BUILDING INSPECTOR XR: STREAMLINING SCAN-TO-BIM WITH VIRTUAL AND MIXED REALITY

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ABSTRACT: *Digitalization in the construction industry is increasingly striving to create digital twins in order to continuously exploit optimization potential in the management and utilization of existing buildings. Building Information Modeling (BIM)-based as-is or as-built documentation represents a promising basis in this context, which requires creating a geometric model for example based on point clouds as well as semantic enrichment in a Scan-to-BIM workflow. Conventionally, this is carried out manually by specialists on 2D screens and often is time-consuming and costly. The project "Building Inspector XR" addresses these issues and presents an intuitive solution for BIM-based as-is/as-built documentation using X-Reality (XR). In Virtual Reality (VR), BIM models are created off-site from point clouds and then are verified in Mixed Reality (MR) on-site. By integrating (partially) automated methods and targeting user-friendliness in our solution, Scan-to-BIM can be realized more efficiently and intuitively. In this paper, the focus lies on the innovative aspects of our XR application which encompass VR and MR environments, automation support, modeling schemes in compliance with BIM standards, and the registration of models in reality for MR. Additionally, the paper shows the interconnected toolchain that facilitates an efficient Scan-to-BIM workflow.*

KEYWORDS: *Building Information Modeling, Virtual Reality, Mixed Reality*

1. INTRODUCTION

The global and cross-industry trend of digitalization is increasingly shaping the construction industry as well. As a comparatively less digitalized industry, there is a great need for the development and implementation of digital methods in the construction industry in particular. The linchpin of the digital transformation in the construction industry is the cooperative working methodology Building Information Modeling (BIM). Compared to traditional methods, BIM offers the potential to improve communication and coordination between all construction stakeholders, make management for cost and time more efficient, and achieve higher levels of detail in digital building models by incorporating component-specific semantics in addition to geometry. Although the use of BIM is applicable across the entire lifecycle of buildings, in reality the collaborative working methodology is predominantly used for new structures. For existing buildings, BIM has not yet been applied frequently, although it could create added value for operation and utilization by enabling the resulting digital as-is/as-built models to be used to represent and evaluate the existing condition of the building and, based on this, to plan possible maintenance measures, carry out simulations or organize issue management more efficiently.

For the application of BIM in this context, it is first necessary to capture the existing buildings. In most cases, such an acquisition process is carried out by means of laser scanning (terrestrial or mobile) or photogrammetry. The result of these procedures is a 3D point cloud. The subsequently necessary process of generating a digital building model from the available point cloud is summarized under the term "Scan-to-BIM" and is currently mainly implemented manually on two-dimensional screens using keyboards and mice. Therefore, we identified the need to improve the Scan-to-BIM process, by making it more intuitive in a 3D space using X-Reality (XR). In this paper, we present the project “Building Inspector XR”, which includes both a Virtual Reality (VR) and Mixed Reality (MR) application, for the intuitive creation of as-is/as-built BIM models based on existing point clouds.

2. BACKGROUND

2.1 Reality Capturing

As a holistic approach to documenting structures, BIM places more far-reaching demands on building surveying. To meet these requirements, various methods of reality capturing are employed, including photogrammetry, terrestrial laser scanning and mobile laser scanning.

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Photogrammetry is a method of deriving geometric information of an object from images (Luhmann, Robson, Kyle, & Boehm, 2014). A distinction is made between mono- and stereo-photogrammetry. While mono-photogrammetry is based on the analysis of single images, stereo-photogrammetry uses pairs of images to measure objects, such as buildings. Using photogrammetry, areas that are difficult to access can be surveyed with a comparatively high information density with Structure from Motion/Dense Image Matching. The respective achievable geometric accuracy is subject to a number of factors, such as the camera technology, the resolution of the individual images, the type of reference point determination (Donath, 2008) and specifically the image scale.

In addition to photogrammetry, laser scanning forms another practical method for building acquisition and is considered the leading technology for the acquisition of 3D spatial information with high density (Lari, Habib, & Kwak, 2011). From a functional point of view, a distinction is drawn between laser scanners with impulse and phase measurement methods. Impulse measurement determines the time of flight of the laser beam, while phase measurement evaluates the phase shift of the reflected signal. While laser scanners with the phase comparison method are characterized by a significantly higher number of recorded points per second, laser scanners with the impulse measurement method offer a significantly higher range. Terrestrial laser scanning is characterized by stationary acquisition of local 3D data of the object from different locations and subsequent registration of the data of all locations relative to each other. In contrast to this, mobile laser scanning continuously acquires 3D data while the object is in motion and registers the data via positional information.

