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**TECHNOLOGY-RELATED CHALLENGES IN IMPLEMENTING MIXED
REALITY (MR) TECHNOLOGY IN PRECAST CONCRETE PRODUCTION**

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Abstract: Mixed Reality (MR) technology, combining digital information with the real world to provide a better display of information, is gaining a growing interest in the construction industry. Regardless of the benefits of MR systems in construction, the proper implementation of them in each phase of a construction project requires thorough investigation and experimentation. In prefabricated construction the construction phase is divided into two phases: prefabrication off-site and assembly on-site. The workflow of implementing an MR system in off-site manufacturing is quite different. This paper aims to identify some challenges in implementing MR technology in the prefabrication phase by considering precast concrete production as a case study. The paper primarily focuses on MR implementation during the quality control (QC) inspection tasks, as these tasks are concerned with proper visualization and interpretation of the design information. A solid slab production process is first chosen for process analysis, and the main steps from the design to the shipping of a cast unit are described. Then, a brief overview of the MR system is presented, and more specifically, the features of the Trimble Connect application on Microsoft HoloLens 2 are introduced. Accordingly, some of the opportunities for improvement are identified and explained. The identified improvements will help industry practitioners, specifically in precast concrete production, to gain better insight into how and to what extent they can leverage these technologies.

Keywords: Mixed Reality, Precast Concrete, Quality Control, Trimble Connect, Technology Challenges

1 INTRODUCTION

1.1 Background

Precast concrete is cast in a controlled environment for use elsewhere. It is a mobile material that presents a more reliable construction quality and a shorter construction time in comparison with cast-in-place concrete (Richardson 2003). Therefore, it is critical to check and maintain the quality of precast concrete elements during the manufacturing process, after production, and before release for shipping (Ahn et al. 2019). At a concrete cast unit assembly line, workers find the installation locations of cast unit components by carrying and frequently checking the 2D drawings. Currently, the quality control (QC) inspectors check the assembly using the same set of 2D drawings. These tasks are often time-consuming and labor-intensive, which increases the frequency of defects (Wang and Cheng 2017). Subsequently, these defects may require frequent rework requests, which inflicts additional costs on the project (Mirshokraei et al. 2019).

The emerging technology of Building Information Modeling (BIM) provides a collaborative way of multidisciplinary information storing, sharing, exchanging, and managing throughout the entire lifecycle of

the construction project, including the planning, design, construction, operation, maintenance, and demolition phase (Eastman et al. 2008). Although BIM produces a multi-dimensional digital representation of a project's physical and functional characteristics (Mirshokraei et al. 2019), it is often integrated with various visualization technologies. For instance, Augmented Reality (AR) and Mixed Reality (MR) essentially add virtual data to the user's perception of the real world (García-Pereira et al. 2020) and therefore provide an intuitive and interactive visualization of BIM models for users.

A clear definition of MR, AR, and Augmented Virtuality (AV) is provided by (Milgram et al. 1995), where AR refers to augmenting the real background of the operator with virtual contents (e.g., texts, images, videos, and virtual objects). In this definition, AV, as opposed to AR, uses computer graphic images or videos as the background, and they superimpose the real-world elements. However, MR is considered an environment that consists of a blending of real and virtual objects. As shown in Figure 1, AR and AV are both subcategories of MR and are mutually exclusive. For Virtual Reality (VR), lying at the right end of the RV continuum, the environment is considered one in which the operator is totally immersed in a completely synthetic world (Chen et al. 2020). These emerging technologies, usually integrated with BIM, are being adopted in different sectors to facilitate construction management, including site monitoring and inspection (Hyong and Jang 2009), and to improve workplace productivity and quality (Kang et al. 2013).

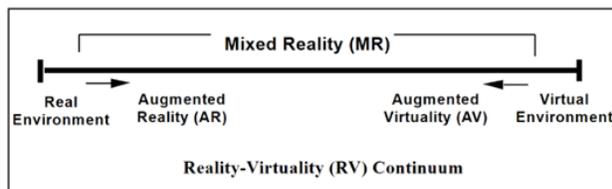


Figure 1: Milgram's Reality-Virtuality Continuum (adapted from Milgram et al., 1995)

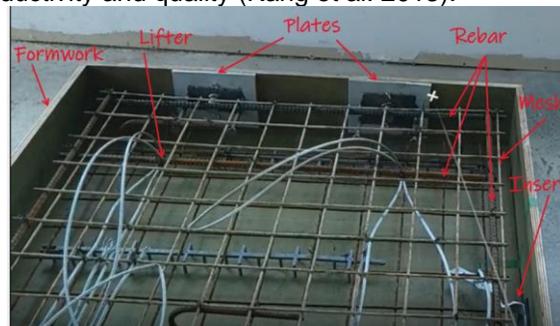


Figure 2: Components of a solid slab cast unit.

