.
Play	Toggles between "idle" and "running" state.
Show Model	Shows an interactable 3D model of the system.
Show Info	Shows system-specific info boxes at anchor positions.
Real-Time	Shows real-time data and simulation (only mock-up).
Add Marker	Creates an interactable red marker.
Extra	Activates sub-menu with extra functions.

Source: Own

3.2 Mandatory Features

3.2.1 Augmented Information (Media Boxes)

Show Info. The show info functionality depends on the local anchor system (Subsection 3.1.2). Once the anchors' world transforms are saved and loaded, the show info method will look for each anchor's position and display the dialogs according to the order of anchoring. The dialogs are then loaded as depicted in Fig. 9.



Source: Own

Fig. 8: *Show model environment*

Source: Own

Fig. 9: *Samples of info boxes*

Add Marker. The Add Marker functionality creates a general marker (red) that transforms dynamically (Fig. 10), which means that it can be moved and scaled. This type of marker **cannot be saved**. This feature's purpose is to specifically emphasize some points of interest from the laboratory.

3.2.2 Interactive Zittau Flow Tray Model

Show Model. The Show Model action activates and makes visible a scalable (transform dynamic) 3D Model of the system. When activated, two specific function options will be shown (Fig. 8; Tab. 3).

Tab. 3: *Show model action list*

Name	Action
Lock	Locks the 3D model's world transform properties.
Add L. Marker	Adds a green lab marker.

Source: Own

The lab marker differs from the general marker (red) in that the Lab marker will move and rescale relative to the 3D model's world transforms. The position properties relative to the 3D model's transform properties can be optionally stored to mark key points in the 3D model that can later be automatically loaded.

Extra Menu Action List. The extra interactable activated sub-actions were developed to set up the technical configuration of the virtual environment (Fig. 11; Tab. 4).

Source: Own

Fig. 10: *General marker*

Source: Own

Fig. 11: *Extra menu*

Tab. 4: *Extra Menu Action List*

Name	Action
Remove L. Markers	Removes L. Markers (green).
Save L. Markers	Saves L. Markers' (green) position relative to the 3D lab scan model.
Add Anchors	Creates an anchor.
Remove Anchors	Remove all anchors.
S. Anchors	Saves anchors transform relative to world origin coordinate.
Remove M.	Removes general (red) markers.
Show Anchors	Show anchors as world objects (mesh visible).

Source: Own

3.2.3 Flow Simulation (Mock-Up)

A minimum requirement for the project's duration was the availability of a simulation and visualization of water flow in the ZFT, at least in the holographic 3D model of the PWR. This was achieved through an animated flow of blue dots (water particles) moving from the source to the sink of the ZFT model. This can be seen in Fig. 14 and is accessed via the Real-Time button in the application's main menu (Tab. 2).

The ability to move and scale this holographic object also allows it to be attached to its real-world counterpart in the lab, as demonstrated in Fig. 13. Currently, the flow simulation is not linked to real data. However, it serves as an initial mock-up to "make the invisible visible", taking advantage of one of AR's core benefits.

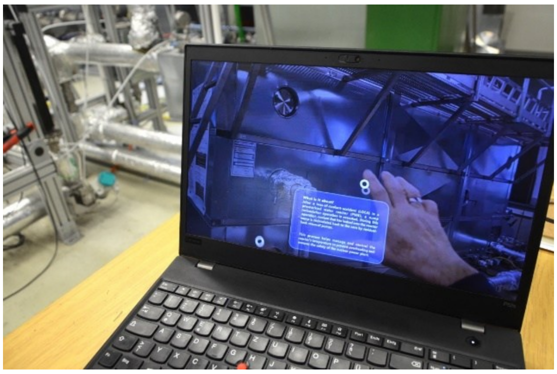
3.3 Expert Evaluation

Following the initial demonstration and testing (Fig. 12, 13, 14), three laboratory staff members, who are ZFT domain experts, provided an evaluation of the AR application.[4] Accordingly, they positively evaluated the system for its user-friendly and intuitive interface. They noted the defects in the 3D geometry caused by reflective metallic surfaces but did not consider them significantly limiting for the intended application.

Even in its current stage of development, the system was deemed suitable for laboratory tours and onboarding sessions for new employees. The staff assessed the efforts required for rescanning after possible modifications of the test rigs as moderate and manageable in everyday operations. The ability to highlight safety-relevant areas and equipment in the virtual model was identified as added value for training and safety briefings, which was not previously considered.

