X-Reality for intuitive BIM-based as-built documentation

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Key words: Building Information Modeling, Virtual Reality, Mixed Reality

SUMMARY

Building Information Modeling (BIM) is increasingly being used in the construction industry for planning new structures, while existing structures are hardly considered at present, even though digital methods can lead to significant added value, especially for operation and maintenance. For applying BIM to existing structures, these usually must be surveyed first. Typically, the as-built/as-is state is captured by geodetic means as a point cloud using laser scanning or photogrammetry, from which in a subsequent step a BIM model is derived (Scan-to-BIM) in a tedious and cost-intensive manual process. This is mainly because automation is still scarce. Moreover, current workflows require expert software and only use 2D screens, often with a mouse and a keyboard, for modeling.

The project "Building Inspector XR" aims at improving the Scan-to-BIM process for as-is documentation by employing X-Reality (XR), including Virtual Reality (VR) and Mixed Reality (MR) with incorporated automations, to aid the user. Core benefits of XR environments are that users can perceive and interact with 3D objects much more intuitively in comparison to modeling software running on 2D desktop screens, for example because it corresponds more to natural vision and object scale is conveyed better. VR and MR have technology-specific advantages and disadvantages. While VR offers the possibility to sketch 3D BIM models of structures easily and quickly independent of the user's location, it requires data for context, for instance a point cloud of the built situation. The quality of the point cloud heavily influences the visual appearance of the virtual environment. MR on the other side relies on reality for context, thus, has much more detail, but is restricted to on-location workflows and physically correct user interactions. Therefore, in the project we combine the benefits of both technologies. The initial BIM model is created in VR from a point cloud and completion of it is possible in MR by displaying the model georeferenced on-site, so elements that are hidden or unavailable in the point cloud or semantic object properties can be added. An accurate registration of the model to reality, i.e., accurate georeferencing, is crucial for this. The output of the workflow is a standardized Industry Foundation Classes (IFC) model, which can be opened in any IFC-compliant software.

The paper addresses key-aspects of the project "Building Inspector XR", as for example transferring BIM to VR and MR, and highlights core components of our XR solution such as supporting automations, modeling schemes according to BIM standards and model registration for MR to realize an efficient Scan-to-BIM workflow.

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1. INTRODUCTION

Building Information Modeling (BIM) is becoming increasingly popular in the construction industry for planning new structures, as it allows for better collaboration and coordination among project stakeholders, improved cost and time management, and enhanced design quality. However, the use of BIM for existing structures is not as common, even though digital methods can lead to significant added value for operation and maintenance, for example for energy simulations, lifecycle assessments, or facility management (Volk et al., 2014). For applying BIM to existing structures, a process such as Scan-to-BIM (Wang et al., 2019) is required to obtain a digital model of the structure, which today involves several lengthy manual processes. This work is typically done on desktop computers with keyboards and mice, which is not as intuitive as it should be, since the three-dimensional BIM models are shown on flat two-dimensional computer screens.

To address these issues, we propose to improve the Scan-to-BIM process for as-built/as-is documentation by employing X-Reality (XR) technologies, including Virtual Reality (VR) and Mixed Reality (MR), to aid the user. The use of XR environments enable users to perceive and interact with three-dimensional objects in a more intuitive manner, as it corresponds more to natural vision and better conveys object scale. The initial BIM model is created in VR from a point cloud and completion of it is possible in MR by displaying the model georeferenced on-site, so elements that are hidden or unavailable in the point cloud or semantic object properties can be added. An accurate registration of the model to reality, i.e., accurate georeferencing, is crucial for this.

2. BACKGROUND

This chapter covers the theoretical background for intuitive BIM-based as-is documentation in XR. For this, Scan-to-BIM and XR are explained and a brief overview of related work is presented.

