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Using Immersive Technologies and Digital Twins in a Real World with Non-Orthogonal Coordinate Systems

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Abstract. The paper describes the use of immersive technologies and Digital Twins in the architecture, engineering, and construction (AEC) industry. Immersive technologies have immense potential to improve interdisciplinary collaboration as they utilize a visual representation of virtual objects in their real-world perspective. This immersion facilitates effective communication between all parties involved, e.g. to identify errors during the planning and construction of buildings. A specific example of such interdisciplinary collaboration is kitchen planning. The architect draws the house and room plans, the kitchen planner plans the kitchen according to the homeowner's wishes and the craftsmen then carry out their installations according to the plans for electricity, water, and heating. All plans are based on flat floors and perpendicular walls. However, this is rarely the case in a real building. The challenge with the exact visual representation of virtual objects in the real world using AR therefore lies in the positioning of objects such as a cupboard in relation to the non-orthogonal coordinate systems that result for each room from the real floors and walls. The paper presents an assistance system that integrates immersive technologies and Digital Twins. It is a solution approach for the transformation of object properties based on orthogonal coordinate systems into the non-orthogonal coordinate systems prevalent in reality. With the assistance system, the kitchen planner can create his plans using virtual reality (VR), customers can experience their kitchen virtually and the craftsmen can then be guided using augmented reality (AR), e.g. by precisely localising drilling positions for cabinets.

Keywords. Transdisciplinary Engineering, Virtual Reality, Augmented Reality, Assistance System, Collaborative Construction

Introduction

The increasing integration of immersive technologies and Digital Twins (DTs) is catalyzing a transformative shift across various industries, prominently within the architecture, engineering, and construction (AEC) domain. Immersive technologies encompass a spectrum of tools that enable users to immerse themselves in virtual or augmented realities, engaging interactively within these environments [1]. These technologies engender immersive and captivating experiences by engaging the user's senses, providing a sensation of physical presence even within virtual realms. Key types of immersive technologies, also called eXtended Reality (XR), include Virtual Reality

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(VR), Augmented Reality (AR), and Mixed Reality, each offering unique capabilities and applications [2].

These technologies facilitate the creation of virtual environments wherein users can interactively engage with 3D representations while simulating real-world scenarios. The adoption of immersive technologies holds the promise of enhanced efficiency, cost-effectiveness, and more precise planning and execution of construction projects [3].

Immersive technologies are significantly impacting the AEC industry. For instance, on-site workers can receive detailed visual support from digital data or remote experts while maintaining hands-free operation, thereby streamlining workflows and enhancing productivity [4].

In real-world scenarios, structures and landscapes often deviate from perfect orthogonality, presenting complex geometries beyond traditional orthogonal coordinate systems' capabilities. The exploration of non-orthogonal coordinate systems aims to capture and model this complexity accurately, facilitating more precise simulations and planning. By adapting to non-orthogonal conditions, potential errors can be minimized, thereby improving the accuracy of Digital Twins and enabling better-informed decisions and optimized project execution [5].

However, the utilization of non-orthogonal coordinate systems in the real world poses several challenges, particularly concerning accurately aligning virtual objects within these environments. In this study, we delve into the concept of leveraging immersive technologies and Digital Twins within non-orthogonal coordinate systems, exemplified through the context of kitchen planning and construction. This exploration seeks to elucidate strategies for overcoming challenges and maximizing the potential of immersive technologies and Digital Twins in non-orthogonal environments within the AEC sector.

1. Related Work

The role of Digital Twins in the planning, construction, and maintenance of buildings is diverse and promising. Digital Twins (DTs) have the potential to advance the operational and maintenance phase across various application domains by enhancing building efficiency and reducing costs [6][7][8]. They enable the creation of intelligent operational and maintenance systems based on machine learning and predictive capabilities to monitor the condition of buildings, predict future states, and proactively take actions [9]. Furthermore, Digital Twins can support the construction and maintenance of historical buildings by integrating innovative workflows and technologies to strengthen preservation and conservation efforts [10]. The application of Digital Twins in building planning and construction can also enhance the efficiency and quality of green building operation by bolstering operational cost management capabilities and driving automation and information technology advancements in the industry [11]. Overall, research indicates that Digital Twins hold significant potential to enhance the efficiency, sustainability, and economic viability of buildings.

