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Synergizing BIM, Digital Twin, and XR: An Approach for Real-Time Building Analysis and Enhanced Laboratory Management

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1 ABSTRACT

The emerging shift in the use of innovative and digital technologies in the architecture, engineering, and construction (AEC) industry promises an opportunity to create consistent, system-intelligent buildings that provide a reliable source of all relevant information about the building for maintenance, technical management, or decision-making processes in real time. For this vision, the integration of Building Information Modeling (BIM), Digital Twins (DTs), Internet of Things (IoT), and Extended Reality (XR) in the context of operative building management and research data utilization within laboratory environments proves to be essential to leverage smart buildings as an enabling pillar of a smart city. This paper presents a novel approach for in situ generation of 3D building models from point cloud scans, providing a valid real-time representation of the existing state of a building. This process significantly enhances the accuracy and utility of BIM in existing structures where pre-existing digital models are not available.

Further, we delve into the enrichment of these models with IoT sensors strategically placed within building spaces. These sensors are designed to monitor indoor air quality and occupancy through motion detection, offering a comprehensive view of the buildings environmental and usage patterns. This real-time data, coupled with the integration of laboratory measurement devices and their DT, facilitates a more dynamic and responsive building management system. In contrast to the majority of current approaches and concepts in research, the resulting models emphasize live data and, in accordance with the definition of a DTs, reflect the state and feedback representation bidirectionally into the virtual space and vice versa back into the physical space substantiated by XR technologies.

An essential component of our methodology is the development of interfaces between the BIM model and DTs of laboratory equipment, seamlessly incorporating the generated research data into the building model. This integration ensures that the BIM model remains a central, up-to-date repository of both physical and functional characteristics of the building and its contents.

Moreover, we introduce a collaborative XR environment, enabling transdisciplinary teams to interact with and analyze the BIM model and associated data in a highly immersive and intuitive manner. This XR platform fosters enhanced collaboration and decision-making, bridging the gap between various stakeholders involved in building management and research. The approach demonstrates the potential of utilizing advanced technologies to not only create these models post-construction but also to continuously update and enrich them with operational data, thereby facilitating a more efficient and informed management process. Providing standardized interfaces to smart buildings with the BIM and IoT information obtained through the concepts presented can also create added value in the context of smart cities through clusters of such smart buildings.

This paper contributes to the field by showcasing how the synergy of BIM, DTs, IoT, and XR can revolutionize building management and Research Data Management (RDM), offering a comprehensive, real-time, and interactive digital representation of physical spaces and their operational dynamics.

Keywords: Research Data Management, Extended Reality, Building Information Modelling, Augmented Reality, Digital Twin

2 INTRODUCTION

The integration of modern disruptive technologies as a part of the digital transformation holds potential in all areas of public life, industry, as well as within research institutions (Lehmann et al. 2023). It opens up a broad variety of opportunities to enhance the efficiency and functionality of buildings especially under the premises of Construction 4.0 as well as laboratory environments. Static building information or Building Information Modeling (BIM) data can be combined with real-time Internet of Things (IoT) data in order to create contextualized information. Such Digital Twins (DTs) as comprehensive digital representations with live IoT data can enrich BIM data with operational data and thus go beyond historical or static data compilations (Nasaruddin et al. 2018; Temidayo et al. 2018). Extended Reality (XR) and Virtual Reality (VR) devices can process this contextualized DT information for different operators and serve as a basis for collaboration or improvement. In addition, the information provided by the DTs can also be utilized as a partial blueprint for smart city objects (Coupry et al. 2021).

Central to this approach is the idea of creating a comprehensive digital representation of buildings through the generation of 3D models from point clouds, serving as a foundation for optimizing building operations. These models can not only depict physical space but also integrate various digital experimental setups and laboratory equipment used in research institutions. By utilizing these digital models, various use cases can be derived to make building and laboratory operations more efficient. Another aspect is the direct integration of Research Data Management (RDM) into the digital model. By linking research data to the corresponding building and laboratory areas, researchers can seamlessly access the required data and utilize it for further knowledge generation. To harness the maximum potential from the various technologies, a holistic interaction approach is required. This involves not only the use of point clouds and IoT devices but also the development of a XR application that enable users to interact with the DT.

This paper deals with the question of how buildings and laboratories at research institutions can be intelligently geared with research equipment, users such as employees or students in the context of barely accessible BIM data and integrated RDM. Therefore, the state-of-the-art is assessed based on current literature in section 3 followed by the introduction of the detailed use case in section 4. Section 5 presents the overall concept, followed the implementation in section 6. After a qualitative validation and discussion in section 7, section 8 summarizes and provides future work prospects.