2.1 Scan-to-BIM

In a first step, the as-is state must be surveyed, which is typically done using geodetic methods like laser scanning or photogrammetry. These methods generate a point cloud, i.e., a large set of data points that represent the physical and appearance characteristics of the structure, such as its shape, size, and color. Photogrammetry is computationally comparatively complex, nevertheless, photogrammetry enables the acquisition of areas that are difficult to access with a reasonably high information density. The geometric accuracy achieved in each case is dependent on several factors, such as the camera sensor, the image resolution, image texture,

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image scale and the calibration accuracy. Laser scanning is considered to be the leading technology for acquiring 3D spatial information with high density (Lari et. al, 2011). Laser scanning is based on the acquisition of 3D coordinates by means of phase comparison or pulse measurement. While laser scanners with the phase comparison method are characterized by a significantly higher number of captured points per second, laser scanners with the pulse measurement method offer a considerably higher range. Furthermore, a distinction is made between mobile, stationary, or terrestrial laser scanners. Due to the high density of the captured points, both methods automatically provide a 3D point cloud as a result.

Subsequently, a digital 3D model must be modeled from the point cloud by hand. For modeling, normally (3D) computer-aided design (CAD) or BIM authoring software, such as Autodesk Revit (Autodesk, 2023), are used. When multiple software is utilized, it is necessary to be able to exchange and combine the models. Since many programs implement proprietary file formats, a standardized data format is required for the interoperability of BIM software products (Borrmann et al., 2021). A widely used standard are the Industry Foundation Classes (IFC) (buildingSMART, 2023), a manufacturer-independent data format for the comprehensive description of BIM models.

2.2 X-Reality

XR is a term used to describe a range of technologies that allow users to experience immersive environments and interactive simulations. The term encompasses VR, Augmented Reality (AR), and MR. VR is a computer-generated simulation of a three-dimensional environment that can be explored and interacted with, for example using a VR headset. The user is fully immersed in the virtual world and is unable to see the real world (Jerald, 2015). AR and MR overlay digital information, such as text, images, or 3D models onto the user's view of the real world. This can be done using a smartphone camera to capture reality which is then shown on the smartphone display with additional information (Blut & Blankenbach, 2021) or an AR/MR headset with a see-through visor to observe reality directly into which the digital information is projected (Becker et al., 2021). According to Azuma (1997), AR is characterized by three main features: (1) it combines real and virtual elements, (2) it combines virtual and real objects in three-dimensional space, (3) it is interactive in real-time. MR combines elements of both VR and AR to create a seamless blend of the virtual and real worlds, as shown in a concept by Milgram et al. (1994). In MR, virtual objects can interact with real-world objects and vice-versa. XR technology has a wide range of potential applications, including entertainment, education, training, and therapy. It is also used in fields such as architecture, engineering, and product design. The field of XR is rapidly evolving, with advances in hardware and software making it more accessible and affordable for consumers and businesses. XR technology in BIM for example enables virtual representations of structures before they are built for identifying potential issues and optimizing the design and construction process. This can lead to cost savings, improved quality, and increased safety on the construction site. While VR can be employed to create fully immersive experiences, allowing stakeholders to walk through a building, explore different design options, and identify any potential issues, AR and MR allow stakeholders to overlay digital information, such as technical data or virtual 3D building models, onto the physical building, for example to visualize the building's performance (e.g.

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energy consumption), or perform as-planned/as-built comparisons in real-time (e.g. Becker et al., 2021). Therefore, the use of XR technology in BIM is becoming in general more prevalent. Most applications focus on visualizing existing BIM data, but do not consider that for many structures there often are no digital 3D models or even digital plans available, therefore, these must first be digitized. There are some solutions available that use XR, but these are very limited in terms of their modeling or editing capabilities. The following section gives a short overview.

2.3 Related work

The real-time 3D architectural visualization software Twinmotion (Epic Games, 2023a) and Enscape (Chaos, 2023) allow users to quickly create high-quality images, panoramas, standard or 360° VR videos of their 3D models or view these in VR. It can also be used to create animations and walkthroughs. Both require pre-built models from 3D modeling software (e.g. Autodesk Revit). Modeling functionalities are mainly limited to dragging and dropping existing 3D objects using the desktop computer editor. AR or MR functionalty is not available. VR Sketch (VR Sketch, 2023) is one of the most similar approaches to our solution. However, it does not provide any functionalities for BIM, thus, components cannot be modeled according to BIM standards. Also, importing point clouds is not possible. For BIM in AR, GAMMA AR (GAMMA Technologies S.à r.l., 2023) enables superimposition of BIM models on the construction site to avoid errors and for component-accurate monitoring. Modeling is not possible though. BIM Holoview (BIM Holoview Ltd., 2023) combines VR and MR and enables users to view BIM models in VR with the Meta Quest 2 (Meta, 2023) and in MR with the Microsoft HoloLens (Microsoft, 2023). The models are limited to Autodesk 3D Revit and Navisworks files though. Point clouds cannot be viewed and modeling is not possible.
The broadest approach is Unity Reflect (Unity Technologies, 2023), which provides functionalities to view BIM models in different formats in VR, AR and MR on multiple devices. Creating BIM models at runtime is not possible though.