The output of each of these methods is a high variety of 3D points representing the respective surface of the acquired object. These 3D point clouds can be used for further analysis and modeling.

2.2 Scan-to-BIM

In addition to the surveying workflow, the holistic BIM approach to the acquisition, management and exchange of building information also has implications for the processing and modeling of data (Blankenbach, Schwermann, & Becker, 2021). The process of creating or reconstructing as-is/as-built BIM from 3D point cloud data is called Scan-to-BIM. For this process, individual geometric elements such as walls, doors or windows are initially created on the basis of the point cloud data. Additionally, to the geometric model, attributes such as materials, dimensions or further semantic information are linked and documented to the corresponding objects. Subsequently, the resulting BIM model is validated and checked for possible errors or inaccuracies to ensure compliance with requirements and standards. Currently, this process is predominantly handled manually by professionals using (3D) computer-aided design (CAD) or BIM authoring software, such as Autodesk Revit (Autodesk, 2023). While automated solutions for this process are being progressively developed in both research and industry, each of the currently available off-the-shelf Scan-to-BIM software packages presently still requires significant manual user input making the entire process cumbersome and error prone (Son, Kim, & Turkan, 2015).

2.3 State of the art

(Adekunle, Aigbavboa, & Ejohwomu, 2022) compiled a systematic literature review network analysis on the topic of Scan-to-BIM in 2022. According to this, Scan-to-BIM is being researched worldwide with a view to finding more efficient solutions, which occasionally also include the use of VR and AR technologies for information management. However, specific works are not mentioned since the paper focusses to summarize, categorize and analyze the different topological backgrounds and their nationally backgrounds. Therefore, no specific work for modeling in VR or Augmented Reality (AR)/MR is addressed. (Wu, Hou, & Zhang, 2021) and (Alizadehsalehi, Hadavi, & Huang, 2020) show studies that aim to compile various publications related to BIM and XR applications. (Wu et al., 2021) outlines a BIM-XR application as a system combining a BIM database and a human-machine interactive interface for context-aware visualization and interaction. Generally, it highlights that XR can enable modifications and updates to the BIM model and offers intuitive visual representations and interactive experiences within the BIM context. However, the study primarily emphasizes the visualization aspect and does not present detailed approaches for geometric and semantic BIM modeling in VR or MR environments. Specifically, the focus is on AR/MR for post-construction BIM model adjustments, while VR is considered mainly for visualization purposes. (Alizadehsalehi et al., 2020) discuss the benefits of XR technologies for construction project simulation and present a comprehensive overview of XR applications. Nevertheless, while acknowledging the potential of using XR with BIM for interactive visualization, the study focuses on approaches to transform pre-designed BIM models into XR rather than intuitive modeling in VR and MR.

Commercial products such as Enscape (Chaos, 2023) or Twinmotion (Epic Games, 2023a) allow a visualization of 3D models in VR as well as creating images, animations or walkthroughs, however, both require importing previously created models and do not provide the possibility of modeling, except for simple drag and drop functions via the desktop computer editor, in VR. Further XR possibilities, such as the transformation into AR or MR, are also not possible. In comparison to our solution, VR Sketch (VR Sketch, 2023) presents a similar approach. Nevertheless, it lacks comprehensive BIM capabilities, making it incapable of conforming to BIM standards when modeling components. Moreover, the software does not support point clouds. Arkio (Arkio, 2023) offers a platform specifically developed for collaborative design and architectural conception, focusing on free geometric modeling in a VR environment. For this, existing BIM models and 2D plans can be imported as a data basis and the created 3D geometric models can be exported into selected BIM authoring software, such as Autodesk Revit or BIM360. However, Arkio does not provide BIM-specific functionalities to ensure BIM-compliant (as-built) modeling, like complying with existing standards, providing standardized component catalogs or semantic enrichment. Also, Arkio is limited to proprietary file formats and does not contain the option of exporting to the open Industry Foundation Classes (IFC) (buildingSMART, 2019) standard. 3D models can also be created and edited in AR, but this feature is limited to tabletops. GAMMA AR (GAMMA Technologies S.à r.l, 2023) on the other hand offers the possibility to overlay BIM models on construction sites. This integration aids in error prevention and precise component monitoring. Nonetheless, it does not support actual modeling activities. BIM Holoview (BIM Holoview Ltd., 2023) combines VR and AR/MR to enable users to view BIM models using Meta Quest 2 (Meta, 2023) and Microsoft HoloLens (Microsoft, 2023). However, it is limited to Autodesk 3D Revit and Navisworks files, restricting modeling functionalities. Unity Reflect (Unity Technologies, 2023) encompasses the broadest range of capabilities. It allows users to view BIM models in various ways, including VR, AR/ MR, on multiple devices, nevertheless, it does not support the creation of BIM models in real-time.

