Constructible Design for Off-site Prefabricated Structures in Industrial Environments: Review of Mixed Reality Applications

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Abstract –

Studies have shown that early design finalization is important for projects utilizing Off-site Prefabrication and final assembly on site. Freezing engineering design at an early stage has various advantages such as streamlined manufacturing and timely transportation to site as well as timely deployment of adequate resources on site for assembly. However, it is very important to ensure correct design that can be transported, assembled and erected on site in Brownfield Industrial environments. EPC (Engineering, Procurement and Construction) companies have traditionally adopted a "Suit-to-site" approach, where structural members are largely tailored to fit at the site in order to avoid rework. This approach requires mobilization of a large number of resources to site and consumes a lot of time for the fabrication and installation works. Mixed Reality (MR) systems can be used to ensure correct design which can then ensure accurate fabrication and quick installation of structures. This paper reviews the applicability of different MR systems to the concept of Constructible Design for early design finalization in a brown-field Industrial engineering environment. Structural design review is correlated to different tasks of construction that must be performed on the field. Applicability of different components of MR systems is then evaluated for these tasks. This paper finally concludes with selection of suitable MR systems for deign evaluation based on correlation between construction work tasks and components of MR systems.

Keywords –

Design Validation; Augmented Reality; Design Review; Assembly of Structures; Off-site Prefabrication; Constructability Review; Industrial Structures

1 Introduction

Construction in brownfield industrial environments is largely a complex affair due to the large number of variables presented by a pre-existing industrial facility. The rapid shift in construction technology towards prefabrication and assembly at site requires a shift in focus to early design finalization [1]. Any modifications to design at a later stage cannot be incorporated as such changes will lead to major impacts to schedule or budget or both. This is largely due to the fact that changes to a prefabricated module will result in changes to connected modules. Moreover, making modifications or changes at site is time consuming as well as labour intensive - ultimately a costly exercise. In order to ensure a design, a Mixed Reality system could prove to be instrumental with review of a design before its fabrication.

Mixed Reality is a widely accepted term that was first proposed by Milgram et al. and can be expressed as a spectrum with any form of hybrid combination of Virtual Reality (VR) and Augmented Reality (AR) [2] (Fig. 1). Because of its evolution, MR today not only concentrates on graphics and displays but also incorporates various interactions with users including gesture recognition and spatial registration (interaction with surrounding environment). Owing to rapid development of technology in the past decade, differentiation between AR and MR can often be difficult [3]. For this reason, both AR and Augmented Virtuality (AV) - including use of AV on desktop-based systems, are considered as MR for the purpose of this review and their applicability to Brownfield Industrial Construction.

Construction in Brownfield industrial environment, especially for addition of a new facility, expansion of existing plant or re-purposing the process in an existing plant is described as challenging at best. One of the most critical tasks in such a project is to erect structures suited to site conditions in an existing facility within imposed time constraints. Such activities can be made more accurate, quicker and safer if all the structures related to

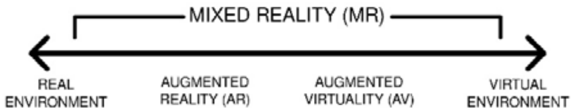

Figure 1. Reality-Virtuality Continuum.
Source: Milgram el al[2]

these activities can be accurately estimated, fabricated off-site and delivered to site for assembly or direct installation.

This paper explores the applicability of Mixed Reality (MR) technologies for early design finalization. The aim of such early design finalization is to arrive at an acceptable level of design accuracy which in turn can facilitate timely fabrication, delivery and installation of tie-in structures thereby avoiding any rework or fabrication work at site. This paper concludes by recognizing See-through Head mounted devices as the most suitable MR systems that can be used to evaluate different work tasks in construction, thereby ensuring a correct design.

2 Review Methodology

For the purpose of review, this paper has been divided into the following sections:

1. Mixed Reality applications
2. Constructability of a Structure and enhancement with MR systems

While discussing the evolution of MR applications, tabulation of features as well as advantages and shortcomings of the more recent and relevant applications has also been done. The purpose of this classification is to then correlate applications with principles of Construction (Work Tasks) in section 4.3. Recommendation of suitable MR systems to reach early design finalization with respect to various facets of design is presented in Section 5.