3 RELATED WORK

Digital Transformation has become an indispensable premise across a broad range of fields and industries in order to exploit its ingrained advantages of increasing efficiency and effectiveness in operations. (Aghimien et al. 2018) The approach of using innovative digital technologies in the architecture, engineering, and construction (AEC) industry has been solidified as 'Construction 4.0' as an integral pillar of the fourth industrial revolution. (Temidayo et al. 2018) As part of these efforts, BIM is emerging as a pivotal methodology for the digital representation of physical and functional building information over the entire life cycle. The emerging transformation implies a shift away from the traditional design paradigm towards the goal of creating consistent, system-intelligent buildings that provide a reliable source of all relevant information about the building for maintenance, technical management, or decision-making processes in real time (Hotový 2018). Nevertheless, the realization of BIM is associated with certain obstacles by which the methodologies potential remains limited. Current applications notably show constraints in terms of scalability, interoperability, or remote support, preventing the information from being used reliably by the user (Liu et al. 2023) and further restricts interaction between different fields. The main benefits of implementing BIM range from efficient monitoring, administration, planning and maintenance of ongoing operations and assets to improved information sharing and visualization (Lu et al. 2019).

To make this vision a reality, various IoT technologies such as DTs or XR applications enable the successful implementation of BIM aiming to consolidate various information streams and integrate further knowledge into building process workflows (Liu et al. 2023). In addition to the mere representation of the physical counterpart, further intelligence can be incorporated into the digital representation through functionalities such as simulation systems, machine learning algorithms or visuality through XR technologies in order to provide the potential to achieve added value.

The DT builds on the premise that all systems can be portrayed in dual form by having a digital representation in addition to their physical counterpart. Descriptions, measurement data or changes in the state of the physical system are reflected in the virtual space and vice versa. The DT has its roots in product lifecycle management, where the original objective was to depict the entire lifecycle of the physical counterpart in a virtual representation (Grieves, 2023). Enabling a holistic representation of the physical counterpart depends on the data that is continuously collected and stored in the virtual entity. The reliable availability of this data is the prerequisite for creating added value and knowledge generation for a sustainable research landscape. In the context of RDM, data must be handled according to the following principles: Findable, Accessible, Interoperable, and Reusable (FAIR) (Mons 2018). These can be explicitly implemented in particular through the use of DT approaches in laboratory environments (Lehmann et al. 2023). Also, the DT facilitates interoperability between different software and platform entities through a single channel which is a fundamental characteristic of the BIM concept and crucial to the success of a project (Flamini et al. 2022).

Shirowzhan et al. (Shirowzhan et al. 2022) explore the application of selective technologies for enhancing urban intelligence within smart cities through the utilization of DTs. Their research emphasizes the role of virtual representation technologies in supporting decision-making processes. Smart cities and the associated efforts to transform the AEC industry can therefore be improved by utilizing these opportunities. Accordingly, the concept of the DT appears to be an ideal approach when realizing BIM in the modern construction industry. Various approaches using the DT concept in BIM can be found in the literature. Nasaruddin et al. (Nasaruddin et al. 2018) describe a rudimentary concept framework to utilize DTs for BIM. Sensor data for predictive maintenance use cases, optimization and visualization are considered. Flamini et al. (Flamini et al. 2022) develop the dynamic DT, which serves as the foundation for the plant's SCADA functionalities to manage the technical functions. In combination with XR technologies, the supervision and technical management is ensured over the entire life cycle. Building on this, Loggia et al. (Loggia et al. 2024) and Flamini et al. (Flamini et al. 2022) have extended the original approach to ensure electrical safety in order to offer rapid intervention in the event of an error. Despite the fact that the concept of DTs appears to be beneficial for the realization of BIM, achieving full implementation still seems to be challenging. Deng et al. (Deng et al. 2021) define various research gaps and characteristics for modern implementations of BIM DTs. Among other things, further research is needed regarding real-time monitoring, IoT data collection, performance prediction of building condition through simulations, machine learning techniques or the ability to facilitate decision-making through the integration of humans into the control loop.