3. METHODOLOGY

The Building Inspector XR revolutionizes the process of building inspection by harnessing the power of VR and MR technologies. This chapter presents an overview of the process chain involved in the Building Inspector XR, covering its architecture, hardware and software choices, and the functionalities it offers. Through the utilization of point clouds and BIM models, accurate pose tracking, and seamless integration of virtual content into the physical environment, the Building Inspector XR system streamlines the Scan-to-BIM process.

3.1 X-Reality for Scan-to-BIM

The XR BIM system is the foundation of the Building Inspector XR. Fig. 1 illustrates the system's structure, where a point cloud, generated through photogrammetry or laser scanning, serves as the initial data in VR. With the point cloud as a context, the user creates a BIM model, which can be exported as an IFC file for interoperability or brought into MR for on-site enhancement. This seamless interchangeability between VR and MR enables efficient workflows, supporting models based on the IFC building and waterways domain. Choosing the right hardware and software is crucial for the success of an XR system. For the Building Inspector XR system, the Valve Index (Valve Corporation, 2023) and the Microsoft HoloLens 2 were selected. The Valve Index, a tethered VR headset, provides high-quality pose tracking necessary for accurate movements in VR. On the other hand, the Microsoft HoloLens 2 was chosen for its MR capabilities, including accurate pose tracking, gesture-based interactions, and immersive visuals. Software plays a significant role in the Building Inspector XR system, with Unreal Engine (UE) (Epic Games, 2023d) serving as the development framework of choice. UE offers a broad application field beyond gaming, supporting various file formats and a wide range of hardware, including the Valve Index and the Microsoft HoloLens 2. The system leverages relevant plugins to extend its functionalities, such as the Datasmith Plugin (Epic Games, 2023c) for importing IFC files and the LiDAR Point Cloud Plugin (Epic Games, 2023b) for importing point clouds. The open source nature of UE allows for customization and modifications to the core engine functionalities.

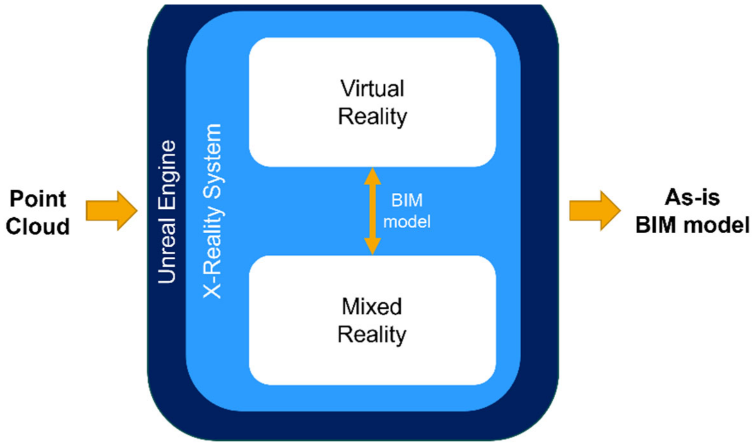

Fig. 1: Architecture of the Building Inspector XR.

The LiDAR Point Cloud Plugin on the one side offers an import interface and on the other side point cloud rendering methods to visualize the point clouds in UE. For starting the modeling process in XR, the initial point cloud can be provided in a couple of different formats, such as XYZ, PTS, LAS/LAZ or E57. Once available in the system, multiple parameters of the LiDAR Point Cloud Plugin ensure that the point clouds are rendering efficiently. We configured the plugin so that the point clouds are visualized with the highest quality possible, while maintaining a high performance. A highly detailed presentation of point clouds is crucial, so that as much information can be derived from the data as possible during modeling. Like this, small details of the environment can be already identified and modeled from the point clouds, enhancing the value of the BIM model, and minimizing additional modeling work later in MR or post processing (Fig. 2).