3. BIM IN X-REALITY

In this section we describe the key-points of our solution and how specific parts were realized. Among others, the implementation of the general XR BIM system is detailed and supplemented by VR and MR specifics.

3.1 X-Reality BIM System

Figure 1 depicts the architecture of our XR BIM system. Following Scan-to-BIM, the input of the system is a point cloud reflecting the as-is situation, which serves as initial data in VR. The origin of the point cloud is not relevant and can be created by photogrammetry or laser scanning. Using the point cloud as context, the user creates a BIM model. Once finished, the BIM model can either be exported as a standardized IFC file, which can be opened in an arbitrary IFC-capable software or brought into MR to enhance it on-site. With our solution, models are interchangeable between VR and MR, allowing efficient workflows. Currently, we support models according to the IFC building and waterways domain.
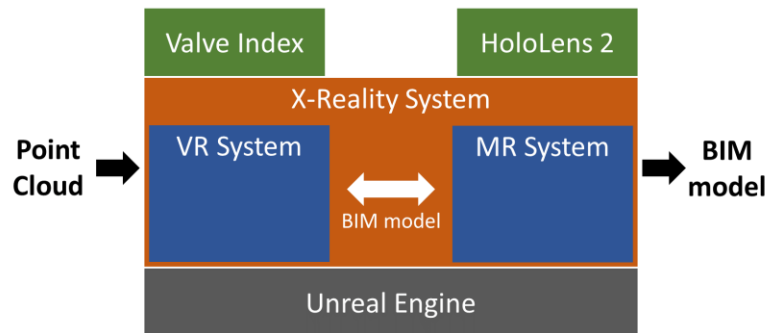
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Figure 1: Architecture of the presented solution.

Generally, when designing a XR system choices must be made concerning for example the hardware, which includes devices such as VR, AR, and MR headsets to provide the necessary display and input technology for the user to experience the XR content, and software, which includes the tools and platforms used to create and deliver the XR content, such as game engines, 3D modeling software, and software development kits (SDK) for XR.

In terms of hardware, we designed our system for the Valve Index (Valve Corporation, 2023) and the Microsoft HoloLens 2. Basically, there are three different types of VR systems available on the market, standalone headsets, tethered headsets, and Cave Automatic Virtual Environments (CAVE). The standalone headsets include all necessary components to provide VR experiences already in the headset. This comes at the price of limited computing power, thus, possibly reduced image and pose tracking quality. High quality pose tracking is important for accurate movements in VR, since it keeps track of the user's movements in the real world and transfers these into the virtual world. A pose refers to the six degrees of freedom, therefore, the user's translation and rotation. With the goal of accurately modeling BIM components, we chose the tethered variant, because it provides us the required capabilities, as a tradeoff to limited moveability. A CAVE was no option for our solution since it is very costly and requires a dedicated room with specialized hardware. VR headsets on the other hand are available off-the-shelf for anyone at a relatively low price of around 1000 €, making them more accessible.

For AR and MR, we wanted the solution to be just as accessible, which leaves two options, off-the-shelf mobile devices such as smartphones, tablets, or headsets. While smartphone- and tablet-based solutions enable AR and MR without specialized hardware, headsets facilitate more flexibility, for example because the user has both hands free. We found the Microsoft HoloLens 2 to provide the best AR and MR capabilities, including accurate and stable pose tracking, gesture-based interactions, and immersive visuals.