1.2 Literature review: AR in construction quality control practices

Researchers have leveraged AR in facilitating inspections on specific tasks in construction. For instance, the inspection of a site to identify safety issues Park et al. (2013), the inspection of steel columns (Shin and Dunston (2009), reinforced concrete Kwon et al. (2014) and Abbas et al. (2020), and tunneling segment displacement Zhou et al. (2017). Additionally, a few researchers developed integrated frameworks for construction project defect management. For instance, Park et al. (2013) developed a framework for proactive construction defect management using BIM, AR, and ontology-based data collection templates. More recently, (Mirshokraei et al. 2019) proposed a web-based BIM-AR quality management system for structural elements at construction sites. In terms of QC of on-site construction, Chalhoub, Ayer, and McCord (2021) also integrated BIM and immersive AR. The proposed system can enable users (project managers and inspectors) to effectively identify large deviations and missing building elements and check whether recently built elements conform to the intended BIM. The literature above mainly focused on QC and inspection tasks for the stick-built on-site construction. Very few research publications focus on the QC inspection of prefabricated construction; instead, the primary focus of these articles was on the post-assembly inspections that often take place on-site. For instance, Portalés et al. (2018) started the design of an AR-based tool for the inspection of prefabricated buildings. The inspection was carried out on-site and after the assembly of prefabricated elements or modules. García-Pereira et al. (2020) designed a collaborative AR annotation tool to inspect prefabricated buildings in the post-assembly phase on the job site. However, Bae and Han (2021) proposed a vision-based approach using a projector-camera system for off-site QC in modular construction.

1.3 Scope and objective

This paper aims to introduce the application of MR technology in precast concrete production. The paper mainly assesses the technology-related challenges in implementing Trimble Connect, an MR application developed for Microsoft HoloLens 2, to superimpose the 3D BIM models of construction elements on reality.

The results will help precast concrete manufacturers to better understand the potential opportunities for improvement in implementation of MR technology in QC processes.

First, this paper describes an overview of the production processes at Strescon, a precast concrete manufacturer located in New Brunswick, Canada. Then, it introduces the components of an MR system. Finally, the paper points out the technology-related challenges in implementing the MR technology in such a production process based on technology tests that were carried out in the precast concrete plant.

2 OVERVIEW OF PRECAST CONCRETE PRODUCTION PROCESS AT STRESCON

Strescon is a concrete company located in Saint John, New Brunswick, Canada. The company produces a variety of concrete products, including structural (e.g., slabs, columns, beams) and concrete architectural elements of buildings, as well as bridge girders, parking garages, maintenance holes, and catch basins. Strescon leverages digitization technologies by modeling the details of building elements in a well-developed BIM computer-aided design software called Tekla Structures. The design information is then conveyed to the shop floor as detailed 2D drawings (blueprints). Using 2D drawings as a reference, precast concrete elements are inspected thoroughly in the controlled environment of the shop floor; subsequently, they are shipped to the site for final assembly.

A typical precast unit normally consists of steel reinforcement bars in a variety of sizes, shapes, and finishing materials, as well as hardware (steel and plastic plates) that is placed in the casting bed before pouring the wet concrete. Additionally, a precast element can contain customized inserts, such as connectors to other steel or concrete elements or reinforcement and lift hooks. These components are also totally or partially submerged by the wet concrete, which is initially held within plywood or steel formwork. After casting concrete cast units at the fixed casting locations, they are lifted by cranes, transferred to the yard, and loaded for storage and shipping. Figure 2 shows an example of a concrete solid slab components prior to being cast.

The design process starts with receiving architectural and structural drawings and then selecting elements in the design that can be precast. The designers at Strescon identify these elements and generate their specialized layout, elevations, and connections. After generating the detailed drawings, the designers clarify any questions and complications with the architect. Then, the design team and detailers proceed with detailing each cast unit in Tekla Structures, put all the details in the model, and generate a drawing that is unique for each cast unit to be cast.

The shop drawings are then transferred to the scheduling department, where the scheduler sets up the pouring schedule in collaboration with the project manager, plant engineer, and plant superintendent. At this point, the 2D drawings are distributed to all people involved in the production process.