Fig. 2: Point cloud in VR.

In XR, but especially in VR, rendering performance is crucial for a smooth and realistic user experience. A high frame rate of 90 frames per second (FPS) or higher is recommended to reduce motion sickness and enhance the overall user experience. To address the challenge of rendering large amounts of data, optimization techniques are employed. These include an efficient octree data structure and spatial partitioning. Level of Detail (LOD) systems are used to reduce complexity as objects move farther from the camera, improving performance. The VR system provides intuitive interactions for easy BIM model creation. The VR controllers enable users to access the menu attached to the left controller and interact within it. Over the menu all required functionality to create a complete BIM model is accessible to the user, including geometry and semantic data modeling methods, editing tools and export functionality. The right controller is reserved for the actual modeling process. Teleportation allows instant movement to designated spots in the virtual environment, while fly-mode enables reaching higher locations. Pose tracking allows physical movement within smaller areas, accurately replicated in the virtual environment.

In contrast to VR, the MR system of the Building Inspector XR does not require a complete virtual world (Fig. 3). Instead, it integrates the virtually modeled objects into the physical environment. This is specifically challenging, because the virtual elements modeled in VR need to be placed as accurately as possible in reality, so that they overlay their physical counterparts. Like this, the user can inspect elements, for instance by comparing the modeled with the real situation. Also, details can be added to the BIM elements, for example additional attributes such as material or even further geometric information. This is important, if objects or details were not visible in the point cloud, either because they were covered by other objects during reality capturing or too small so that they are hardly or not visible in the point cloud.

Fig. 3: MR application.

Accurate alignment between the virtual and physical worlds is achieved through pose tracking, which seamlessly integrates the virtual and real elements. The system employs a Visual Simultaneous Localization and Mapping (V-SLAM) algorithm on the Microsoft HoloLens 2 for accurate pose tracking. This algorithm keeps track of the user's pose (position and orientation), thus, of the Microsoft HoloLens 2, keeping virtual objects robustly anchored to a location in reality. To achieve an initial accurate alignment between the virtual objects and reality, a registration method is employed. The Building Inspector XR system utilizes the Kabsch–Umeyama algorithm (Umeyama, 1991), a widely used method for aligning and comparing similarity between two sets of points in multidimensional space. The goal of the algorithm is to find the optimal rigid transformation matrix that aligns one set of points to another set of points. It can roughly be broken down into three steps:

1. Calculate the centroids of both point sets.
2. Transform both datasets to the origin and then calculate the required rotation.
3. Calculate the required translation and scale.

For MR registration, this can be used by defining corresponding points in the virtual world and reality. Optimally, points are chosen that can easily be identified in both spaces, for instance the corners of a door or window (Blut & Blankenbach, 2021). We therefore provide the means for users to actively select corresponding points in the BIM model and in reality. The gesture-interaction system of the Microsoft HoloLens 2 allows easy and intuitive point selection using fingers. And with the spatial understanding of the Microsoft HoloLens 2, points can accurately be placed in reality. Since the points need to correspond to each other, we provide numbered spheres that simply must be placed in the desired spots by drag-and-drop interaction (Fig. 3). Once all spheres have been placed, the user only needs to confirm to perform the instant alignment. This referencing process can be repeated as needed to maintain accuracy.

Once virtuality and reality have been aligned, the user can start the inspection or modeling process. Due to the head-mounted nature of the Microsoft HoloLens 2, the user has both hands free for interactions. We provide a floating menu with the same UI and functionalities as in VR, so that creating a BIM model is as intuitive in both spaces but optimized for the technology. Creating and interacting with objects using Microsoft HoloLens 2 is as easy as using the point or pinch-gesture.

3.2 BIM-compliant as-is/as-built modeling

By combining VR and MR, the Building Inspector XR enables the creation of models completely in 3D space. Furthermore, modeling as well as interactions are carried out intuitively by gestures and voice input. In terms of functionality, we placed emphasis on advanced geometric modeling, linking semantic object data, and compliance with standards for ensuring a standardized BIM model (as-is/as-built model). Within the scope of the associated research project, we focused on the as-is/as-built BIM modeling of building as well as water engineering structures.