We based our developments on a game engine since it provides the necessary framework to create a XR application, with important functionalities readily available. Some important parts of a XR system are high quality rendering with a high performance and means to interact with the virtual content. A game engine typically provides among other things a rendering engine, interaction methods, a physics engine and networking capabilities out-of-the-box. The rendering engine is responsible for generating the visual output of the game, including lighting, shading, and special effects. Today, the use of game engines also extends beyond the gaming industry, as they are being used in various fields such as architecture, automotive, film and

television, and more. We chose Unreal Engine (UE) (Epic Games, 2023b), because it specifically has a broad application field next to gaming, thus, supports many file formats and supports a wide array of hardware, such as the Valve Index and Microsoft HoloLens 2. If not natively available in the engine, UE can be extended with additional functions via plugins. For instance, the Datasmith Plugin (Epic Games, 2023c) allows us to import IFC files and the LiDAR Point Cloud Plugin (Epic Games, 2023d) enables importing point clouds. Furthermore, UE is completely open source, so that arbitrary changes can be made to core functionalities of the engine.

Our XR system offers a uniform Graphical User Interface (GUI) in both system parts, VR and MR, but the interactions with the GUI are tailored to fit the specific environment. The GUI layout is shown in Figure 2. The menu includes modeling functionalities such as a catalog, from which pre-created objects can be inserted and edited in the scene, a modeling function, which allows the user to freely create objects and edit them and a cut function that enables the user to perform Boolean operations. Using the hierarchy, the user can structure the modeled objects and add semantic information, and using the metadata function, the user can add object properties. Lastly, the models can be deleted or saved.
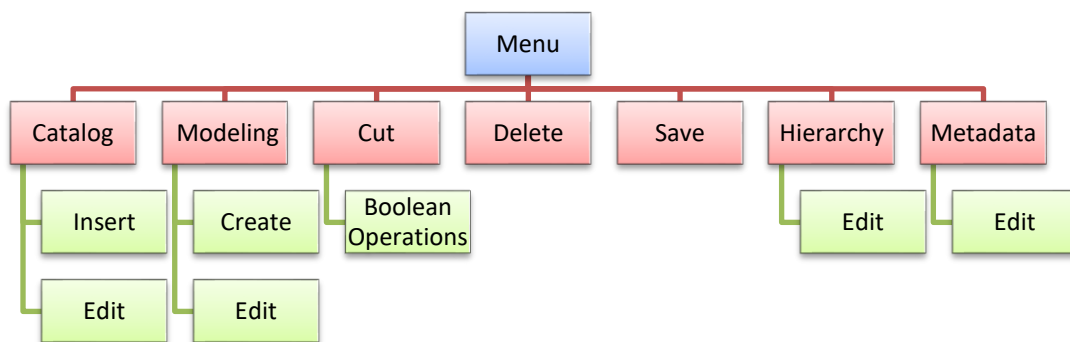

Figure 2: GUI of the X-Reality system with modeling functionalities.

3.2 Virtual Reality System

Realizing the VR system involved multiple challenges, specifically concerning the rendering performance. An important measure is the frame rate. When the frame rate is low, the movement in the virtual environment may appear choppy and can cause discomfort for the user. According to Akenine-Moller & Hoffman (2019) with a frame rate of 90 frames per second (FPS) or higher, the virtual environment appears smoother and more realistic, which can help to reduce motion sickness and improve the overall user experience. In our case, we are dealing with large amounts of data that need to be loaded and visualized in real-time. Specifically point clouds often contain millions of points and can be many gigabytes large. We employ multiple optimizations, for example an efficient octree data structure, which enables spatial partitioning, downsampling and search operations (Figure 3, left). Each node of the octree contains a previously defined maximum number of points that are distributed as evenly as possible. Thus, the nodes can be used as detail levels of the point cloud. In addition, only the nodes that are within the user's sight are kept in the graphics memory (culling). This allows us to visualize

very large point clouds with little graphics memory. The Level of Detail (LOD) system is used to reduce the complexity of a point cloud as it gets farther away from the camera. This helps improve the performance by reducing the number of points that need to be rendered at a distance and makes it possible for us to visualize large point clouds, as for example shown in Figure 3 (right), or very detailed views, so that large and small elements can both be modeled. We also apply a streaming method, so not all point data must be loaded into memory at once but is made available only when necessary.

Figure 3: Underlying octree -green- to increase performance (left); Example of a large point cloud being rendered in our VR system (right).