The first production floor step is for the carpenters to construct the forms based on the 2D shop drawings, then the QC inspector verifies the formwork and allows the workers to proceed with placing the reinforcement, hardware, and inserts. For example, for a solid concrete slab, they start by installing any required plates or inserts on the bottom face, laying a layer of wired mesh, tying longitudinal reinforcement or crossing bars to the mesh, and then precisely fastening lift hooks at their designated locations based on the drawings.

Depending on the design complication of a cast unit to be cast, the number and timing of QC inspection tasks may vary during assembly. The QC inspector always does a final inspection for the proper installation of all components; when satisfied, they order the concrete. In the concrete batch plant, a lab technician performs concrete sampling and testing before any cast unit is poured and makes sure it complies with the design requirements. The cast unit is then ready for concrete pouring, and once it is properly cast, it is cured for a day or two before it is ready for lifting. The crane operators lift the cast unit and transfer it to the yard, where the final inspector verifies the overall dimensions and surface finishing. The final inspector also makes sure there are no cracks or any conflicts in the cast unit as per the 2D drawings. Once verified, a sticker is attached to the cast unit, which contains important information about that specific cast unit (e.g., cast unit number, weight, job number, and producer). The cast unit is then transferred to the yard, and the yard superintendent prepares the schedule for shipping to the building site.

3 MOTIVATION

Some concrete cast units consist of quite a few reinforcing bars as well as hardware and inserts, and all are tied together on top of each other as shown in Figure 2. The representation of such a complex system on a 2D paper drawing makes it both difficult and time-consuming for the workers to interpret, which can eventually create errors in the assembly process and impose requests for rework.

As opposed to 2D paper drawings, 3D models that are usually modeled in a BIM environment, such as Tekla Structures, represent the different objects in the cast unit with various colors and a 3D view. In contrast, 3D is much more intuitive for people to interpret and use the design information during the assembly process. However, currently, the 3D BIM model is not transferred to the production plant, remains in the detailing department, and only 2D drawings are transferred to the production crew. Although people can return to the office, open a Tekla Structures model and look at the model, it is time-consuming to leave the workplace, load the model in the office and come back. Moreover, the user may have difficulty recalling what they saw in the office, and unintended misinterpretations may happen. Therefore, we are motivated to efficiently transfer the design information generated in the BIM model, load this model for use in the shop, and be able to superimpose the virtual 3D hologram of the model on real objects to thereby quickly and intuitively identify any defects in the cast unit to be cast.

Although MR technologies such as Trimble Connect provide a variety of features that can facilitate the visualization of the BIM model in the production line, the implementation of this technology in a manufacturing plant is still in its infancy. The section below first introduces the MR technology in construction, followed by section 5, which explains some technology-related challenges that would make the Trimble Connect application more efficient in a prefabricated plant.

4 INTRODUCING MIXED REALITY (MR) TECHNOLOGY IN PRECAST CONCRETE

A recently published literature review article by Cheng et al. (2020) states that a complete MR system requires the following components: (1) spatial registration, (2) display, (3) user interaction, (4) data storage, and (5) multiuser collaboration. Spatial registration combines real and virtual environments by calculating the corresponding relation of both virtual and real-world coordinate systems and is divided into two categories of marker-based (e.g., 2D image recognition, and 3D object recognition), and markerless (Global Positioning System, Wi-Fi, Radio Frequency Identification, Simultaneous Localization, and Mapping, etc.). Moreover, MR experience can be displayed in various forms, including desktop, projection, hand-held, and head-mounted display (HMD). Additionally, users can interact through a combination of any of the following forms, including keyboard and mouse, touchscreen, controller, camera/motion sensor, and voice sensor. Finally, in general, an MR device may use local or external storage (Cheng et al. 2020).

The user interface (UI) of MR systems plays an important role in choosing an MR device for industry application. The UI refers to the user experience provided by the display method and the convenience of the interaction method Cheng et al. (2020). Recently, construction industry practitioners showed interest in mobile display devices such as tablets/smartphones and HMDs as opposed to heavy desktop displays. In terms of interaction, hand-held display devices such as tablets provide a portable version of desktop display, where practitioners can interact with the MR content simply by using different touchscreen gestures. However, with hand-held devices, the user is required to hold and touch the device when using the MR application, leading to difficulty for them to perform other tasks at the same time. Compared to hand-held devices, the practical advantage of HMDs is the ability to free users' hands by providing eye gaze interaction and voice command features, as well as maintaining a partially immersive environment for users as opposed to non-immersive forms of display (e.g., desktop, hand-held, projection). Therefore, HMDs have potential to help users interact more intuitively with the virtual content and be able to use their hands during their MR experience.