3 Mixed Reality Applications

3.1 Literature review of work done on Mixed reality in Industrial Construction

Since its conception, Mixed Reality (MR) has been developed to facilitate human-computer interaction. MR has been implemented in devices using various technologies – right from Desktop based applications to Wearable Head Mounted Displays (like the Microsoft Hololens and Google Glass [4] [5]) being used in the Architecture, Engineering, Construction and Owner-operated (AECO) industries.

When it comes to Industrial Construction, Mixed reality has seen applications in areas such as Inspections, Planning and Monitoring of construction work, equipment and material management, training of skilled workers and implementing certain safety management systems. However, MR can also be used to facilitate design reviews of critical structural elements.

Shin et al. reviewed the applicability of Augmented Reality (AR) to various construction tasks in 2008 [6]. The mapping of various construction work tasks and activities to the relevant features of AR systems led to identification of areas where AR can be applied to enhance the performance of activities in their research. Tracking of materials on site for increased efficiency by combining AR with WLAN and GPS information was presented by Behzadan et al. in 2008 [7].

Similarly, Rohani et al. demonstrated the use of Mixed Reality (MR) for development of 4D-CAD based construction management systems [8]. Such systems enable construction managers to visualize the design of a structure along with the reality at a glance and are able to translate this information to provide a powerful management platform for planning and controlling projects. Behzdan et al. explored the use of MR to locate computer-generated graphical information in real world environments [9]. Such information spatially located relative to the user can assist in the performance of various complex engineering tasks.

MR is also being used to train workforce and make some of their tasks easier and/or more efficient. Hou et al. conducted an experiment to analyze the benefits of using AR to train students with no prior experience of piping assembly or using AR [10]. They concluded that AR could increase efficiency, reduce errors as well as optimize cost. Wang et al. conducted research on operating simulation system for tower crane based on VR [11].

Another area where VR has facilitated improvement is engineering reviews - In 2017, Berg et al. reviewed the potency of using VR for early decision making on an industry-based case [12]. The visualization aspect of using VR allowed the design team to make decisions ahead of usual stages and saved them a lot of effort on prototyping. In this aspect, production on assembly lines is akin to that seen in a structural fabrication shop. VR and AR can thus be utilized to foresee and tackle assembly related challenges during design stage rather than do that in field during erection stage. Another research on the same lines by Freeman et al. confirms that use of VR for reviews during design stage can lead to significant improvement in participants ability to understand the geometry of the model correctly, confidently, and quickly, as well as in participants ability to correctly and confidently understand the implications of a proposed design change [13].

These researches are now being applied in field in various areas of construction with the help of new technological platforms such as Mobile devices (including Mobile Phones and tables), Google Glass, Hololens and Trimble Sitevision [14].

3.2 Understanding MR systems

In order to understand MR systems, it is necessary to understand their components. A recent state-of-the-art review of MR applications in AECO industries by Cheng et al. has a sufficient categorization of components for analysis [3]. The basic categorization of components falls into the following categories – Display, Spatial Registration, User Interaction and Storage.

For the purpose of this review, we will attempt to categorize the components of the following devices:

- Head-mounted See-through displays (likes of Hololens and Google Glass)
- Head-mounted immersive VR displays (like Occulus Rift, Samsung HMD Odyssey Windows Mixed Reality headset)
- Portable Cellphones and Tablets

Table 1 summarizes the categorization of these components. It can be seen from this tabulation that some devices have certain advantages in a particular area that renders them feasible for particular application. For example, Cell phones or Tablets can be used very effectively for outdoor location-based tracking but lack immersive experience which can be crucial when trying to finalize a design and ascertain its feasibility [15]. Similarly, when reviewing a particular structural design which has multiple engineering interfaces involving multiple approving authorities, mobile devices may not make as much sense as use of an immersive display that allows for group interaction - like a Cave display. Another option for group interaction in field would be to use multiple Mixed reality see-through HMD devices like Hololens that can be paired together for group interactions.

3.2.1 Display:

The most important aspect a Mixed Reality system interacts with a user is the way it displays the graphics along with the real-time visuals. Taking into account the devices considered for this review, displays are categorized into the following types:

- ***VR Displays:*** VR displays are usually either Head mounted or immersive CAVE displays connected to a computer and usually used for VR reviews. These displays can be instrumental in remote design reviews also.
- ***Portable Displays:*** Portable displays are actually integrated into portable devices such as Mobile Phones and tablets. These displays employ either LCD or LED displays integrated in the device.
- ***Immersive see-through HMDs:*** Head mounted displays originated back in the early 1980s. The latest development of display technology allows graphic images projected on transparent glass. This gives the user an immersive experience, making virtual graphics seeming as if real, from user's perspective.