The VR system provides all required interactions to easily create a BIM model. One VR controllers is used to show the menu (Figure 2) and the other to interact with it. For locomotion across longer distances teleportation is available, thus, the user can instantly move to a designated spot in the virtual environment by pointing and clicking. Higher locations can be reached with fly-mode. In smaller areas, pose tracking allows the user to move around physically in the real world, which is then replicated in the virtual environment.

3.3 Mixed Reality System

In comparison to the VR, MR does not require a complete virtual world. For instance, point cloud data is not required, since reality serves as context into which the virtually modeled objects are inserted. Accurately aligning the virtual and physical world, i.e., accurately placing the virtual objects in reality, is crucial for this. Therefore, pose tracking is also a critical component of MR, as it allows the virtual and real worlds to be seamlessly integrated by determining the pose of the user's head and hands in the physical space. However, there are several challenges associated with pose tracking. Basically, there are two problems that need to be solved: First, the 3D model must be registered to reality, i.e., the Microsoft HoloLens 2 and the 3D model must be transformed into a common coordinate system. For instance, given a BIM model, the poses produced by the pose tracking system of the Microsoft HoloLens 2 can be transformed into the structure model's coordinate system. Secondly, all following motions

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must be tracked, so that the virtual elements stay in their assigned physical locations. Figure 4 shows a 3D model aligned with reality on the Microsoft HoloLens 2.
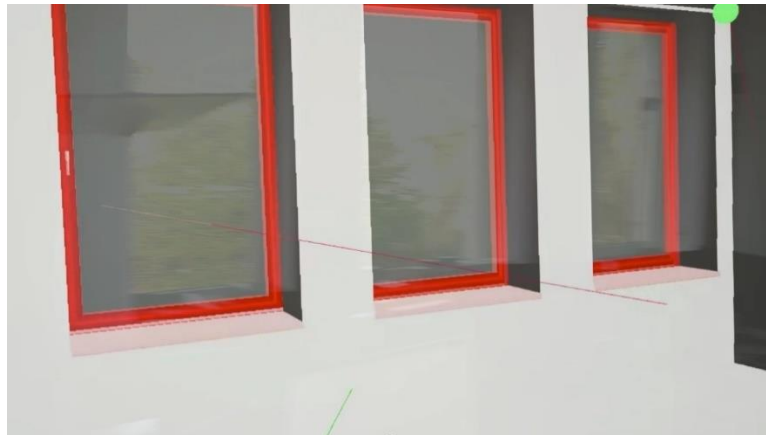

Figure 4: 3D model aligned with reality on the Microsoft HoloLens 2.

Our MR solution provides an accurate registration method that is tailored to the Microsoft HoloLens 2 and integrates with its pose tracking system. It uses 3D points in reality and corresponding 3D points in the BIM model. We obtain the necessary translation, rotation, and scale to register the virtual 3D model to reality utilizing the Kabsch–Umeyama algorithm, as described by Umeyama (1991). The Kabsch-Umeyama algorithm is a widely used method for the alignment and comparison of similarity between two sets of points in multidimensional space. It calculates the optimal transformation that minimizes the root-mean-square deviation (RMSD) between the point pairs by utilizing a combination of translation, rotation, and scaling. The algorithm for determining the optimal rotation was first proposed by Kabsch (1976 and 1978), and later extended by Umeyama to include scaling. In our solution, the user can actively select the corresponding points by gesture. For this, the BIM model is shown in small to the user (Figure 5, left). In reality, numbered spheres are shown to the user that each must be placed in the location corresponding to the selected points in the BIM model (Figure 5, right).
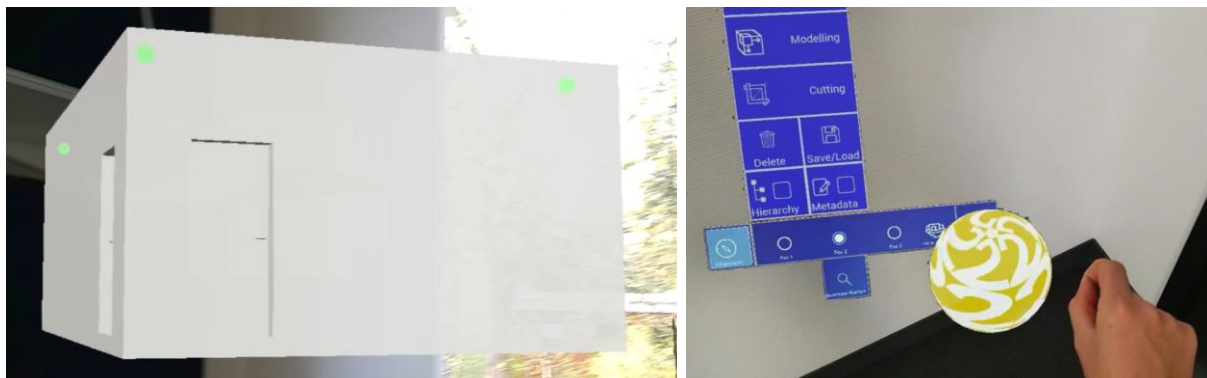