The first see-through HMD was developed by Ivan Sutherland at Harvard (E. Sutherland 1968). Recently, Microsoft released a head-mounted device named HoloLens (Microsoft 2019), that connects users with remote colleagues in real-time and provides hand tracking tools in addition to its head-mounted display. In 2019, Google introduced the Glass application (Google 2021) to the market with an AR function. Magic Leap is about to release its Magic Leap 2 as the latest MR HMDs in 2022 (Magic Leap Inc. 2022). However, these MR HMDs are not particularly customized for construction industry to meet all its requirements.

Accordingly, technology developers in the construction industry are working on introducing more customized forms of HMDs so that construction teams can view 3D BIM models and safely collaborate while at the construction site. For instance, Trimble XR10 with HoloLens 2 is the first device created with the Microsoft HoloLens Customization Program. The device integrates a HoloLens 2 into a hard hat to produce a safety-first MR solution (Microsoft 2022). Additionally, in 2021, XYZ Reality introduces the Atom, a powerful, custom-built engineering tool combining a construction safety headset, AR displays, and in-built computing power (XYZ Reality Ltd. 2022).

This paper focuses on the technical and useability aspects of the Trimble XR10 with HoloLens 2. The product is one of the MR systems that has been frequently leveraged by the construction industry and academics in the last two and a half years since it was first released in late 2019. Moreover, this paper focuses on the Trimble XR10 MR system in a manufacturing environment, such as a precast concrete plant.

The Trimble Connect for HoloLens 2 (TCH) application runs on a Mixed Reality Windows platform developed by Microsoft. The 3D viewer application called Trimble Connect can be installed on Trimble XR10 for HoloLens 2 device (Figure 3) to load the IFC files of a BIM model. BIM Models are usually created in Trimble BIM software package, e.g., Tekla Structures. Some of the most important features of TCH include Trimble Connect Cloud Platform Integration, Real-World Model Alignment Tools, Measurements within and between real and virtual environments, Sequencing tools for step-by-step guidance through sequence model groups, etc. (Trimble 2019), as shown in Figure 4.

5 TECHNOLOGY-RELATED CHALLENGES IN PRECAST CONCRETE PRODUCTION

The functionality of the TCH application and the XR10 device at a construction site is slightly different from its functionality in an off-site manufacturing plant. This is, for one, due to the fact that usually, BIM models represent the 3D visualization and information model of a building or a construction project on-site, whereas, in prefabricated construction, the building components are segregated into modules or structural elements (e.g., slabs, beams, wall panels, etc.), and designed with required connections in a whole building model accordingly. Correspondingly, this section discusses some of the considerations that precast concrete manufacturers may want to review before attempting to implement the technology in their production. The following opportunities for improvement to the interface were identified based on tests that were done in the Strescon manufacturing plant with Trimble XR10 for Microsoft HoloLens 2.



Figure 3: Trimble XR10 for HoloLens 2 device (Trimble 2019)



Figure 4: Radial menu showing different features of the TCH application

5.1 The orientation of the 3D model in the shop floor

As described previously in this paper, each cast unit is an element of the whole building, and therefore its orientation is based on its corresponding location and orientation in the building on-site. However, the cast units will be in a different orientation on casting bed. This is due to the logistic requirements, from the first steps in production to yard handling, storage/blocking, and shipping. Therefore, the location of a lifter is designed in the cast unit, taking into account all mentioned criteria. Then the cast unit bed frame is laid out in the shop based on the size and availability of working tables. For instance, Figure 5 shows a 3D model of a staircase landing. As depicted, the lifters are shown at the bottom of the model. The top of this cast unit

will be the bottom of the staircase landing in the building on-site. However, to construct the cast unit frame, assemble its components, pour concrete, and then lift the cast unit, it needs to be flipped over and laid out upside down on the casting bed, as shown in Figure 6. This is also due to surface treatment considerations for the top surface of the staircase landing, which is actually the bottom face of the casting bed. The problem, in this case, is the extra work required (in comparison with on-site use of TCH) to create the QR code marker, they need first to modify the model positioning and correlate the model orientation with its orientation in the shop. Accordingly, extra tasks are imposed on the workflow of creating and positioning the QR code markers for each single concrete cast unit.