Source: Own

Fig. 12: *Demonstration of the ZFT AR application in practice*



Source: Own

Fig. 13: *Live stream of the see-through view including holograms for by-standers on a computer*

Source: Own

Fig. 14: *See-through view of the AR application with the HoloLens 2 from two different perspectives including the flow simulation in blue*

4 Discussion

Several challenges were overcome in the development of the application, such as selecting and applying a suitable object positioning and reference system to allow, in the end, a truly immersive AR experience for the users and bystanders. Thus, this work contributes to the

[4] https://www.hszg.de/news/durchblick-im-labor-der-zukunft (in German)

establishment of an educational application to explain and make transparent the functionality of a PWR. While other studies have focused on the visualization of radiation in VR (Satu et al., 2024), this work attempts to visualize, among other things, the flow inside a PWR. To achieve this, similar goals are pursued as in Nor et al. (2024), who present sensor data of a water coolant process in AR for maintenance purposes. But this work extends the approach of Nor et al. (2024) with a simulated flow visualization in-situ at the PWR.

Despite the prototype's functionality, not all engineering requirements could be fully implemented as desired. Currently, the technical solution chosen concerning the positioning of the application's reference point still requires the users to stand in the same position when starting the application. Otherwise, the previously stored anchors would no longer appear in the same position.

Due to the shiny (metal) surfaces of the PWT, the 3D scan using HoloLens' built-in functionalities did not provide a sufficient model with enough accuracy. Furthermore, the flow animation in the 3D scan model (Fig. 5 and 12) is only a simulation and not yet connected to the ZFT data in real-time. Finally, the application's usability was just tested through face validity by the involved stakeholders, but it has not yet been tested through a systematic usability survey or similar.

Conclusion

The development of the AR application for the ZFT contributes towards enhancing the educational and practical experience within the long-standing nuclear safety research domain at the HSZG. This project successfully integrated AR technology using Microsoft HoloLens 2, providing users with an immersive and interactive way to understand and interact with the complex processes involved in the sump recirculation operation after a LOCA in a PWR.

Our prototype achieved the core objectives of augmenting the ZFT with static yet movable elements, displaying an interactive 3D model, and simulating flow within this model. These functionalities offer a valuable tool for students and engineers, enhancing their ability to visualize and comprehend the system and its dynamics.

Future research should address the limitations identified in the current prototype and explore avenues for further enhancement and application. Key areas for future research include evaluating the application in practice, improving the anchoring reference system, real-time data and visualization, visualization of the physical object, and the transferability to other devices.

A systematic usability survey would involve testing with a larger and more diverse group of users to gather quantitative and qualitative data on user experience, effectiveness, and areas for improvement. This evaluation will help refine the user interface and overall functionality based on real-world feedback. This can be done already with current and future students and visitors at the Thermal-Hydraulic Test Facilities at HSZG. Further development should focus on a more robust anchoring system to improve the reliability of the reference point positioning, which does not require users to stand in the exact same position each time they start the application.

To fulfil the requirements of real-time data integration and augmentation of the ZFT statuses through cloud services and visualization of accurate system dynamics simulation based on real-time data resources (Subsection 2.1), the flow animation in the 3D scan model should be connected to real-time data from the ZFT. Integrating real-time data will provide a more accurate and responsive visualization, enhancing the application's monitoring and analysis purposes, and for simulation utility. Future research should explore the technical feasibility and methods for seamless real-time data integration and visualization.

Further development efforts should also focus on transferring of the visualization from the 3D scan model to the physical object, the ZFT. This could involve using markers or other tracking technologies to create a MR environment where the flow dynamics are visualized directly on the ZFT. Such an advancement would significantly enhance the applicability in the real-world setting, providing an even more intuitive and tangible interaction for users.

Finally, as the AR technology advances, the application should be adapted and tested on a variety of AR devices. This would ensure that the application remains compatible with the latest hardware and takes advantage of emerging technological capabilities. Research should focus on optimizing the application for different devices, ensuring cross-platform functionality, and leveraging new features to improve user experience. Future research can address these areas and significantly enhance the prototype's functionality, usability, and applicability, making it a versatile tool for engineering education at the ZFT.

In conclusion, this AR application has laid a foundation for future engineering education and research innovations at the ZFT, demonstrating the possibility of creating an augmented laboratory experience with relatively low resources. We can continuously refine and expand its features to improve how complex engineering concepts are taught and understood, fostering deeper user engagement and comprehension.