Figure 5: Setting corresponding points in BIM model (left) and reality (right), to reference the BIM model.

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The spheres can be moved using the pinch gesture and carrying them to the desired location. Once all spheres are set in the right locations, the alignment can be executed from the GUI. The referencing process must only be done once, for example for initialization. Though, if the alignment is not accurate anymore, for instance because of drift, the referencing process can be repeated as often as necessary. Drift usually occurs when using a pose tracking system over longer periods of time or increases with the travelled distance (Blut & Blankenbach, 2021). Pose tracking on the Microsoft HoloLens 2 is realized with a Simultaneous Localization and Mapping (SLAM) (e.g. Durrant and Bailey, 2006), specifically a Visual SLAM (V-SLAM) algorithm (e.g. Mur-Artal, 2015). V-SLAM is a fundamental method in robotics and computer vision and has been widely studied in recent years. It utilizes visual information to estimate the pose of a camera in a given environment. Visual geometric features are detected in the environment and used to create a 3D point cloud map. These features are then matched with newly detected features to relocalize and optimize the current pose.

3.4 Modeling Geometry

We found that modeling objects based on point clouds in XR requires different methods depending on the complexity of the physical object. Therefore, we implemented three different variants: Free, parametric and template modeling.
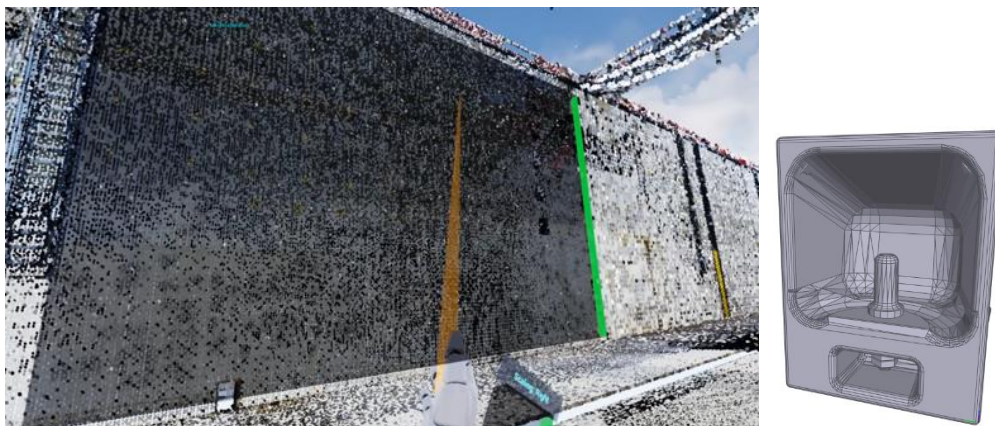

Figure 6: Example creation of a wall in the VR application (left); Example of a pre-modeled component (niche bollard) from the component catalog (right).

The free method is suitable for comparatively primitive objects, such as rectangular walls, floors, or ceilings. For example, a wall can be modeled by specifying only two diagonally opposite points. A solid is then automatically generated, as shown in Figure 6 (left). This allows modeling tasks to be performed quickly and very accurately and ensures that the edges of the object are parallel to each other. For more complex objects with repetitive geometry, the parametric modeling feature can be used to easily create more detailed object models, for example a ladder. The user only needs to input a minimum number of parameters from which all required geometric information is derived. The input parameters are displayed to the user during modeling by means of step-by-step instructions. Following the example of a ladder, the

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user only is required to enter the desired base point, the height, and the width of the ladder. National standards (DIN 18799 and DIN EN 131), for example defining the maximum width of a ladder, are taken into account. The output is a realistic object model according to the specific standard. For very complex objects, which are too difficult to model by hand, an integrated catalog with pre-modeled components including important attributes is available. The object models merely need to be dragged and dropped to their desired positions. An example of such a pre-modeled component is shown in Figure 6 (right) using a niche bollard.