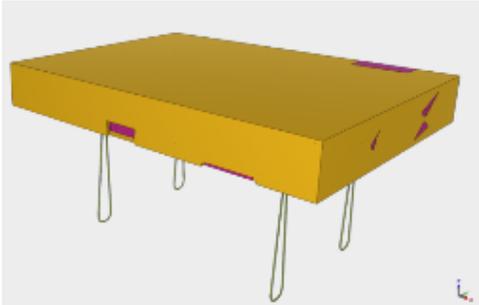


Figure 5: A staircase landing depicted based on its original orientation in the building on-site

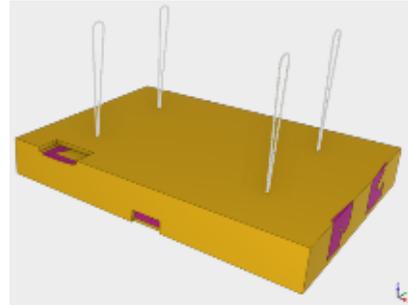


Figure 6: A staircase landing depicted based on its corresponding orientation on the casting bed in the shop floor

5.2 Spatial registration with QR code markers

Trimble Connect uses a marker-based alignment tool to provide a relatively precise superimposition of the 3D hologram of the model onto the real cast unit. However, the markers must be attached on a flat vertical surface. Horizontal or sloped surfaces are not supported by the XR10. Therefore, for instance, the markers cannot be attached horizontally on the bottom surface of the cast bed for spatial registration purposes. Besides, the QR code markers must be printed in 100% scale on a piece of paper, which covers a 6.5 x 6.5 square inches area on the surface. Figure 7 shows an overall view of a reduced-size QR code marker created on Trimble Connect for Web. This requires a flat surface that can fit a 6.5x6.5 inches; however, in some cases, the formwork may be less than 6.5 inches high. Therefore, extra work is required to construct and precisely position a flat surface with an adequate area for the QR code marker. Figure 8 shows an example of a QR code marker attached to the surface of the cast unit formwork.



Figure 7: An overall view of a QR code marker created on Trimble Connect for Web

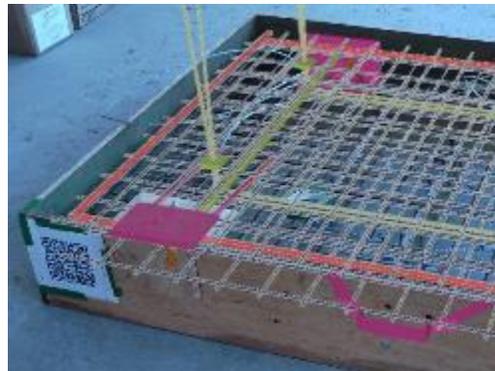


Figure 8: An example of a QR code marker attached vertically on the surface of the cast unit formwork

5.3 Rotational discrepancies between the virtual model and reality

In a geospatial context, drift error occurs when the model drifts away from the original anchored position over time, thereby shifting the entire model away from its correct alignment with the site (Patton 2020). In the current TCH application, over a distance of 50 meters (160 ft), the drift was found to be around 0.19 m. To mitigate the effects of drift errors, Trimble suggests that users keep the radius of their MR work area

limited to less than 50 m. For working beyond these limits, it is suggested that the users realign the model every 50 m (Patton 2020). Now, despite this suggestion regarding drift, small rotational discrepancies are also observed in MR experiences with large cast units, even if the user is fairly close to the QR code marker. This might be due to the inability to have a precise spatial registration based solely on one small QR code marker. Accordingly, in February 2021, Trimble released the new version, TCH 3.3, in which users can load the model that contains multiple markers and align it in the physical space by scanning one or many markers (Ceemalapati 2021).

However, using multiple markers might not be the only solution to eliminate these rotational discrepancies. The arrangement of the QR code markers around the cast unit frame also plays an effective role. For instance, the question of how many markers would be suitable for a precise alignment of a large cast unit model, or what is the suitable method of creating a network of QR code markers for a precise alignment. Therefore, several tests are required to identify the number and location of QR code markers required for a precise alignment.

The other issue that might affect the rotational discrepancies of QR code markers is the squareness of the surface on which QR code markers are attached. Assuming that QR code markers are attached to the formwork of the cast unit, the skewness of the formwork may influence the model alignment. Normally, formwork is constructed as square as possible; however, this does not mean 100% as designed. Formwork measurements can be slightly off, although only if they are within the tolerance based on the PCI manual (PCI Committee on Tolerances 2000). Attaching the QR codes on skewed surfaces (e.g., cast unit formwork), no matter how slight the skewness is, may cause small rotational discrepancies. In other words, when the user looks at the cast unit from the other side, a gradual shift along any of the axis (i.e., x, y, or z axis) may appear, as shown in Figure 9. In the TCH application, users can realign the model manually using the fine tune tool, as shown in Figure 10 (Ceemalapati 2021). This tool helps users move or rotate the model in each direction; the usability of fine tune tool needs to be assessed thoroughly as it requires extra training, tasks, and effort to the workflow of the marker alignment process.