The use of 3D scanning technology in the context of creating point clouds for BIM and XR concepts is a useful application that is based on the reconstruction of real-world architectural environments and offers numerous advantages. These advantages manifest themselves in particular in the increase in efficiency digital reconstruction of existing environments while also increasing the precision of corresponding virtual representation (Coupry et al. 2021). A key aspect that emphasizes the use of point clouds is their ability to capture and document existing structures and environments with extreme precision. By capturing millions of points in a three-dimensional space, point clouds provide a highly accurate digital representation of the real world. Compared to traditional methods of manual surveying or the creation of 3D models through CAD design. The use of point clouds offers a significantly faster and more accurate way of capturing existing environments. The technology thus makes it possible to create previously non-existent digital representations of building (Dolhopolov et al. 2023). Liu et al. (Liu et al. 2021) review different applications of laser scanning in the context of the life cycle of buildings enabling BIM. For this purpose, they analyze the integration of BIM and 3D laser scanning in several domains, such as construction site safety, rescue after disaster, energy modeling or management. Mirzaei et al. (Mirzaei et al. 2022) use terrestrial laser scanners (TLS) to capture point clouds in order to generate geometric DTs of BIM structures. Using a deep neural network, structures are derived from the point clouds and then homogenized and enriched with semantic information. The resulting geometric DT is limited to updating BIM data or monitoring the health status of the building but does not integrate any operational real-time data. Bassier et al. (Bassier et al. 2015) describe different types of laser scanners used in BIM scenarios. They distinguish between TLS, mobile laser scanners (MLS) and airborne laser scanners (ALS). Also advantages and disadvantages of each system are being discussed. Abreu et al. (Abreu et al. 2023) analyze different types of scan applications related to BIM. More precisely they review the differences of feature extraction algorithms in Scan-to-BIM and Scan-vs.-BIM. The two scenarios differ on the one hand in the creation of a digital image of existing building structures, while the other scenario deals with the comparison of existing 3D models with a scan. Kazhdan and Hoppe (Kazhdan & Hoppe 2013) deliver one of the most commonly used algorithms for modeling meshes based on point cloud. The 'screened poisson surface reconstruction' algorithm interpolates watertight surfaces based on point sets. Especially for modeling interior scans algorithm is often one of the best choices. Another decisive factor that supports the use of point clouds is their compatibility with various digital technologies, especially in the area of XR concepts. By integrating point clouds into XR applications such as VR and augmented reality (AR), users can enjoy realistic and immersive experiences in digital environments based on precise measurement data. This opens new possibilities for applications in areas such as architectural visualization, real estate development, virtual tours and simulations (Wu et al. 2023).

4 USE-CASE DESCRIPTION

Utilization and safe operation of research laboratories is a common challenge. The requirement to optimize the use of laboratory space without compromising on safety requires approaches to room monitoring. The use of fragile and vulnerable scanning systems depends on strict laboratory conditions. These systems must function accurately and reliably to provide valid data without compromising laboratory safety. The handling of hazardous materials and the use of lasers in research environments emphasize the importance of stringent safety measures. The ability to monitor and control experiments remotely offers flexibility but raises questions about safety. In particular, ensuring that no unauthorized individuals have access to the laboratories at any time while sensitive experiments are being performed is a top priority.

In addition, different measurement conditions and environmental factors make it difficult to carry out consistent and reproducible experiments. Adapting laboratory conditions to specific experimental demands requires precise control and monitoring systems. Safety precautions must be always maintained. The correlation of measurement data with environmental information presents a further challenge. Finally, the general handling, collaboration and management of experimental data requires an efficient data infrastructure.

These issues illustrate the complexity of modern laboratory operations and scientific processes in research institutions. It highlights the need for solutions to improve efficiency, security, and data management in these critical environments.

5 CONCEPTUAL APPROACH

Since the current state-of-the-art has been determined, the challenges described in the use case can be addressed in more detail and architectural approaches can be elaborated. Initially, these are presented for handling building management and RDM by combining XR, IoT and DT concepts. Therefore, various approaches proposed in the previous work are incorporated in order to meet current requirements. There are initially four relevant branches of work in architecture, which are finally consolidated into one main approach: The capture of 3D building data and derivation and creation of applicable models, the development of suitable IoT devices for monitoring and logging of room parameters, the setup of a suitable real-time framework for mapping, connecting and managing the DTs of the IoT and research items as well as the programming of a suitable XR application as a visualization and interaction interface to all available DTs.

Figure 1 shows the proposed architecture of the operational DT framework, which forms the center of the overall approach and unites all branches. It is divided into three areas: the Physical Twin Space, the Digital Twin Space and the Application Space which are further highlighted in the following.

The Physical Twin Space contains the physical devices which enable the later interaction within the XR environment. Those are named Physical Twins (PTs). A distinction between two types of devices is made in this space. The architecture separates IoT and Device PTs. The IoT PTs must be suitably equipped with appropriate sensors for recording the room parameters and a detector for sensing the presence of occupants. Sufficient robustness of the devices is a prerequisite. IoT PTs are designed to monitor and record environmental parameters while Device PTs are used to conduct measurements, create research data, or regulate the environment. The Physical Twin Space in the architecture contains the PT n as a generic representation of other PTs that can be added in future extensions.