The Building Inspector XR offers users three different approaches to geometric modeling, tailored to the complexity of physical objects. The first method is free modeling (Blut et al., 2023). Simpler objects like rectangular walls, floors, or ceilings can be created by specifying just two diagonally opposite points and the software automatically generates a solid object with parallel edges. This method ensures quick and precise modeling. For objects with more intricate geometry, the parametric modeling feature is available. Users input a minimal set of parameters, from which all the necessary geometric information is derived. Step-by-step instructions guide the users through the process. For example, when modeling a ladder, the user only needs to input the base point, height, and width, with adherence to relevant standards such as the German DIN 18799 for fixed ladder systems on structures. The DIN 18799 specifies that the width of a ladder may be between 400 and 600 mm and that the distance between the ladder rungs must be between 225 and 300 mm. Furthermore, it defines that the first and last rungs should be at least 100 mm and a maximum of 400 mm from their respective ends of the ladder. When the user inputs the required parameters, these value ranges are considered. If any value exceeds or is below the permitted ranges, the respective upper or lower limits are set as new modeling parameters to ensure that the modeled object is in accordance with the prevailing standards. Based on the resulting dimensions of the ladder, the two side rails are first created, and then the number and positions of the individual rungs are automatically generated, considering a standard-compliant entry and exit spacing of 200 millimeters.

In cases where manual modeling proves challenging due to the complexity of the object, the Building Inspector XR provides an integrated catalog of pre-modeled components. These components come with essential attributes and can be easily dragged and dropped into the desired positions. This feature significantly speeds up the modeling process, particularly for highly complex objects. For example, a niche bollard can be quickly inserted using this method (Fig. 4). To enhance modeling capabilities further, the Building Inspector XR enables users to selectively cut out areas defined by the user using Boolean operations. This allows for the insertion of additional components or modifications to existing objects.

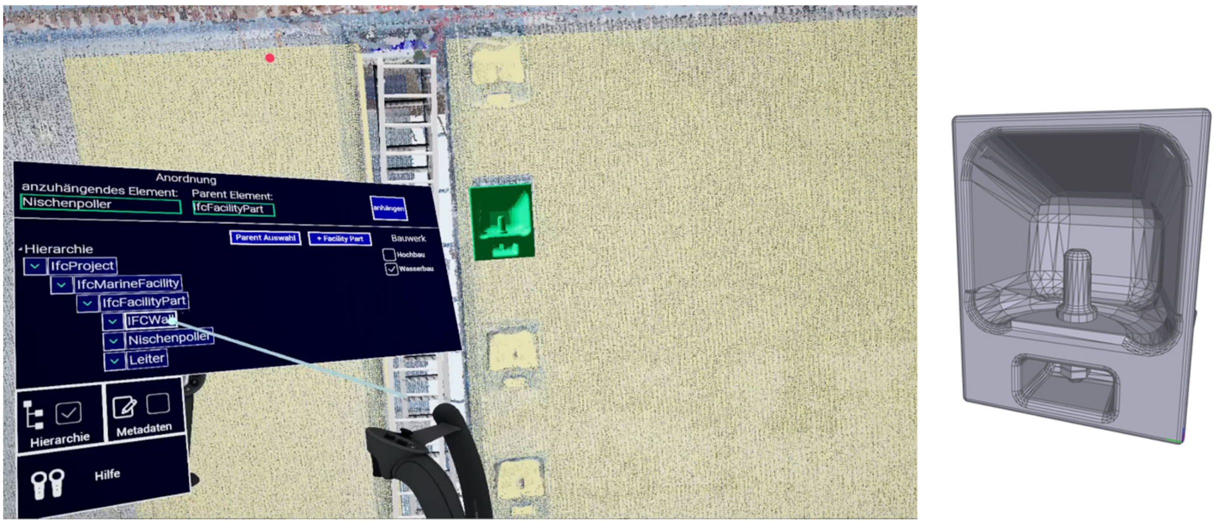

Fig. 4: Placing pre-modeled IFC components in the scene.