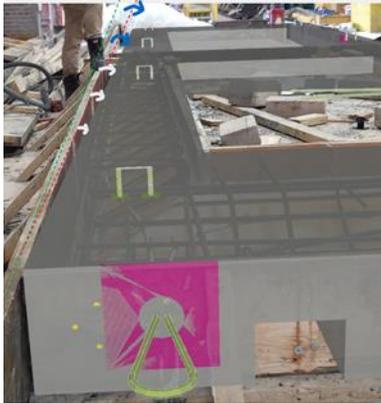


Figure 9: Rotational discrepancies between the model and reality in a large-sized cast unit

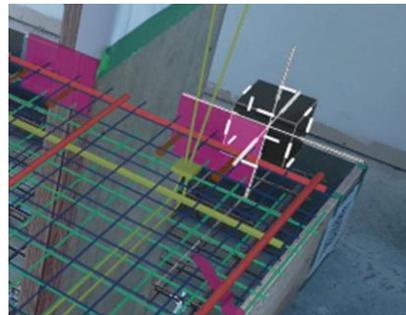


Figure 10: Working with the fine tune tool to manually align the model with reality

5.4 The usability of snapping tool

Within the TCH application, the user can point to two desired virtual objects (e.g., two pieces of rebar), pick the objects using a hand gesture, and measure the corresponding distance between the objects, see Figures 11 and 12. However, the case is different when a user wants to measure the required cover for reinforcement to the formwork, for instance. To determine the actual cover measurement, the user needs to pick the edge of the cast unit and the target rebar inside the cast unit; however, snapping to the edge of the cast unit model requires a lot of effort for the user to perform properly. To facilitate the usability of the snapping tool, the cast unit formwork needs to be modeled so that the user can pick the edge of the formwork as a recognizable object and pick the desired rebar for a proper cover measurement. The 3D BIM model of

each cast unit is exported in Industry Foundation Class (IFC) format from the 3D BIM model of the whole building. Then the IFC file of the cast unit model can be loaded on any of the platforms for Trimble Connect application (i.e., Windows, Mixed Reality Windows on HoloLens, Web, and Android/iOS). However, in practice, in the BIM model of the building, no formwork is modeled, and the cast units are designed based on their demolded phase after production. Moreover, modeling the formwork for each cast unit poses a tedious and time-consuming workflow for the detailing department.



Figure 11: Snapping real objects in TCH



Figure 12: Snapping a real object and a virtual object in TCH

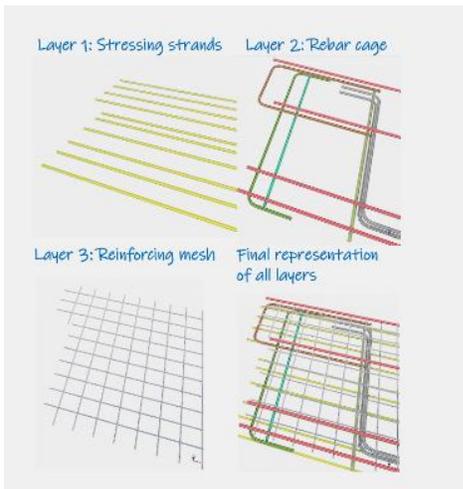


Figure 13: An example of using the sequence tool on Trimble Connect for Windows. Reinforcing objects are classified and shown by color.



Figure 14: A representation of reinforcing objects in the TCH application when using the sequence tool. All objects shown in one color regardless of their classified color in the design model.

In cases like this, the potential solution is to use the “real to model” measurement tool in the TCH application and pick the real constructed formwork and the corresponding virtual rebar, making sure that the cast unit model is perfectly aligned within the real formwork. Figures 11 and 12 demonstrate the snapping function in TCH. Another challenge, in this case, appears when the user tries to identify the discrepancies between the as-built condition and the as-designed model (e.g., the distance between real rebar and its corresponding virtual rebar). The snapping tool does not perfectly pick the real rebar, as it is too small to be picked. Instead, it is more likely to snap to a larger object (e.g., the bottom of the cast unit formwork). To sum up, the challenges in snapping tools limit the functionality of the measurement tool, which is in fact one of the crucial tasks in the QC inspection of a cast unit.