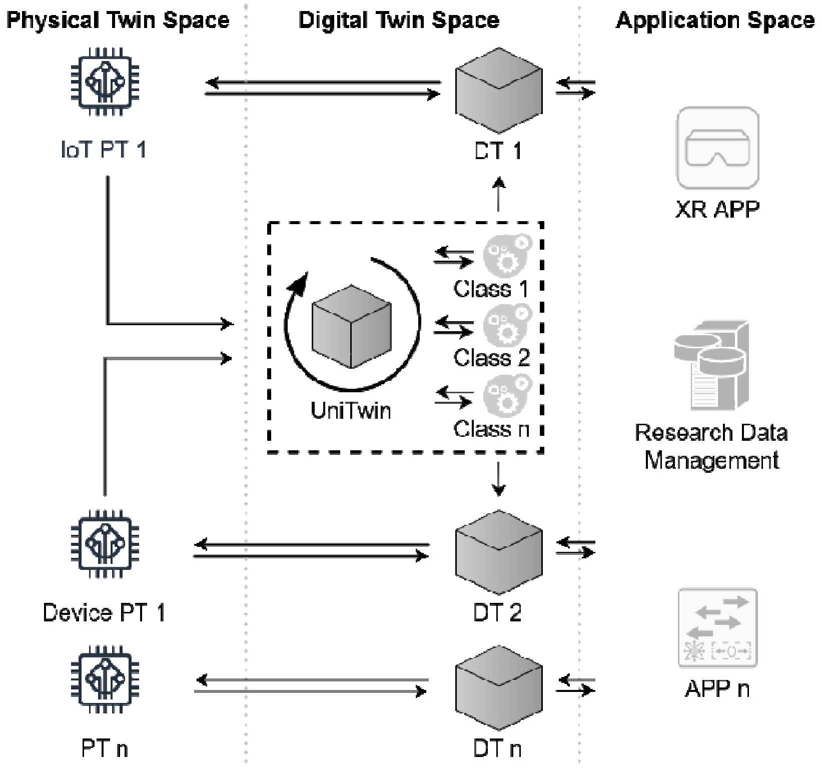

Fig. 1: Conceptual architecture for building management and research data management

Next to the Physical Twin Space the Digital Twin Space is located which acts as the architectures' middleware layer. For the provision of all DTs, a framework published in the previous work [Haeussermann et al. 2023] is utilized. It provides containerized modular DTs based on a given configuration. Therefore, the PTs send their configuration to the so-called Digital Twin Provisioning Service (DTPS). After receiving the configuration, the DTPS starts a so called UniTwin container for each PT. Those containers instantiate various class files depending on the configuration. Then the instantiated DTs establish a bidirectional connection to their associated PTs and connect to the applications or provide defined interfaces to the applications located in the Application Space.

The Application Space includes two key applications to cover the presented use case: the XR Application and the RDM Application. The XR application takes care of the interactions with the physical devices and is an enabler for all use cases such as remote experimentation, remote maintenance or room planning. It is primarily based on the appropriate volumetric scan of current 3D building data. The third element in the Application Space App n is a generic placeholder for any application to be added in the future. With the provided RDM application the DTs are enabled to store gathered data persistently and according to the FAIR criteria. The RDM in this approach highly relies on and integrates with the RDM infrastructure presented in the previous work [Lehmann et al. 2023].

6 IMPLEMENTATION

After outlining the general concepts and approaches, the four main branches within the implementation section are examined in more detail. First, the volumetric scan including the processing of the recorded data is considered. The practical structure of the IoT Device PTs must then be illustrated, followed by the introduction of the DT framework. The XR application forms the completion as the interaction interface of the entire work.

The adaptation of digitization in existing building structures requires the readiness of state-of-the-art 3D scanners, which are considered consolidated technologies. Within this range, divergent systems and methodologies manifest themselves, including Terrestrial Laser Scanners (TLS), Mobile Laser Scanners (MLS) and Airborne Laser Scanners (ALS). A NavVis VLX 3 scanner, which belongs to the MLS genre as a prominent state-of-the-art technology example, was used in the current project. These instruments are characterized by a pronounced user-friendliness and enable the comprehensive mapping of building structures without the need for complex pre-planning and subsequent data merging. However, it should be noted that precision is reduced compared to terrestrial laser scanners and is limited to a few centimeters.

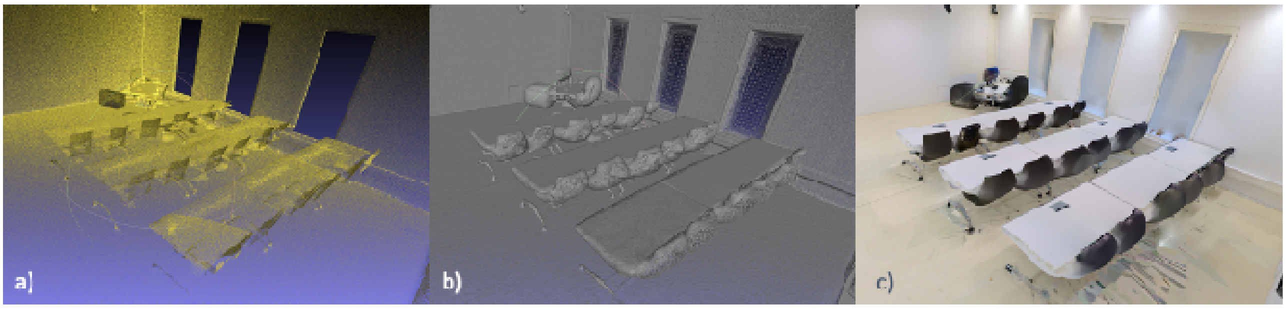

Fig. 2: Different processing steps of the point cloud. a) showing native point cloud without any processing steps b) wireframe of calculated mesh without textures and colors c) colored mesh.