In addition to modeling geometries, we provide a method for selectively cutting out areas defined by the user. This is implemented using Boolean operations. Like this, sections can be cut from objects, such as walls, in order to insert further components, for example the niche bollard. When placing an object into a plane, the user is supported by a plane fitting algorithm, allowing the component to snap to the plane, ensuring good alignment between the objects. This also decreases the required modeling time, as the objects can be fit more quickly in the correct spot.

3.5 Building Information Modeling

In addition to the geometry, the BIM methodology is additionally characterized by the fact that semantic data is assigned to the objects. As data model we adapt the IFCx4.3 standard in the XR BIM system.
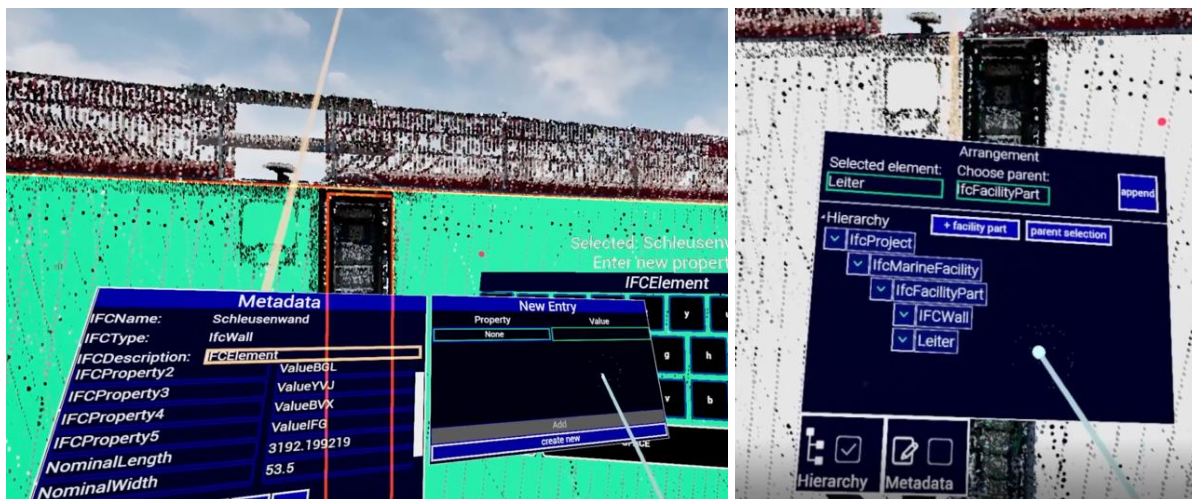

Figure 7: Input of object-specific metadata in VR (left); Classification of modeled object classes in a given IFC hierarchy using the example of a ship lock (right).

The entire modeling process therefore complies with the BIM standard already in the application and ensures that all required information is provided by the user. Within the IFC standard certain attributes are required for each object, such as the name and a description. Further information can freely be assigned to the object. Furthermore, the structure of the IFC standard is subject to a clear hierarchy, so that each modeled object must be assigned to its corresponding level in this hierarchy. Therefore, we include the possibility to classify the object

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and to enter the attribute information as well as to create additional object-specific properties (Figure 7, left). The input of the respective values for the object-specific attributes and properties is done via a virtual keyboard. In addition, the user can directly assign the respective component to the IFC hierarchy. The user decides in the beginning whether the model is from the building or water domain. The basic hierarchy is then generated so that all objects modeled in the following steps can be classified appropriately. Figure 7 (right) shows this using the example of modeling a ship lock.