The integration of Digital Twins into existing workflows of the Architecture, Engineering, and Construction industry is an emerging trend aimed at improving productivity and decision-making across all stages of asset management, including design, construction, operation, and maintenance. Digital Twins are digital representations of physical entities that mimic the status and behavior of their physical counterparts, thus providing a foundation for reliable, data-driven decision-making.

However, the AEC industry faces challenges in the adoption of DTs, driven by a fragmented approach and a lack of interconnected workflows [12].

The implementation of DTs in the AEC industry involves the integration of various technologies such as Building Information Modeling (BIM), Internet of Things (IoT), and Artificial Intelligence (AI). Despite the potential benefits, there is still confusion between the nuanced differences of BIM and DT technologies, hindering their full potential. Additionally, the absence of standardization and formalized standards for DT implementation presents additional challenges [13].

To address these challenges, research suggests focusing on critical components such as technologies, maturity levels, data layers, and functionalities of DTs. Furthermore, improvements in data integrity, integration, and transmission, bidirectional interoperability, non-technical factors, and data security are needed to achieve mature DT applications. An adapted model of Cognitive Digital Twins has also been proposed to support decision-making in building lifecycle management by integrating cognitive capabilities for process optimization [14].

In summary, DTs offer significant benefits for the AEC industry; however, their integration into existing workflows requires overcoming technical and non-technical barriers, improving interoperability, and establishing industry standards [15].

2. Concept

The proposed approach addresses the issue that in reality, the spatial coordinate system R cannot be considered ideal or orthogonal within physical spaces. This discrepancy is particularly relevant in Architecture, Engineering, and Construction, where theoretical planning assumes an orthogonal coordinate system, yet real-world implementation encounters non-orthogonal challenges such as slanted walls and uneven floors altering the angles between planes. The axes of the theoretical coordinate system are assumed to be perpendicular to each other, defining the space RO, whereas in reality, the coordinate system consists of non-orthogonal axes, defining the non-orthogonal space RnO.

The development of this system is grounded in a prevalent real-world scenario in the AEC domain – kitchen construction. Subsequent extensions and developments can be extrapolated from this system to other areas of home construction. This system amalgamates the benefits of immersive XR technology with the advantages of digitization and visualization of Digital Twins, aiming for an immersive and intuitive visualization of kitchen construction blueprints. An additional objective for the transition process is to render it entirely paperless, utilizing digitized document management systems.

In the examined use case, the positioning of a kitchen cabinet within a real space, which encompasses a non-orthogonal coordinate system, is investigated. Four preliminary positioning options have been delineated, as illustrated in figure 1: The object to place (blue), a kitchen cabinet, can be positioned either horizontally (H), vertically (V), or parallel (P) to one of the two reference axes. The decision-making process is manual and individualized, allowing flexibility depending on the nature of the object to be positioned.