References

Egger, J., & Masood, T. (2020). Augmented reality in support of intelligent manufacturing – A systematic literature review. *Computers & Industrial Engineering*, *140*. https://doi.org/10.1016/j.cie.2019.106195

Fang, W., Zhang, T., Chen, L., & Hu, H. (2025). A survey on HoloLens AR in support of human-centric intelligent manufacturing. *Journal of Intelligent Manufacturing*, *36*, 35–59. https://doi.org/10.1007/s10845-023-02247-5

Harm, U., Kryk, H., Hampel, U., Kästner, W., Alt, S. & Seeliger, A. (2022). Lab Scale Experimental Studies for Modeling Possible Zinc Removal Efforts in LOCA Situations. In *Proceedings of 19th International Meeting on Nuclear Reactor Thermal Hydraulics* (*NURETH 19*), Brussels, Belgium

Harm, U., Kryk, H. & Hampel, U. (2023). Flow-dependent zinc corrosion in boric acid-containing electrolytes. *Materials and Corrosion*, *74*(2), 277–284. https://doi.org/10.1002/maco.202213341

Kästner, W., Alt, S., Seeliger, A., Zacharias, F., Harm, U., Illgen, R., Hampel, U. & Kryk, H. (2020): Modelling thermal-hydraulic effects of zinc borate deposits in the PWR core after LOCA – Experimental strategies and test facilities. *atw International Journal for Nuclear Power*, *65*(6/7), 341–345. ISSN 1431-5254.

Kästner, W., Seeliger, A., Alt, S., Förster, T., Gocht, U. & Zacharias, F. (2023). *ATHLET module "Zink Borate" (AZora) – Generic thermohydraulic and physicochemical analyses for the implementation of an ATHLET module for the simulation of thermohydraulic effects of zinc borate deposits in the PWR core*. Final Report, Reactor Safety Research-Project No. 150 1585A.

Krepper, E., Cartland-Glover, G., Grahn, A., Weiss, F.-P., Alt, S., Hampel, R., Kästner, W., Kratzsch, A., & Seeliger, A. (2008). Numerical and experimental investigations for insulation particle transport phenomena in water flow. *Annals of Nuclear Energy*, *35*(8), 1564–1579. https://doi.org/10.1016/j.anucene.2008.01.001

Kryk, H., Hoffmann, W., Kästner, W., Alt, S., Seeliger, A., & Renger, S. (2014). Zinc corrosion after loss-of-coolant accidents in pressurized water reactors – Physicochemical effects. *Nuclear Engineering and Design*, *280*, 570–578. https://doi.org/10.1016/j.nucengdes.2014.09.010

Lindner, F., Reiner, G., & Keil, S. (2025). A behavioral perspective on visualization in manufacturing and operations management: A review, framework, and research agenda. *Operations Management Research*, *18*, 317–352. https://doi.org/10.1007/s12063-024-00534-9

Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1995). Augmented reality: A class of displays on the reality-virtuality continuum. In H. Das (Ed.), *Proceedings Volume 2351, Telemanipulator and Telepresence Technologies*. (pp. 282–292). SPIE. https://doi.org/10.1117/12.197321

Mühlan, K., Przybysz, K. A., Lindner, F., Akrmanová, D., Winkler, D., & Keil, S. (2021). A Review and Implementation Framework of Industrial Augmented Reality. In *2021 26th IEEE International Conference on Emerging Technologies and Factory Automation* (*ETFA*). (pp. 1–4). IEEE. https://doi.org/10.1109/ETFA45728.2021.9613426

Nor, A. A. M., Kassim, M., Minhat, M. S., Ya'acob, N., Azmi, I. N., & Hajar, I. (2024). 3D Augmented Reality on Nuclear Plant Water Coolant Process in RTP Malaysia. In *2024 4th International Conference on Electrical, Computer, Communications and Mechatronics Engineering* (*ICECCME*). (pp. 1–6). Male, Maldives. https://doi.org/10.1109/ICECCME62383.2024.10796400

O'Regan, G. (2022). *Concise Guide to Software Engineering*. Springer. https://doi.org/10.1007/978-3-031-07816-3

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*. *Studies in Systems, Decision and Control* (*SSDC*, *volume 346*). (pp. 243–260). Springer. https://doi.org/10.1007/978-3-030-69189-9_14

Porter, M. E., & Heppelmann, J. E. (2017). *Why Every Organization Needs an Augmented Reality Strategy*. Harvard Business Review. https://hbr.org/2017/11/why-every-organization-needs-an-augmented-reality-strategy

Renger, S., Alt, S., Gocht, U., Kästner, W., Seeliger, A., Kryk, H., & Harm, U. (2018). Multiscaled Experimental Investigations of Corrosion and Precipitation Processes After Loss-of-Coolant Accidents in Pressurized Water Reactors. *Nuclear Technology*, *205*(1-2), 248–261. https://doi.org/10.1080/00295450.2018.1499324

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*. https://doi.org/10.1016/j.pnucene.2024.105104

Tuli, N., Singh, G., Mantri, A., & Sharma, S. (2022). Augmented reality learning environment to aid engineering students in performing practical laboratory experiments in electronics engineering. *Smart Learning Environments*, *9*, 1–20. https://doi.org/10.1186/s40561-022-00207-9