3.6 Saving and Exporting

Once the BIM model is completed in VR and MR, it can be exported in the standardized format IFC. The resulting file is readable in any IFC-compliant software. This means it can be visualized, edited or extended in a BIM viewer or BIM authoring software (e.g., Autodesk Revit). The target IFC version is the recent 4.3, which includes the port and waterways domain next to the building domain. When exporting to IFC all BIM-related objects of VR or MR are written to a IFC file, including data such as geometry, object hierarchy, semantic data and properties. The geometries are converted from UE meshes to vertices and triangles, which are processed for storage in the file. The object hierarchy is defined by the object structure in UE, which reflects the IFCx4.3 standard. The properties held by each BIM object in the UE scene are all written to the file, independent of their name and value.

4. APPLICATION IN PRACTICE

In a first step, the ship's lock is captured as a point cloud using photogrammetry or laser scanning. Subsequently the resulting point cloud is prepared for modeling, for example by cleaning outliers and unnecessary data. Afterwards, the point cloud is imported into the VR application, which allows inspecting the data and creating a 3D model regardless of the location. The initial immersive inspection of the point cloud can give some first insights. Using the free-modeling tool, the walls and floors of the lock are modeled. This is a quick process, since only a minimal amount of user input is necessary. To place ladders and niche bollards, sections are cut from the walls using the Boolean-based cutting tool. For modeling the ladder, the user selects the parametric modeling function and chooses the type ladder. In a step-by-step assistant the user inputs the required parameters and marks the base point in the point cloud. The object is automatically snapped to the wall with the plane fitting algorithm. To model a niche bollard, the user selects the appropriate object model from the component catalog via the menu and places it in the point cloud at the appropriate position via drag and drop. Immediately after the creation, each geometrically modeled object is placed in the IFC hierarchy and descriptive metadata can be assigned to the object. Once a BIM-compliant model has been created in the VR application, it can be saved to continue editing at a later point in VR or be exported to a IFC file. The saved state can also be transferred to the MR application further edited on-site of the model. Once on site, the model is registered to reality using the provided registration method by selecting corresponding points. In the further steps, the generated model can be checked by overlaying it with reality to identify any deviations. Meanwhile, the positions as well as the geometries of the created components can be adjusted if necessary and the object-specific

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information can be adapted or supplemented. The output of this process finally provides a realistic 3D model of the ship lock, which can again be exported as a standardized IFC file, which can be imported to any IFC-compliant software (Figure 8).
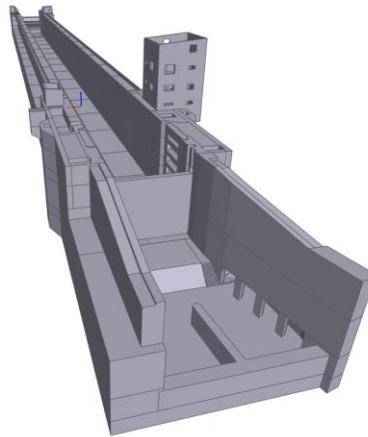

Figure 8: 3D model derived from 3D point cloud.

We found that in comparison to professional and highly complex BIM authoring software, our XR BIM system also allows unexperienced users to create IFC-conforming models. Specifically, the level of immersion of VR and MR eases the handling of the virtual tools and makes complex data such as point clouds and IFC models much more approachable, since they can be viewed and interacted with in a natural way, as used to from reality. We experienced modeling tasks, specifically of large objects, to be done best in VR, because locomotion is much more flexible, while details and object information are best added in MR, due to the better context. Timewise, for example a large wall with a ladder could be modeled in under a minute, which underlines that BIM models can be efficiently created with our system.

5. SUMMARY AND FUTURE WORK

In this project, we aimed to improve the Scan-to-BIM process for as-is documentation by utilizing XR technologies such as VR and MR with automation. We combined the benefits of VR and MR to create an efficient workflow for creating a standardized IFC model of existing structures. Our solution includes the transfer of BIM to VR and MR and the integration of automations, modeling schemes according to BIM standards, and model registration for MR. The outcome of this project is a solution that can be used to create a BIM model of an existing structure with a more efficient and intuitive process. In terms of future work, further research could focus on improving the accuracy of georeferencing and automating it for MR, as well as exploring other potential applications for the XR solution in the construction industry. Specifically, the inspection aspect has large potential and could be further extended. Also, we see many possible improvements using artificial intelligence, for example to automate modeling tasks. Additionally, further testing and implementation of the solution in real-world scenarios could provide valuable insights into its effectiveness and potential for widespread use in the field.

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