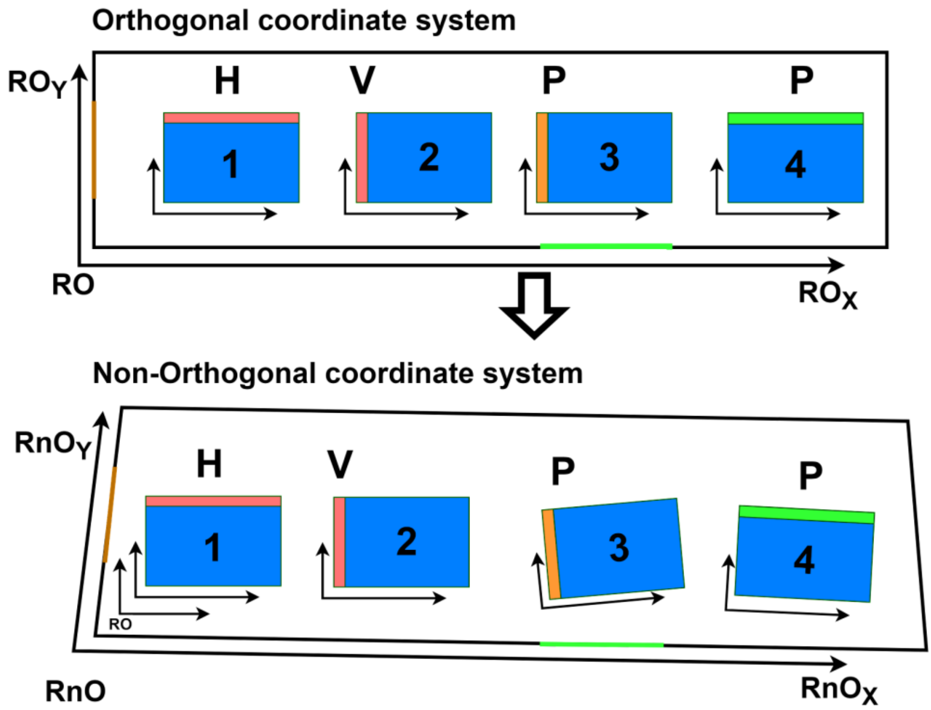

Figure 1. Object orientation methods in orthogonal (top) and non-orthogonal coordinate systems (bottom).

The subsequent diagram depicts the system structure of the assistance system developed within the context of the kitchen construction scenario (see fig. 2). The foundation for applying immersive technologies lies in virtual space planning. Virtual Reality facilitates easier, more effective, and error-free planning for various trades in the AEC sector, especially when working with digital data. In the specific use case, both the kitchen planner and the client can import cabinet models into VR from a server, precisely position them in three-dimensional space, and review the plan within the virtual environment. Subsequently, all pertinent information is relayed back to the server.

Additionally, it is possible to save 3D-Model data or building model data from external databases on the server. The server processes the models to a Unity Asset Bundle and provides it for both applications (VR and AR).

In practice, Augmented Reality can be employed to display Digital Twin information in the real environment. Model data and object information generated during planning are retrieved from the server and projected onto the displays of immersive technologies.

3. Implementation

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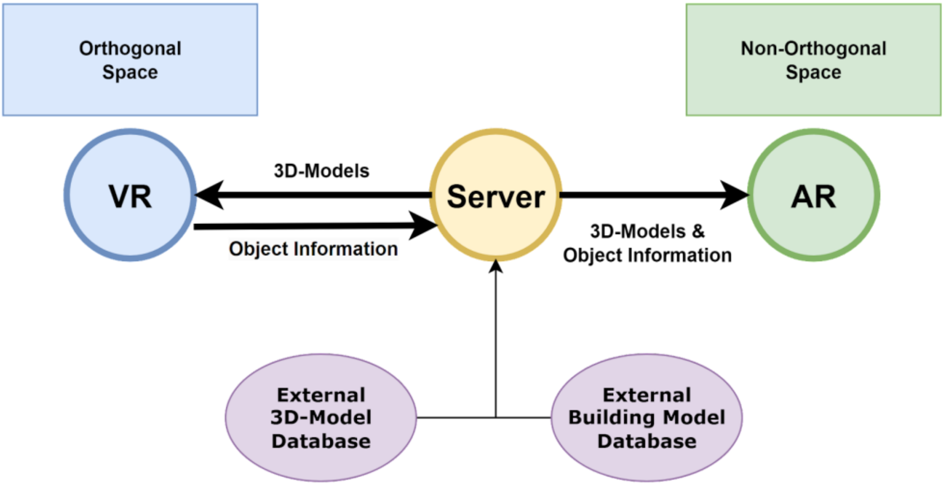

Figure 2. System architecture of concept application.

3.1. Server

A central repository for all types of information was established through a local Express server (.js). This server provides a Unity Asset Bundle to both the VR and AR applications, containing a basic model of a kitchen wall cabinet. Additionally, it enables the VR application to transmit the file generated with object information to the AR application.