3.2.2 Spatial Registration:

Spatial Registration is a feature of MR systems that facilitates "Realistic" experience for the user. The MR system needs to project correct graphics in front of the user's eyes with respect to their motion in real world or in accordance with their commands on a controller device. In order to do this, the device needs to "learn" about its surroundings. This is known as Spatial Registration. The types of spatial registration methods are as follows:

- ***Marker Based:*** Marker-based Spatial registration utilizes a static image also referred to as a trigger photo that a the device scans in order to calibrate its position from the trigger image [16].

Table 1. Categorization of MR System Components

Device Category	Display	Spatial Registration	User Interaction	Storage
See-through HMDs	- Immersive HMD - Immersive Graphic over transparent glass	- Marker Based - Marker-less	- Gestures - Joystick / Controller	- On-board Storage - Cloud storage access
VR Displays	- Immersive HMD	- Marker-less	- Joystick / Controller	- No on-board storage
Portable Cellphones and Tablets	- Portable LCD	- Marker Based - Marker-less - GPS based location tracking	- Touchscreen	- On-board Storage - Cloud storage access

- ***Marker-less:*** Marker-less spatial registration works by accurate measurements of the 6DOF camera pose relative to the real world and matching point features in the current image frame to two spatially separated reference images [17]. This eliminates the necessity for any marker for spatial registration.
- ***GPS Based:*** GPS based spatial registration uses the global position and 3-Dimensional orientation of an MR system in an outdoor environment for calibrating the superimposition of 3D graphics with respect to the real world. This is made possible by use of a GPS tracker and 3DOF orientation tracker in conjunction [9].

3.2.3 User Interaction

In the previous sections we saw how virtual images aligned with the real world. Taking this functionality a step further, MR systems allow the interaction of virtual objects with the real world to simulate real-world collisions, occlusions and interactions [18]. In the context of construction, this interaction can be very helpful when evaluating feasibility of a design or simulating construction or assembly sequences. Modes of interaction available on devices are:

- ***Touch Screen:*** Predominantly used on Mobile MR systems such as Cellphones or Tablets, a Touch Screen allows user to interact by clicking on the projected image on the device. Various gestures such as pinch, pan and rotation can help to interact with the available information.
- ***Joystick or Controller:*** Joysticks or controllers can be used with most MR systems. However, for immersive HMDs, a controller becomes necessary if the display is not transparent (i.e. not see-through) as interactions with real world will not be very intuitive.
- ***Hand Gestures:*** See-through HMDs have a distinct advantage when it comes to user interaction. Combining the marker-less image tracking with the see-through display, the device is able to recognize users' hand gestures and allows interaction of the Virtual Graphics with the real world by executing commands relayed by hand gestures.[4]

3.2.4 Storage

Access to storage on a MR system can enhance its usability in construction industry. This feature enables the device to function independently.

- ***On-board Storage:*** If the device has storage built-in, it is called on-board storage. With on-board storage, virtual models can be directly loaded onto the device and can be accessed in field readily.
- ***Cloud Storage:*** Devices that can access internet via cellular network can use virtual models and other data stored on cloud drives. A clear advantage in this case would be the ability to use a single device on multiple sites as models need not be loaded on to on-board storage or ability to access very large models that are too big for on-board storage drives.

4 Constructability of a Structure and enhancement with MR systems

4.1 Design in a Brownfield Environment

In the context of industrial construction, a brownfield construction site is a site which is either located within an operational facility - such as a capacity expansion project or a new facility being installed to enhance product quality within an operating plant.

The major challenges of a Brownfield Construction Project consist of access through an operational facility, ascertaining location of underground facilities and structures, safety concerns due to an operational facility and schedule related concerns [19]. In order to carry out construction in a safe and timely manner, it makes sense to prefabricate structures off-site and then assemble them with minimum manpower deployment and in minimum possible time.

Also, another issue that arises out of adopting Off-site prefabrication and On-site Assembly is that of customization. Any structure that has been manufactured off-site cannot be modified on site within the scheduled time or budgeted cost [1]. Accuracy of design and fabrication is, therefore, of paramount importance.