The integration of the captured building into interactive XR scenarios as well as into the concept of the DT requires the transformation of the point cloud resulting from the scan into a mesh. The open-source software MeshLab is used for this purpose. It should be noted that several pre-processing steps are essential in order to eliminate error points (noise) and other anomalies in the point cloud (see Figure 2a). This can be realized by means of filtering or outlier detection. Furthermore, the calculation of normals is essential in order to determine the spatial orientation of the points, which is of fundamental importance for the subsequent mesh generation.

Once the point cloud has been pre-processed, the actual generation of the mesh can begin. For this purpose, the 'Screened Poisson' algorithm is recommended, which connects points with the same orientation based on the calculated normals and interpolates a continuous surface (see Figure 2b, 2c). Despite the interpolation, redundant surfaces can occur during the mesh calculation, which must be removed during post-processing. Surfaces can be selected and eliminated based on a defined edge length.

Due to the objective of this article to implement the generated point cloud on virtual reality headsets / Head Mounted Devices (HMDs) as well as on lightweight platforms such as standalone HMDs (e. g. VIVE XR Elite, Microsoft HoloLens 2) or tablets and smartphones, the native point cloud was initially used for the present use case to display the environment. Within the described application scenario, no interaction with the environment is planned for the time being, which is why the point cloud can be used instead of a mesh without further processing. This makes it possible to reduce one process step and the associated effort.

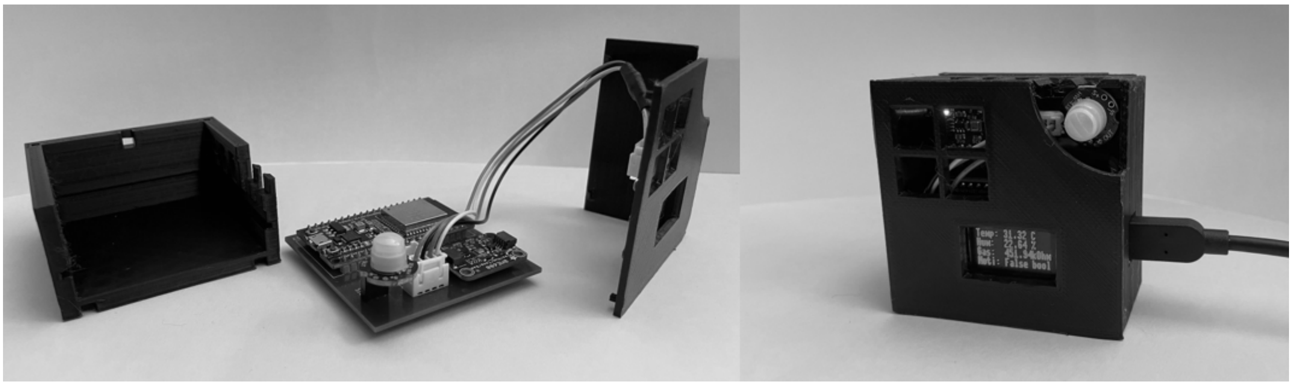

Fig. 3: Design of the IoT indoor air quality measuring device for detecting indoor air characteristics and room occupancy

According to Figure 3, an integrated measuring system was developed as an IoT device PT to measure the indoor air and presence parameters. The integrated NodeMCU microcontroller with ESP32 processor was selected as the basis for performance and cost reasons. One of the great advantages of the microcontroller is the direct integration of wireless communication such as WiFi or Bluetooth. To record the air values, a breakout board with the Bosch sensor BME 680 which detects relative humidity, barometric pressure, ambient temperature, and gas (VOC) was used. The passive infrared sensor SR602 was installed to detect movement within the dedicated supervision area. An OLED display also shows all measured values. The display and the gas sensor are both connected via I2C. The microcontroller software is based on Micropython and opens an interface to the DT framework with the given components. In order to achieve sufficient robustness, a suitable printed circuit board was designed and produced as well as an adequate housing was designed and printed.