3.2. Virtual Reality

The Virtual Reality application was developed on a Windows 11 laptop utilizing Unity software. For the laboratory experiments, a standalone headset from Meta (Quest 2) with inside-out tracking and controller input was employed. By opting for this headset, such as the kitchen builder can work virtually anywhere, harnessing the full potential of immersive technologies (Fig. 3).

The core functionality of the software revolves around importing building data and 3D models from a server and positioning these models within the virtual environment. Upon launching the application, the building model data can be loaded into the headset. In the example, this environment comprises a square room with orthogonal walls/floor (Fig. 4).

Within this environment, a basic model of a wall cabinet can be imported from the server, pre-equipped with fundamental information. Utilizing the user interface, users can create the room coordinate system and object coordinate system through surface detection, subsequently positioning the cabinet precisely as desired. Once the VR planning is complete, all information can be written into a JSON file and stored on the server. This file contains position, rotation, scale, and model properties, ensuring the positioning is unequivocally saved.

Figure 3. Digital planning using VR headset.

Figure 4. VR application for kitchen planning.

3.3. Augmented Reality

The Augmented Reality application is designed to overlay previously planned or created digital data onto the real world. To test the application, a corner space consisting of two white, textureless boards and one brown textured board was created in the laboratory (Fig. 5). The right board was intentionally fixed at an angle of 10° to build the basis for a non-orthogonal coordinate system.

Within the application, the JSON file created in the VR application and the Unity Asset Bundle containing the 3D-model of the cabinet can be loaded from the server. Subsequently, the three planes defining the three-dimensional space must be defined within the AR application. Surface detection and a simple UI are implemented for this purpose, with the underlying principle that the software's usability must be as straightforward as possible to generate added value on the construction site.

Once the three planes are defined, the AR application derives a non-orthogonal coordinate system from them, which serves as the origin for object placement. Figure 6 illustrates the positioned wall cabinet along with the drill positions visualized in pink. There can also be seen a clear offset between the rear wall of the wall cabinet and the wall to which the cabinet is to be attached.

Figure 5. User with AR glasses in test environment.

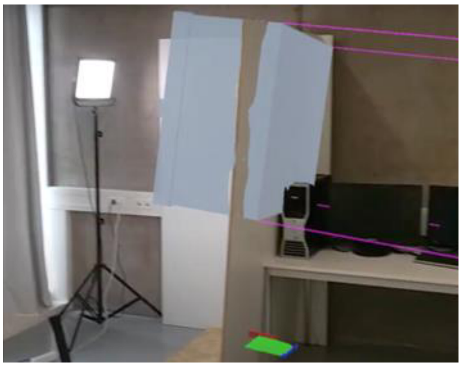

Figure 6. Cabinet visualization in test environment.

4. Conclusion & Future Work

In conclusion, this paper has explored the integration of immersive technologies and Digital Twins within the architecture, engineering, and construction (AEC) industry, focusing on the challenges posed by non-orthogonal coordinate systems in real-world scenarios. Through the development of an assistance system, we have demonstrated a solution approach for transforming object properties based on orthogonal coordinate systems into the non-orthogonal coordinate systems prevalent in reality.

The presented system, exemplified through the context of kitchen planning and construction, harnesses the capabilities of immersive technology and digitization to facilitate intuitive visualization of construction blueprints. By enabling virtual space planning in Virtual Reality (VR) and overlaying Digital Twin information in Augmented Reality (AR), our system empowers stakeholders to collaboratively plan and execute construction projects with greater precision and efficiency.

While our current research represents a significant step towards addressing the challenges of non-orthogonal coordinate systems in the AEC industry, several avenues for future usability remain to be explored. First of all, the current accuracy of the virtual representations in non-orthogonal environments is at the moment not sufficient. In future work, it is necessary to investigate alternative methods for orientation and positioning as well as for environment tracking and to test alternative hardware.

Further steps include more extensive integration of databases, the connection to Building Information Modeling (BIM) and the improvement of the user interface and experience.