5.5 Colored representation of the rebar cage is unavailable when using sequence tool

In the TCH application, a sequence tool is designed to give users a walk-through of the steps involved in the construction of a model from scratch in a specified order (Trimble Inc. 2021). Users first need to create

their desired sequence using the sequence tool on Trimble Connect for Windows, and then they will be able to load the sequence in the TCH application. Figures 13 and 14 show a few sequence steps on Trimble Connect for Windows and on Trimble Connect for HoloLens 2, respectively. As shown, the concrete reinforcing components (e.g., rebar, strands, and mesh) are designed in different colors based on their assigned class color in Tekla Structures. This color classification allows designers to distinguish the object properties in the design process more manageable. However, the color representation of the reinforcing components is not visible when the sequence tool is launched in the TCH application. This limits the proper representation of sequence steps when a user tries to superimpose the sequence on the real cast unit. The sequence tool can help the QC inspectors better identify the order of reinforcement layers that need to be assembled in the cast unit and, therefore, identify any conflicts. However, the lack of color visibility, in this case, limits the user's ability to make the most of the sequence tool's functionality.

6 CONCLUSION AND FUTURE STEPS

Leveraging the benefits of MR technology is gaining more interest than ever in the construction industry. However, properly implementing this technology, and ensuring it meets the requirements and expectations of industry practitioners, may result in some challenges. Specifically, the challenges may appear where the construction process is different from a conventional on-site construction and is instead in an off-site manufacturing environment. This paper investigated some of these challenges, particularly in the process of testing an MR system (i.e., the TCH application) in the QC inspection tasks of precast concrete production: 1) The orientation of concrete elements on-site, in some cases, varies with the orientation of its corresponding cast unit in the precast concrete shop. This adds extra workflow create a QR code marker (i.e., the users need first to reposition the model based on its orientation in the shop floor). 2) Spatial registration with QR code markers requires a flat vertical surface for the QR code marker to attach. A flat vertical surface, which is also within a reasonable distance to the cast unit (ideally attached to the formwork), may not always be accessible on the working tables in the shop. Therefore, additional measures are required to perform the spatial registration of the model correctly (e.g., constructing a vertical surface that can be easily attached and detached to each cast unit and making sure it is perfectly square). 3) In large-sized cast units, the question of how many QR codes and in what locations they should be attached to the cast unit is another challenge in the implementation process. A preliminary test indicates the need for at least 3 QR codes at a maximum distance from each other around the cast unit. 4) Another challenge appears when the user needs to snap objects in the model for measurement purposes. Snapping small objects can not be performed appropriately as some objects such as rebar and mesh are too small and are not easily selected. Consequently, the user may have difficulty selecting the right objects in the model when doing a QC inspection task. 5) Finally, in cases where the user launches the sequence tool in the TCH application, the color representation of the rebar cage is not available, and that makes it difficult for the user to distinguish each sequence step. To sum up, these challenges are opportunities for improvement both for the technology developers to improve the features of the MR system and for the industry practitioners to have an insight into the measures they should consider before implementing the MR technology. Future work is needed to customize the implementation of an MR system by performing tests both on users to identify the usability of the application features and on the real cast units in the shop to eliminate the spatial registration challenges.

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8 REFERENCES

Abbas, Ali, JoonOh Seo, and MinKoo Kim. 2020. "Impact of Mobile Augmented Reality System on Cognitive Behavior and Performance during Rebar Inspection Tasks." *Journal of Computing in Civil Engineering* 34 (6): 04020050.