In the Physical Twin Spaces two PTs are implemented. As IoT PT 1 the described IoT measuring device is used to monitor environment parameters in order to provide insights about conditions from remote. For the Device PT 1 a Hyperspectral-Near Infrared (NIR)-Imager built at the research institute is utilized, to generate relevant research data. The NIR-Imager is driven by a LattePanda Delta 3 which provides a Flask-RESTful-API for the communication with the DTs. Both PTs are located in the same physical location and are enhanced with the ability to pass their configuration to the Digital Twin Space. The framework utilizes the containerization environment Docker and the images DTPS as well as UniTwin at a centralized server cluster at the research institute. The PTs from the Physical Twin Space provide their configuration to the DTPS via HTTP and are provided with a custom UniTwin container. After instantiation the UniTwin container represent the DTs. The DTs establish bidirectional connection to their associated PTs and to the applications in the Application Space. As outlined in the conceptual approach the RDM application is part of the presented RDM infrastructure. Therefore, it uses a combination of InfluxDB and Dataverse to provide the ability to store various kinds of data in FAIR manner. The open-source time series database InfluxDB is used to store discrete data points from the IoT PTs. Besides InfluxDB, Dataverse is used to store data which is not suitable for storing with InfluxDB like NIR-images generated by the Device PTs. Dataverse is an open-source application used to store research data in repositories while improving the publishing, citing as well as versioning of that data.

The operative procedure of its implementation is as follows. After the DTs are provided by the DTPS the IoT PT 1 transmits environment parameters to its DT. Those parameters include relative humidity, barometric pressure, ambient temperature, VOC, and motion inside the monitored area. The DT takes care of storing the Data in the InfluxDB and transferring it to the XR application. Thereby it enables monitoring the room remotely inside the XR application. Meanwhile, with the instantiation of its DT, the scanner is in standby mode and waits for commands. These commands can be given physically on the device or in the XR application and include the start and stop command for a scan as well as its reset. However, it must be emphasized that the DT with its access to all information has the ultimate decision on the execution. In the case the scanner is started manually the DT is informed about the intend to start a scan. To release the scanner for starting, the DT checks the state of movement monitored by the IoT PT 1 by requesting the state from the corresponding DT. If movement is present in the room the DTs aborts the start command in order to prevent harm for people inside the room. Otherwise, it approves the start and notifies the XR application about the new condition of the scanner. In case the scan is started via the XR application, the process is reversed. The XR application sends a start command to the DT which checks for movement with the IoT PTs DT. If movements are present in the room the DT cancels the start of the scanner. In the absence of movement, the DTs sends the start command to the scanner which begins to scan. The DT of the scanner also takes care of checking movements continuously while scanning with the measurement devices DT and immediately stops the scan if movement is detected.

In the final step, the XR application combines all the components described to interact with the overall system. It was developed with Unity 2021.3.22f1. This game engine allows the platform-independent creation of applications that work on various HMDs as well as in 2D environments. The system offers users the possibility to use XR applications on a variety of devices, from computers and mobile devices such as smartphones and tablets to immersive HMDs. These can be used either stand-alone or in combination with a workstation. By intelligently linking the game engine and third-party software, stationary VR systems such as powerwalls and CAVEs can also be used. These systems offer the advantage that, in contrast to HMDs, several people can participate in a session simultaneously and collaboratively. The developed solution enables flexible adaptation to different situations. For example, if the laboratory environment is not available, strict safety measures make its use difficult, or access is not possible due to security reasons, the previously created scan can be displayed. This facilitates orientation and enables a virtual tour of the laboratory without having to go to the site. In contrast, optical see-through HMDs or video pass-through HMDs offer the possibility to extend the current environment with virtual screens. These allow the display of current telemetry data of the desired physical device in real time.