4.2 Evaluation of Constructability

Constructability of any structure can be divided into various work tasks that must be completed in order to complete a construction activity [6]. The evaluation of Constructability stems from ability to perform these work tasks as planned and to the design standards. Shin et al. identified work tasks as well as construction activities that can benefit from Augmented Reality based on technology suitability [6]. This study identified the following tasks that benefit from Augmented Reality applications - *Layout, Excavation, Positioning, Inspection, Supervision, Commenting and Strategizing.*

The above mentioned work tasks, in that study, were adopted from J Everett and evaluated against features of AR systems that would enhance the performance of these tasks [20]. Out of the identified tasks, the work tasks that are important for ensuring assembly of prefabricated structures are *Layout, Excavation, Positioning and Strategizing*. Table 2 summarizes the opportunities identified in this study for improvement of work tasks by implementation of MR.

Table 2. Opportunities for evaluating Prefabricated structural design and assembly using Mixed Reality

Work Tasks	Opportunity
Layout and Positioning	Creation of virtual reference points for superimposition on a reviewer's view. This eliminates the need for physical marking the reference points by extensive surveying process to ensure correct location of a structure. This is followed by, projection of a 3D model of prefabricated structure based on reference points. This ensures evaluation of interfaces with existing structures and avoids any last-minute modifications to fit the structure on site (Suit-to-site works)
Excavation	Creation of a 3D reference for superimposition of subsurface structure for a reviewer's view. This will ensure sufficient space for excavation and can ensure constructability of underground structures like foundations.
Strategizing	Projecting 3D image of the complete task can help in visualizing the sequence of various tasks to optimize construction or assembly process and to estimate on-field time of critical machinery.

4.3 Correlation of Work Tasks with MR system features

4.3.1 Layout and Positioning

Fixing layout for the structure being evaluated is largely dependent upon identifying correct reference points on the field and then marking the location of structure with respect to reference points. MR systems can reduce the marking efforts and time required for identifying correct location of a given structure by projecting the virtual image through a MR system. Similarly, Positioning of a virtual 3D image of the structure being evaluated, allows the reviewer to understand its relationship with the surrounding structures and equipment (above ground structures) and also helps to visualize any existing loads that may need to be accommodated into the prefabricated Structure. Refer Table 3 for correlation.

4.3.2 Excavation

In a Brownfield environment with underground structures and facilities, it is very important to be able to visualize the extent of excavation for installation of a structure. Any subsurface structural interfaces that do not come to fore with As-built information can be discovered by an on-site review using an appropriate MR system. This is especially important as foundations need to be ready to receive prefabricated structure for installation. Refer Table 4 for correlation with MR Device Components.

4.3.3 Strategizing

The task of strategizing requires analysis of the actual process of assembly and erection of a prefabricated structure. This process takes into account operations such as logistics, assembly, lifting as well as connecting to any existing interfaces. Strategizing is very different from other work tasks as it is not performed exclusively on site and requires collaboration between different teams. Refer Table 5 for correlation with MR Device Components.

5 Conclusion

Based on Correlation of Work Tasks with MR system features in Section 4.3, we can conclude that see-through HMDs present the best features for reviewing design of prefabricated structure in a brownfield industrial installation. They have the most immersive experience of review - all the while being able to see the real world. They have one of the more accurate spatial registration capabilities which can be further enhanced by use of external attachments to a centimeter level accuracy. User-interaction while using these is very easy and doesn't require any additional device or controller for inputs. These devices can be used for expert reviews as well as collaborative reviews and can help to discover any potential issues for assembly and final installation - thus helping to finalize a structural design much earlier. Another advantage of using these devices for reviewing a critical design is the enhanced customer experience that builds more confidence towards a design firm's capabilities.