Vásquez-Carbonell, M. (2022). A Systematic Literature Review of Augmented Reality in Engineering Education: Hardware, Software, Student Motivation & Development Recommendations. *Digital Education Review*, *2022*(41), 249–267. https://doi.org/10.1344/der.2022.41.249-267

Winkler, D., Lindner, F., Mühlan, K., Przybysz, K. A., & Keil, S. (2022). Informationstechnologien der Zukunft – Video- und Augmented-Reality-basierte Montageanleitungen für die technische Bildung. In *15. Ingenieurpädagogische Jahrestagung 2021*. https://www.researchgate.net/publication/362125362_Informationstechnologien_der_Zukunft_-_Video-_und_Augmented-Reality-basierte_Montageanleitungen_fur_die_technische_Bildung

Yim, H. B., & Seong, P. H. (2010). Heuristic guidelines and experimental evaluation of effective augmented-reality based instructions for maintenance in nuclear power plants. *Nuclear Engineering and Design*, *240*(12), 4096–4102. https://doi.org/10.1016/j.nucengdes.2010.08.023

APLIKACE ROZŠÍŘENÉ REALITY PRO POHLCUJÍCÍ LABORATORNÍ ZÁŽITEK: ŽITAVSKÁ PRŮTOKOVÁ VANA

Integrace rozšířené reality (AR) do výuky inženýrství může zlepšit výuku složitých konceptů. Tato studie představuje inženýrský proces a prototyp aplikace AR pro žitavskou průtokovou vanu (Zittau Flow Tray) s využitím Microsoft HoloLens 2 a Unity 3D. Aplikace poskytuje informace o provozu recirkulace v jímce po havárii se ztrátou chladicí kapaliny v tlakovodních reaktorech. Mezi hlavní funkce patří interaktivní 3D modely, simulace proudění a dynamické překryvy informací. Počáteční testování potvrdilo základní funkce aplikace, i když problémy, jako je přesnost určení polohy uživatele a integrace dat v reálném čase, přetrvávají. Budoucí vylepšení se zaměří na zdokonalení těchto aspektů a rozšíření použitelnosti aplikace na různých platformách AR.

EINE AUGMENTED-REALITY-ANWENDUNG FÜR EIN IMMERSIVES LABORERLEBNIS: DIE ZITTAUER STRÖMUNGSWANNE

Die Integration von Augmented Reality (AR) in die Ingenieursausbildung kann die Lernerfahrung durch die Bereitstellung immersiver und interaktiver Tools für komplexe Konzepte verbessern. Diese Studie stellt die Entwicklung einer AR-Anwendung für den Zittauer Flow Tray (ZFT) an der Hochschule Zittau/Görlitz vor. Die Anwendung nutzt Microsoft HoloLens 2 und bietet Informationen über die Sumpfumwälzung nach einem Kühlmittelverlustunfall in Druckwasserreaktoren. Zu den wichtigsten Funktionen gehören interaktive 3D-Modelle, Strömungssimulationen und dynamische Informationsüberlagerungen, die das Verständnis von Studierenden und Ingenieuren verbessern sollen. Erste Tests haben die Kernfunktionen der Anwendung bestätigt, obwohl es noch Herausforderungen wie die Genauigkeit der Benutzerpositionierung und die Echtzeit-Datenintegration gibt. Künftige Verbesserungen werden sich auf die Verfeinerung dieser Aspekte und die Erweiterung der Nutzbarkeit der Anwendung auf verschiedenen AR-Plattformen konzentrieren.

APLIKACJA ROZSZERZONEJ RZECZYWISTOŚCI DLA WCIĄGAJĄCEGO DOŚWIADCZENIA LABORATORYJNEGO: ŻYTAWSKA WANNA PRZEPŁYWOWA

Wprowadzenie rzeczywistości rozszerzonej (AR) do kształcenia inżynierskiego może poprawić jakość nauczania złożonych pojęć. Niniejsze opracowanie przedstawia proces inżynieryjny aplikacji AR oraz prototyp Żytawskiej Wanny Przepływowej (Zittau Flow Tray) przy wykorzystaniu Microsoft HoloLens 2 i Unity 3D. Aplikacja dostarcza informacji o operacjach recyrkulacji z miski olejowej po awarii z wyciekiem płynu chłodniczego w reaktorach wodnych ciśnieniowych. Kluczowe funkcje obejmują interaktywne modele 3D, symulacje przepływu i dynamiczne nakładki informacyjne. Wstępne testy potwierdziły podstawowe funkcje aplikacji, choć nadal istnieją wyzwania, takie jak dokładność określenia pozycji użytkownika i integracja danych w czasie rzeczywistym. Przyszłe ulepszenia skupią się na dopracowaniu tych aspektów i poszerzeniu możliwości wykorzystania aplikacji na różnych platformach AR.