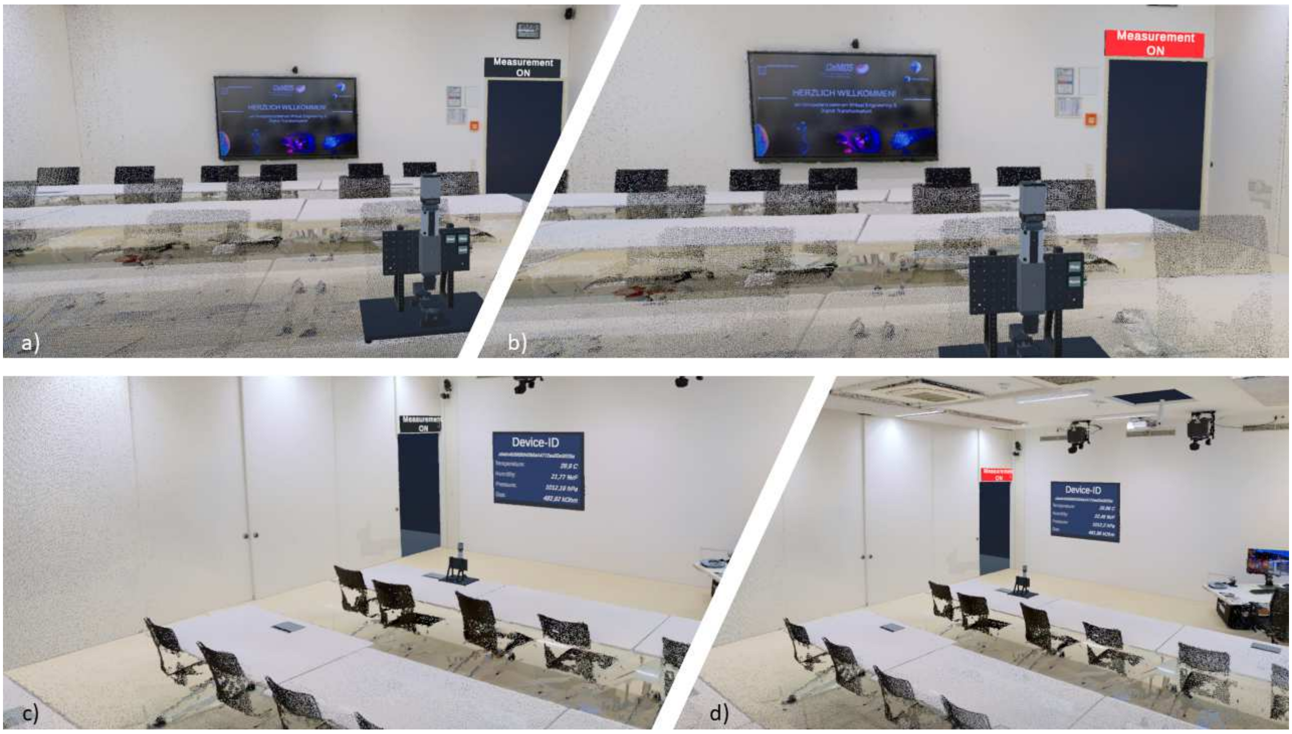

Fig. 4: Different views from the session of the Varjo XR-3. a) Shows that no one is in the room and a corresponding scan can be started b) Based on the signal, the user can recognize that someone is in the room and a measurement cannot be started. c & d) In addition to the telemetry data, it can be seen whether someone is in the laboratory (red a movement has been detected)

Using the volumetric scan as the basis for the XR application offers several advantages. First, it eliminates the time-consuming process of creating a VR environment from scratch. The scan already provides a detailed and realistic representation of the environment that can be directly imported into the application using the custom Pcx importer (https://github.com/keijiro/Pcx/) for Unity. This saves time and resources and allows to focus on developing the actual application. In addition, using a volumetric scan provides greater accuracy and immersion compared to manually created VR environments. The scan captures the environment in its actual state, including all details and features. This allows users to move and interact in the virtual or mixed environment as if they were in the real environment. However, providing surface (mesh) information is essential for real interaction, such as detecting collision or similar events. This requirement was not necessary for the built environment here, so it can be considered negligible. Another advantage of using a volumetric scan is the ability to combine the environment with other sources, such as 3D models of test setups. Additionally, sensor data or information from BIM can be integrated into the scan to create an even more comprehensive and realistic representation of the environment.

The data connection of the XR application is established via the M2MQTTforUnity Plugin. This plugin enables communication with an MQTT broker to receive and send data and control commands. The user can react to the received data depending on the situation. For example, motion sensors can signal the user whether someone is currently in the laboratory or not, which is indicated by a light signal. In parallel, the sensor values of the PT can be retrieved and visualized in real time (see Figure 4c, d). In addition, the PT can be controlled via the application. If there is no person in the laboratory, the scanning process can be started by the application. However, if someone is in the laboratory, the scan can only be started after receiving the release signal (see Figure 4a, b). Furthermore, a direct connection to RDM is integrated via a dashboard. This allows relevant measurement campaign parameters and metadata to be stored directly with the automatically generated measurement data and linked to the currently prevailing environmental parameters.

This exemplary application uses the Varjo XR-3 data glasses, which are equipped with Ultraleap Gemini (v5) hand tracking. This technology enables users to interact with the digital world in a natural way. With the help of the Ultraleap sensor, the HMD can precisely capture the movement of the hands and fingers. The application reacts accordingly to the gestures and thus enables intuitive control. By using the hands to interact with the virtual objects a similar interaction as in the physical world is given to the user. This allows for quick and easy operation of the XR application, even for new users. Direct interaction with the virtual environment through hand gestures promotes a higher level of immersion, users feel more present in the virtual world and can concentrate better on the application. This additionally reduces accessibility barriers as no additional controllers or input devices are required. It not only saves costs but also reduces the complexity of the application and makes it more flexible and mobile. This is because users do not have to carry additional devices with them or familiarize themselves with the operation of controllers. This increases the flexibility and mobility of the XR application, as it can be used anywhere and at any time. As well as with inside-out tracking, no separate tracking area or installation of tracking systems is required. This further simplifies the use of the application. Direct interaction with the hands thus makes working in the virtual environment more efficient and productive.