A plane fitting algorithm assists users in accurately placing objects on a plane, ensuring proper alignment between components and reducing modeling time. For the detection of surfaces the Random Sample Consensus (RANSAC) algorithm is used. The goal is to find, in several iterations, the area where the largest number of points from the point cloud lie in a plane, i.e., where the distances of all points to the respective plane are minimal, by randomly selecting three points to form a plane in each iteration. Then, the distances of the remaining points to the plane are determined. The plane of the best iteration is stored. RANSAC ensures that outliers are effectively eliminated (Fig. 5).

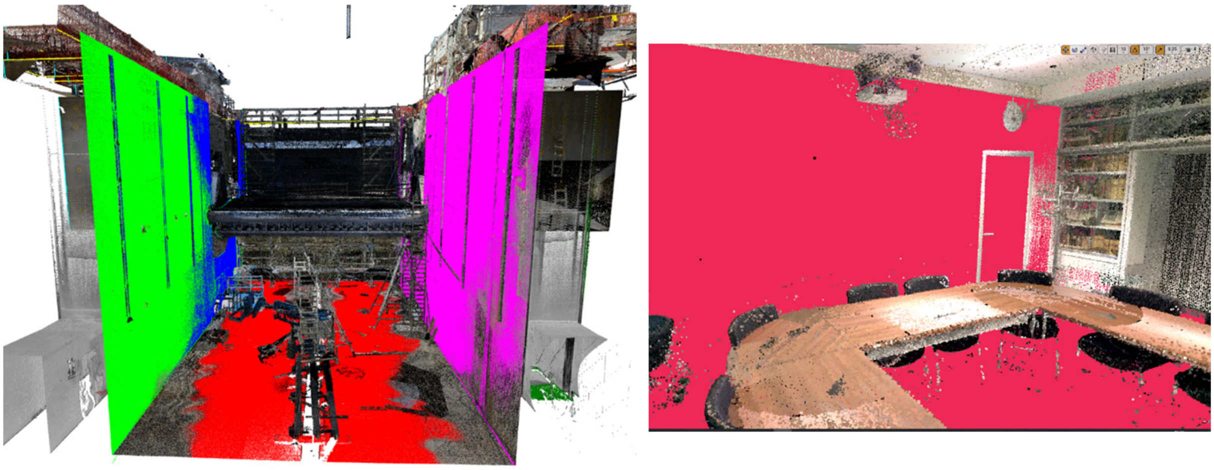

Fig. 5: Detected planes using the plane detection algorithm.

The Building Inspector XR not only focuses on geometry but also emphasizes the assignment of semantic data to objects. By adopting the IFCx4.3 (buildingSMART, 2023) standard as its data model, the software ensures compliance with BIM standards throughout the modeling process. Users can input specific attributes such as name and description for each object, and additional information can be freely assigned using IFC's property sets. The software follows a clear hierarchical structure, enabling users to classify objects, create object-specific properties, and assign components to the IFC hierarchy. Adhering to the IFC hierarchy is crucial for effective BIM implementation. Furthermore, it ensures that modeled objects are correctly classified and organized within the BIM model, facilitating efficient data exchange and collaboration among project stakeholders. The IFC data model is reflected 1:1 already in the application, so that BIM models can easily be exported without loss of data. This was solved by creating the corresponding IFC classes in UE and placing them according to the place in the IFC hierarchy in the UE scene graph. When the user during the modeling process creates a new object, this object can be filled with attributes according to the standard and placed as a parent or child of other objects.

Moreover, the Building Inspector XR facilitates the export of the completed BIM models in the standardized IFC (IFCx4.3 standard) format. The resulting IFC file in STEP Physical Format (IFC-SPF) is readable in any IFC-compliant software, allowing for visualization, editing, and extension of the model using BIM viewer or BIM authoring software.

The integration of water engineering structures into the Building Inspector XR further enhances its versatility and applicability in various construction projects. Users can now model, analyze, and visualize not only buildings but also water engineering elements such as locks, dams, and canals. The inclusion of these new IFC classes demonstrates the commitment to providing a comprehensive XR BIM solution that caters to a wide range of construction disciplines.