Furthermore, the existing concept solely focused on examining the generation and subsequent manipulation of the Digital Twin from the orthogonal coordinate system to the non-orthogonal coordinate system. However, the feedback loop of gathered data originating from a non-orthogonal coordinate system back into an orthogonal coordinate system was entirely overlooked in this study. Yet, this aspect holds significant importance for the prospective utilization of immersive technologies and Digital Twins within the AEC sector in the foreseeable future.

In summary, the ongoing evolution and integration of immersive technologies and Digital Twins offer immense potential to revolutionize the AEC industry by enabling more efficient, collaborative, and informed decision-making processes. By addressing the challenges posed by non-orthogonal coordinate systems, our research contributes to advancing the state-of-the-art in immersive construction technologies and lays the groundwork for future innovations in this field.

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References

[1] V. Drobnyi, Z. Hu, Y. Fathy, and I. Brilakis, Construction and Maintenance of Building Geometric Digital Twins: State of the Art Review, *Sensors*, Vol. 23, 2023.

[2] M. Pregnolato, S. Gunner, E. Voyagaki, et al., Towards Civil Engineering 4.0: Concept, workflow and application of Digital Twins for existing infrastructure, *Automation in Construction*, Vol. 141, 2022, p. 104421.

[3] D.G. Broo and J. Schooling, Digital twins in infrastructure: definitions, current practices, challenges and strategies, *International Journal of Construction Management*, Vol. 23, 2023, pp. 1254–1263.

[4] O.C. Madubuike, C.J. Anumba, and R. Khallaf, A review of Digital Twin applications in construction, *Journal of Information Technology in Construction (ITcon)*, Vol. 27, 2022, pp. 145–172.

[5] S. Kıvrak and G. Arslan, Using Augmented Reality in Construction Project Activities, *Tamap Journal of Engineering*, 2019, p. 64.

[6] R. Bortolini, R. Rodrigues, H. Alavi, L.F. Vecchia, and N. Forcada, Digital Twins' Applications for Building Energy Efficiency: A Review, *Energies,* Vol. 15, 2022, 7022.

[7] Y. Zhao, N. Wang, Z. Liu, and E. Mu, Construction Theory for a Building Intelligent Operation and Maintenance System Based on Digital Twins and Machine Learning, *Buildings*, Vol. 12, 2022, 87.

[8] C. Coupry, S. Noblecourt, P. Richard, D. Baudry, and D. Bigaud, BIM-Based Digital Twin and XR Devices to Improve Maintenance Procedures in Smart Buildings: A Literature Review, *Applied Sciences*, Vol. 11, 2021, 6810.

[9] D. D. Eneyew, M. A. M. Capretz, and G. T. Bitsuamlak, Toward Smart-Building Digital Twins: BIM and IoT Data Integration, *IEEE Access,* Vol. 10, 2022, pp. 130487–130506.

[10] F. Rosa, Digital Twin solutions to historical building stock maintenance cycles, *IOP Conference Series: Earth and Environmental Science*, Vol. 1073, 2022, p. 012013.

[11] H.M. Carlin, P.A. Goodall, R.I.M. Young, A.A. West, An interactive framework to support decision-making for Digital Twin design, *Journal of Industrial Information Integration*, 2024, 41, 100639.

[12] M. Oditallah, M. Alam, and P. Ekambaram, Digital Twins in AEC Infrastructure and Building Management Systems, Proceedings of the 2nd International Conference on Civil Infrastructure and Construction (CIC 2023), 2023, https://doi.org/10.29117/cic.2023.0094.

[13] M. Afzal, R.Y. Li, M. Shoaib, et al., Delving into the Digital Twin Developments and Applications in the Construction Industry: A PRISMA Approach, *Sustainability*, Vol. 15, 2023, 16436.

[14] M. Abu Shamma, P. Pereira, J. Martins, and N. Ramos, Digital Twins for Construction Assets Using BIM Standard Specifications, *Buildings*, Vol. 12, 2022, 2155.

[15] I. Yitmen, S. Alizadehsalehi, İ. Akıner, and M.E. Akiner, An Adapted Model of Cognitive Digital Twins for Building Lifecycle Management, *Applied Sciences,* Vol. 11, 2021, 4276.