7 VALIDATION AND DISCUSSION

After the implementation has been completed with the aggregation of all necessary value-adding modules, a qualitative validation and discussion can take place in regard to the related work. To this end, the four synergy fields being worked on can be analyzed here: the volumetric capturing of building data, the development of the IoT indoor measuring devices, the setup of the DT framework and the design of the XR application for displaying and interacting with all aspects of the content.

With the design of the physical IoT devices, rudimentary ambient monitoring could be realized. The results could be contextualized for the research experiments and serve to ensure the safety of the experiments. Furthermore, direct integration into the DT framework was realized with self-provisioning capabilities.

Bidirectional data and information processing was ensured regarding the architecture and interconnection of the DTs. This allows heterogeneous physical devices to be made available to the backend for example state-of-the-art IT analyses, calculations, or decision-making algorithms. The container-based structure of the UniTwin framework ensures scalability and platform independence, as well as autonomous provision of the physical devices by means of self-description methods. The APIs to the DTs opened up to the backend offer the greatest possible flexibility. However, it must be considered that as the number of DTs increases, the management effort for the entire framework and the documentation effort for interfaces and provided containers also increases.

Without existing 3D BIM building data, a state-of-the-art MLS scanner was used to generate volumetric buidling information. This allowed the differences in the results to be highlighted and compared. Using a volumetric scan also has challenges. The size and complexity of the scan data can make processing and rendering in the XR application difficult. It is therefore important to use suitable software and hardware to efficiently handle and process the data and ensure a smooth user experience. Depending on the scan, more post processing may be necessary to make the data performant on the respective devices. The calculation of meshes from the point cloud is also time-consuming. From this perspective, it can be advantageous, depending on the application scenario, to outsource the computing power to a dedicated computer and, depending on the performance, only transmit a corresponding stream to each end device. In addition, it is important to note that volumetric scans are static representations of the environment. Dynamic elements such as moving objects or people or avatars in a collaborative session require separate logic in the XR application, which still needs to be implemented. In the XR application, decisive features for the realization of the described use case could also be implemented. For example, remote maintenance and experimental scenarios are now feasible. To ensure the safety of this remote application, interlocking mechanisms were adapted through the interaction of the room sensors, the actual scanning measuring device and the XR application. Another major advantage is the interface to the RDM, whereby the measurement results can be FAIR compliant semantically enriched with metadata and context within the application.

Overall, it could be demonstrated that the integrated approach of BIM, DTs, IoT, and XR has the potential to leverage institute building management and operation of research environments synergistically. The establishment of such a joint platform makes it possible to engage in collaborative and interdisciplinary scientific discourse with the help of these technologies used. Creating an adaptive, interactive, and data-driven approach not only supports operations but also advances research and development through enhanced access to and use of data.

8 CONCLUSION AND FUTURE WORK

The synergy and combination of the technological palette of digital transformation proved to be promising for the presented work. Combining all approaches promises successful outcomes for conducting and planning in remote and collaboration scenarios. This is especially relevant for research institutions increasingly relying on digital tools to enhance efficiency, productivity, and innovation. This overall architecture not only captures the physical layout but also incorporates digital tools and laboratory equipment used in research settings, enhancing operational efficiency. The approach also integrates RDM with these models, enabling researchers to easily access and apply relevant data for further studies. To fully exploit these technologies, a method is employed, involving point clouds recordings, IoT devices, and the creation of XR applications for interactive engagement with DTs.

The main contributions here are the generation and processing of a point cloud for the later development of an XR application in order to collect non-existing BIM data. Furthermore, the development of physical IoT room monitoring systems, which are represented within the DT framework alongside scientific measurement systems. Ultimately, an XR application combines all sub-branches into an overall solution and forms the interaction level of the entire structure with adaptive FAIR compliant RDM for research institutions. Developing a flexible, engaging, and data-centric strategy not only aids operational processes but also propels research and development forward by improving data accessibility and utilization. Overall, the entire use case emerged from the daily problems at the research institute and therefore proved to be very promising with the results available.

However, there are some limitations that need to be taken into account in the future. For example, approaches and options must be sought to ensure the execution time for clean mesh results from the creation of the point cloud. Depending on the size and use case of the XR application, the calculation via a graphics card cluster must be considered. In the future, it is planned to further investigate experiments regarding real-time recordings and processing of point cloud recordings. The framework should also be expanded to include further use cases, such as the expansion and depth of integration of research equipment, the allocation of research resources, collaboration and transdisciplinary studies and the general expansion to additional laboratory areas at the institute. The scaling and clustering of several buildings considered in this way would also be interesting to examine in the smart city context.

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