4. BUILDING INSPECTOR XR IN PRACTICE

In this section the practical experience with the Building Inspector XR is described. To evaluate the Building Inspector XR, we modeled an office. To obtain the base data for modeling, first, the office and the surroundings of the office were captured with the geodetic terrestrial laser scanner Riegl VZ400 and contained 21 million points (Fig. 6). Subsequently, the resulting point cloud was cleaned from outliers and unnecessary data and exported as a LAS file, since the format proved to work well with the UE LiDAR Point Cloud Plugin. With LAS, importing goes quickly and all data is transferred correctly. On a computer with an AMD Ryzen 9 3900X 12-Core Processor with 3.80 GHz, 32 GB RAM and a M.2 SSD, the LAS file could be imported in less than a second. Importing the same point cloud in E57 format took roughly 20 seconds.

Fig. 6: Point cloud from terrestrial laser scanner of an office in the Building Inspector XR.

A model was created in VR and then later transferred to the Microsoft HoloLens 2. The registration method for aligning the virtual world with reality proved to be efficient, so that the previously modeled objects overlayed their physical counterparts accurately. Three corresponding points were used. The distribution of these three points across the room was crucial, so that an optimal transformation could be calculated. Therefore, we placed on point in the corner of the room, one point on the other side of the room on the corner of a window and the third point on the corner of the door in the wall between the first two points. This provided the maximum distribution of points in the room. The resulting alignment had an accuracy of under 1 cm. After modeling, the BIM model was exported as a IFC-SPF. The created BIM model, i.e., the resulting IFC file then could be loaded without problems in different BIM viewers, such as BIMvision (datacomp, 2023).

The evaluation showed that the Building Inspector XR has a distinct advantage over professional and highly complex BIM authoring software. Inexperienced users could effortlessly create IFC-conforming models using this system. The immersive nature of VR and MR played a significant role in this achievement as it made handling virtual tools and dealing with complex data like point clouds and IFC models much more accessible. Users found the interface intuitive and were able to interact with the models in a natural manner, similar to real-world interactions. The users' experiences revealed that certain modeling tasks, particularly those involving large objects, were most efficiently performed in VR. The flexibility of locomotion in the virtual environment allowed for quicker and more fluid modeling. On the other hand, when it came to adding finer details and object-specific information, the MR application proved to be more advantageous due to its ability to provide better context for these additions. One notable result of the system's efficiency was the ability to model a substantial structure in only a short time. This speed and ease of modeling emphasized the system's capability to create BIM models in a highly efficient manner. Overall, the combination of VR and MR in the XR BIM system demonstrated its potential to empower users, regardless of their experience level, to produce accurate and conforming BIM models in a more intuitive and time-effective way.

5. CONCLUSION

With the Building Inspector XR, we aim to enhance the Scan-to-BIM process by developing an efficient workflow that incorporates VR and MR, ensuring the creation of BIM-compliant as-is/as-built models in a standardized IFC structure, which includes the latest state of the art and thus in addition to building construction also water engineering classes. By transferring BIM to VR and MR, integrating automation, implementing modeling schemes based on BIM standards, and facilitating model registration for MR, we have successfully developed a more intuitive workflow in this context, as users can experience a more immersive and interactive environment for modeling and inspecting existing structures, especially using XR technologies.

For now, we have focused on building and water structure engineering with a selection of elements, therefore, the current capabilities of the Building Inspector XR do not cover all structure types and components but demonstrate the efficiency of our approach. We believe that the Building Inspector XR has the potential to expand its applications in the construction industry. By leveraging artificial intelligence, opportunities to automate modeling tasks can be explored, improving efficiency and reducing human error. In addition to progressively expanding the functionalities of the Building Inspector XR, the inspection aspect, in particular, holds significant promise for further development and extension. To validate and refine the solution, further testing and implementation in real-world scenarios is essential. This would provide valuable insights into the effectiveness and practicality of the Building Inspector XR in real-world construction projects and enable further optimizations and adjustments based on feedback and requirements.