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- Ahn, S, S Han, and M Al-Hussein. 2019. "2D Drawing Visualization Framework for Applying Projection-Based Augmented Reality in a Panelized Construction Manufacturing Facility: Proof of Concept." *Journal of Computing in Civil Engineering* 33 (5).
- Bae, JuHyeon, and SangUk Han. 2021. "Vision-Based Inspection Approach Using a Projector-Camera System for Off-Site Quality Control in Modular Construction: Experimental Investigation on Operational Conditions." *Journal of Computing in Civil Engineering* 35 (5): 04021012.
- Ceemalapati, Sree. 2021. "Trimble Connect for HoloLens 3.3 | Release Notes." Trimble. February 2021.
- Chalhoub, Jad, Steven K. Ayer, and Kieren H. McCord. 2021. "Augmented Reality to Enable Users to Identify Deviations for Model Reconciliation." *Buildings*, no. February.
- Chen, Keyu, Jianfei Yang, Jack C.P. Cheng, Weiwei Chen, and Chun Ting Li. 2020. "Transfer Learning Enhanced AR Spatial Registration for Facility Maintenance Management." *Automation in Construction* 113 (July 2019).
- Cheng, Jack C. P., Keyu Chen, and Weiwei Chen. 2020. "State-of-the-Art Review on Mixed Reality Applications in the AECO Industry." *Journal of Construction Engineering and Management* 146 (2): 03119009.
- E. Sutherland, Ivan. 1968. "A Head-Mounted Three Dimensional Display." In *Fall Joint Computer Conference*, 5:391–94.
- Eastman, Chuck, Paul Teicholz, Rafael Sacks, and Kathleen Liston. 2008. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*. John Wiley & Sons, Inc. Hoboken, New Jersey: John Wiley & Sons, Inc.
- García-Pereira, I, C Portalés, J Gimeno, and S Casas. 2020. "A Collaborative Augmented Reality Annotation Tool for the Inspection of Prefabricated Buildings." *Multimedia Tools and Applications* 79 (9–10): 6483–6501.
- Google. 2021. "Discover Glass Enterprise Edition." 2021. <https://www.google.com/glass/start/>.
- Hyoung, Do, and Won-suk Jang. 2009. "Automation in Construction Utilization of Ubiquitous Computing for Construction AR Technology." *Automation in Construction* 18 (8): 1063–69.
- Kang, Shih Chung, Ying Chieh Chan, Chiao Yun Lu, Jihn Sung Lai, and Tim Hau Lee. 2013. "Development of Virtual Equipment: Case Study of the Venturi Tube Experiment." *Journal of Professional Issues in Engineering Education and Practice* 139 (4): 281–89.
- Kwon, Oh Seong, Chan Sik Park, and Chung Rok Lim. 2014. "A Defect Management System for Reinforced Concrete Work Utilizing BIM, Image-Matching and Augmented Reality." *Automation in Construction* 46: 74–81.
- Magic Leap Inc. 2022. "Magic Leap 2 The Most Immersive AR Platform for Enterprise." Magic Leap Inc. 2022.
- Microsoft. 2019. "HoloLens 2." Microsoft. 2019. <https://www.microsoft.com/en-us/hololens/hardware>.
- . 2022. "Trimble XR10 with HoloLens 2." Microsoft. 2022.
- Milgram, Paul, Haruo Takemura, Akira Utsumi, and Fumio Kishino. 1995. "Augmented Reality: A Class of Displays on the Reality-Virtuality Continuum." In *Telemanipulator and Telepresence Technologies*, 2351:282–92. SPIE.
- Mirshokraei, Mehrdad, Carlo Iapige de Gaetani, and Federica Migliaccio. 2019. "A Web-Based BIM-AR Quality Management System for Structural Elements." *Applied Sciences (Switzerland)* 9 (19).
- Park, Chan-Sik Sik, and Hyeon-Jin Jin Kim. 2013. "A Framework for Construction Safety Management and Visualization System." *Automation in Construction* 33: 95–103.
- Park, C.-S., D.-Y. Lee, O.-S. Kwon, and X. Wang. 2013. "A Framework for Proactive Construction Defect Management Using BIM, Augmented Reality and Ontology-Based Data Collection Template." *Automation in Construction* 33: 61–71.
- Patton, Nathan. 2020. "Precision and Accuracy of Holograms in Trimble Connect for HoloLens."
- PCI Committee on Tolerances. 2000. *Manual for Quality Control for Structural Precast Concrete Products*.
- Portalés, C, S Casas, J Gimeno, M Fernández, and M Poza. 2018. "From the Paper to the Tablet: On the Design of an AR-Based Tool for the Inspection of Pre-Fab Buildings. Preliminary Results of the SIRAE Project." *Sensors (Switzerland)* 18 (4).
- Richardson, John. 2003. "21 - Precast Concrete Structural Elements." In *Advanced Concrete Technology*, edited by John Newman and Ban Seng B T - Advanced Concrete Technology Choo, 3–46. Oxford: Butterworth-Heinemann.
- Shin, Do Hyoung, and Phillip S Dunston. 2009. "Automation in Construction Evaluation of Augmented Reality in Steel Column Inspection." *Automation in Construction* 18 (2): 118–29.
- Trimble. 2019. "Trimble XR10 with HoloLens 2."
- Trimble Inc. 2021. "Trimble Connect for Windows User Guide: Using Sequences." Trimble Connect. July 21, 2021.
- Wang, Qian, and Jack C P Cheng. 2017. "Automated Estimation of Reinforced Precast Concrete Rebar Positions Using Colored Laser Scan Data" 32: 787–802.
- XYZ Reality Ltd. 2022. "Engineering-Grade Augmented Reality." XYZ Reality Ltd. 2022.
- Zhou, Ying, Hanbin Luo, and Yiheng Yang. 2017. "Implementation of Augmented Reality for Segment Displacement Inspection during Tunneling Construction." *Automation in Construction* 82: 112–21.
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