Table 3. Correlation of MR System components with work tasks for Layout & Positioning

MR System Components	**Work Tasks**	**Layout & Positioning**
Display	VR Display	VR Displays can be used for conducting a Virtual Reality design review or for reviewing any structures remotely when access to a site is restricted [21].
	Portable Display	Device camera is able to produce image of real world on the screen, which is then superimposed with the Virtual image. The only disadvantage with this display is that one hand is occupied with holding the device.
	See-through HMD	These displays have an inherent advantage as the real world is seen through transparent glass and the virtual image is projected on the glass producing an immersive display.
Spatial Registration	Marker-based	A quick and accurate way to calibrate the device camera [22], this technique, however, requires installation of markers on sites. Accordingly, this technique can be adopted for smaller projects.
	Marker-less	Marker-less registration is able to self-calibrate the device to its surroundings by comparing them with pre-captured reference images [17 and thus results in a seamless experience. Also, with marker-less registration, changes to the scene can be detected with the MR system, highlighting any potential clashes.
	GPS-based	GPS based spatial registration on mobile devices has an accuracy of ±10 metres. However, attachments such as Trimble Sitevision are able to enhance the accuracy of measurement and location up to 1 cm [14]. The only disadvantage of using GPS for spatial registration is that it requires clear view of sky and can have issues in tight spaces that experience "Canyon" effect.
User Interaction	Touchscreen	The only disadvantage of using a touchscreen is that it requires use of both hands - one to hold the device and other for interacting with the device.
	Hand Gestures	Identifiable by select MR systems, Hand-gestures can be an excellent way of providing input to a device. Using hand gestures for input also means that both hands are free while not providing any input.
Storage	On-board	On-board storage can be particularly useful when using the device independently and on a remote location devoid of any cellular network or WiFi access. However, this can also be a limiting factor when using large files.
	Cloud	Advantageous when accessing large files and when a single device is used across multiple projects / locations. Needs proper wireless network.

Table 4. Correlation of MR System components with work tasks for Excavation

MR System Components	**Work Tasks**	**Excavation**
Display	VR Display	Can only be used for remote reviews. Not suitable to review on-going activity.
	Portable Display	Portable Displays can be used for reviewing interface with subsurface structure but have a narrow field of view since they are small and non-immersive.
	See-through HMD	See through HMDs provide the maximum information in an immersive environment. Reviewing the structural interfaces for excavation using See-through HMDs can help to discover any potential issues [12].
Spatial Registration	Marker-based	Marker-based spatial registration can be effective when reviewing a specific area for interfaces during excavation as it needs pre-installation of markers.

MR System Components	**Work Tasks**	**Excavation**
	Marker-less	Marker-less spatial registration would be preferred for evaluation of subsurface structural interfaces as it can identify any changes to the site's surroundings.
	GPS-based	Using GPS-based spatial registration is not particularly accurate to a centimeter level of accuracy. However, if used with enhancements such as Sitevision [14], it can be used to review work done.
User Interaction	Touchscreen	Pinch action on a touchscreen can be used to closely examine a virtual model and may prove to be useful due to limited field of view.
	Joystick / Controller	When reviewing a site remotely, it may be necessary to use keyboard and mouse as controllers to navigate withing the model or recording of the review.
	Hand Gestures	Hand gestures, when coupled with see-through HMDs allow interaction and feedback without use of additional equipment.
Storage	On-board	Particularly useful when using the device independently and on a remote location devoid of any cellular network or WiFi access.
	Cloud	Advantageous when accessing large files and when a single device is used across multiple projects / locations. Needs proper wireless network.

Table 5. Correlation of MR System components with work tasks for Strategizing

MR System Components	**Work Tasks**	**Strategizing**
Display	VR Display	Useful for desktop reviews, a VR display like CAVE can be useful in team reviews related to assembly and lifting activities required for erection of a prefabricated modules [12].
	See-through HMD	Some HMDs have collaborative capabilities and can be used for reviewing activities using virtual holograms.
Spatial Registration	Marker-based	Marker-based registration can be used for on-site team reviews.
	Marker-less	Marker-less registration is intuitive and can be used while strategizing. When users are seated around a table, wearing see-through HMDs, the devices can read the table's surface and project holograms for review.
User Interaction	Touchscreen	Large touchscreen displays can be used to convey ideas by marking while carrying out group reviews.
	Joystick / Controller	Keyboard and mice are generally used to navigate within a virtual space. Animations showing performance of important activities may also require user inputs to start, pause and end.
	Hand Gestures	Hand gestures can be useful when carrying out reviews using see-through HMDs. Users can interact with holograms using hand gestures to navigate to different areas of a hologram or to highlight, zoom-in and out of the views.
Storage	On-board	Very important for VR or CAVE reviews as the virtual models require a lot of storage. However, this may not be the apt storage solution for multiple HMDs accessing the same virtual model.
	Cloud	Can be used to ensure currency of the virtual model and also ensures that multiple users can access the same virtual model and review its feasibility.

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