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REFERENCES

Adekunle, S. A., Aigbavboa, C., & Ejohwomu, O. A. (2022). Scan TO BIM: A systematic literature review network analysis. *IOP Conference Series: Materials Science and Engineering*, *1218*(1), 12057. https://doi.org/10.1088/1757-899X/1218/1/012057

Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2020). From BIM to extended reality in AEC industry. *Automation in Construction*, *116*, 103254. https://doi.org/10.1016/j.autcon.2020.103254

Arkio (2023, September 21). Retrieved from https://www.arkio.is/

Autodesk (2023, July 18). Retrieved from https://www.autodesk.com/

BIM Holoview Ltd. (2023, July 18). Retrieved from https://www.bimholoview.com/

Blankenbach, J., Schwermann, R., & Becker, R. (2021). Bauwerksvermessung und BIM. In *Building Information Modeling* (pp. 475–505). Springer Vieweg, Wiesbaden. https://doi.org/10.1007/978-3-658-33361-4_25

Blut, C., & Blankenbach, J. (2021). Three-dimensional CityGML building models in mobile augmented reality: a smartphone-based pose tracking system. *International Journal of Digital Earth*, *14*(1), 32–51. https://doi.org/10.1080/17538947.2020.1733680

Blut, C., Kinnen, T., Schellong, F., Heidermann, D., Bleimann-Gather, G., & Blankenbach, J. (2023). X-Reality for intuitive BIM-based as-built documentation. *Proceedings of the FIG Working Week 2023 "Protecting Our World, Conquering New Frontiers" Orlando, Florida, USA*. Retrieved from https://www.fig.net/resources/proceedings/fig_proceedings/fig2023/papers/ts05d/TS05D_blut_kinnen_et_al_11918.pdf

BuildingSMART (2019, June 20). Industry Foundation Classes (IFC) - buildingSMART International. Retrieved from https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/

BuildingSMART (2023, July 31). IFC4.3.1.0 Documentation. Retrieved from https://ifc43-docs.standards.buildingsmart.org/

Chaos (2023, July 18). Retrieved from https://enscape3d.com/

Datacomp (2023, July 27). BIMvision. Retrieved from https://bimvision.eu/de/

Donath, D. (2008). *Bauaufnahme und Planung im Bestand: Grundlagen - Methoden - Darstellung - Beispiele* (1.

Aufl.). *Praxis*. Wiesbaden: Vieweg, F. https://doi.org/10.1007/978-3-8348-9236-2

Epic Games (2023a, July 18). Retrieved from https://www.twinmotion.com/en-US

Epic Games (2023b, July 20). LiDAR Point Cloud Plugin Overview. Retrieved from https://docs.unrealengine.com/5.2/en-US/lidar-point-cloud-plugin-overview-in-unreal-engine/

Epic Games (2023c, July 27). Datasmith - Unreal Engine. Retrieved from https://www.unrealengine.com/en-US/datasmith

Epic Games (2023d, July 27). Unreal Engine. Retrieved from https://www.unrealengine.com/de

GAMMA Technologies S.à r.l (2023, June 27). Retrieved from https://gamma-ar.com/

Lari, Z., Habib, A., & Kwak, E. (2011). An ADAPTIVE APPROACH FOR SEGMENTATION OF 3D LASER POINT CLOUD. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XXXVIII-5/W12*, 103–108. https://doi.org/10.5194/isprsarchives-xxxviii-5-w12-103-2011

Luhmann, T., Robson, S., Kyle, S., & Boehm, J. (2014). *Close-range photogrammetry and 3D imaging* (2nd edition). Berlin: De Gruyter. https://doi.org/10.1515/9783110607253

Meta (2023, July 18). Retrieved from https://www.meta.com/de/en/quest/products/quest-2/

Microsoft (2023, July 18). Retrieved from https://www.microsoft.com/de-de/hololens

Son, H., Kim, C., & Turkan, Y. (2015). Scan-to-BIM - An Overview of the Current State of the Art and a Look Ahead. In *Proceedings of the International Symposium on Automation and Robotics in Construction (IAARC)*. International Association for Automation and Robotics in Construction (IAARC). https://doi.org/10.22260/isarc2015/0050

Umeyama, S. (1991). Least-squares estimation of transformation parameters between two point patterns. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *13*(4), 376–380. https://doi.org/10.1109/34.88573

Unity Technologies (2023, July 18). Retrieved from https://unity.com/products/unity-reflect

Valve Corporation (2023, July 27). Valve Index. Retrieved from https://store.steampowered.com/valveindex

VR Sketch (2023, June 18). Retrieved from https://vrsketch.eu/

Wu, S., Hou, L., & Zhang, G. (2021). Integrated Application of BIM and eXtended Reality Technology: A Review, Classification and Outlook. *Proceedings of the 18th International Conference on Computing in Civil and Building Engineering: ICCCBE 2020*, 1227–1236. https://doi.org/10.1007/978-3-030-51295-8_86