3D VISUALIZATION TECHNIQUES IN THE AEC INDUSTRY: THE POSSIBLE USES OF HOLOGRAPHY

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SUMMARY: *Different visualization techniques are used to display and communicate information in the architecture, engineering, and construction (AEC) industry. While 2D representations have been historically used to communicate designers' intent, 3D representation technologies have been increasingly used in the AEC industry. In this regard, designers gained more flexibility to express their 3D designs on one hand, and to communicate their intent to involved stakeholders on the other. However, current 3D visualization tools still rely on different forms of screens as a communication interface between information stored in a computer and involved users which may affect the interpretability of modeled information. In this context, this study explores the use of holography to represent and share construction information in both the design and construction phases of AEC projects. This paper reviews the current state of art in holographic visualization, examines the various techniques used to create holograms, evaluates the potential use of holography in construction, and compares it to other physical and digital modeling methods currently in use. The authors speculate on the future of this technology in construction environments in conjunction with the use of Building Information Modeling (BIM). In effect, this paper helps construction companies and researchers find out how the benefits brought by holographic models compare currently and in the near future to other rapidly evolving platforms such as the computer tablet and augmented reality technologies.*

KEYWORDS: *Holography, Virtual Reality, Augmented Reality, Visualization, Building Information Modeling.*

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1. INTRODUCTION

Construction is an information-driven process where project's data is generated, communicated, and shared among different involved stakeholders throughout the various phases of design, construction, and operation. In this context, representing construction information is of crucial importance to ensure common understating among stakeholders and to avoid value loss related to data misinterpretation. Moreover, the reliable development and sharing of design intent from one discipline to another, and from one phase of a project to another is of crucial importance. In this regard, several visualization techniques have been developed by the AEC industry with major advancement occurring in the last few decades. While current visualization techniques enhanced the overall representation of construction data, they still depend on screens as an interface between information stored in a computer and the users. In this regard, this paper explores the use of holography as a revolutionary medium to represent and share information outside the boundaries of conventional display tools. Several holographic display techniques are investigated to assess their possible uses as reliable data representation tools in the AEC industry.

Knowing the relatively poor performance of the AEC industry, efforts has been expended to develop techniques that increase project productivity, enhance work quality, and reduce project delivery time (Azhar et al., 2008). In particular, the need to successfully implement complex-shaped buildings within time and budget constraints, has brought to light the potential of computer-aided design and manufacturing technologies (CAD/CAM) as well as Building Information Modeling (BIM) (Ku et al., 2008). These systems offer the means to accurately create a detailed, interactive, and informative virtual model of the project and in turn support the design, procurement, fabrication, and construction activities required to realize the building (Eastman et al., 2008). Through the integration of 2D and 3D drawings as well as non-graphical data within the same model, gaps in understanding between the various project stakeholders has been reduced. This in turn has minimized inefficiencies, mistakes and delays throughout the life cycle of the project (NBIMS, 2007). However, this form of visual design communication does not satisfy the legal framework required for construction, as the only design documents legally approved for construction are still the 2D drawings (Côté et al., 2013).

Despite the growing relevance of BIM in construction projects and the increasing awareness of the importance of practice models (CURT, 2004; AIA/AGC, 2006), the AEC industry has still to let go of its reliance on 2D drawings in the relay of data. Information exchanged between project stakeholders in 2D format is often subject to misinterpretation resulting in requests for information (RFIs) and change orders (COs) (Meadati, 2009). In other words, difficulty in 3D visualization from 2D drawings is hindering project progress through the undiscovered errors or their late identification (Sheppard, 2004). In that respect, several techniques have been formulated to mollify the effects of this phenomenon. Holography, for one, promises to be an efficient transformation of the current 2D drawings into a hybrid physical/digital format by utilizing 3D BIM models to create holographic prints of the project. Furthermore, holographic prints only scratch the surface of the potential of holography. Recent research has allowed for the creation of an interactive 3D representation of a model floating in mid-air. This technology, known as holographic display, revolutionizes the way information is exhibited to project stakeholders and tightens the gap between models and reality.

For a smooth transition from 2D drawings to 3D models supported by BIM, the industry's reluctance to change existing work practices and hesitation to learn new concepts and technologies must be minimized (Gu and London, 2010). The top two reasons for not implementing BIM on projects are "Lack of expertise within the project team" and "Lack of expertise within the organizations". This indicates that there is potential for education and training providers to fill this void and "bring the industry up to speed" (Eadie et al., 2013). Yet, there are members who "refuse to learn" and that also applies for BIM (Yan et al., 2008). Conveniently, holographic display has the potential to improve the utility of BIM by allowing a more enjoyable as well as interactive and responsive experience of the model. In the same sense, holographic display provides a medium to achieve higher levels of collaboration between project participants as it presents the opportunity to display the model floating in mid-air while the stakeholders stand around it and discuss (Blinn, Tayeh, and Issa, 2018). Indeed, it has been shown that there exists a direct correlation between a maximized collaboration on a project and achieving maximum benefits from the BIM technology (Migilinskas et al.; 2013).

Although BIM 3D models can significantly enhance coordination among different involved stakeholders during the design and engineering phases, they are underutilized on construction sites. Constructors still require 2D drawings with defined dimensions and gridlines to be able to execute works accordingly. In this regard, and in an attempt to reduce the reliance on 2D documents, the industry witnessed several developments in advanced visualization methods such as virtual reality (VR) and augmented reality (AR). These technologies allow users to merge into a partial or complete virtual representation of the construction project where BIM models are projected. Although these technologies present a technological shift towards bringing the 3D models to site, they are still in their development period and are still relying on special goggles or setups most of the times. Thus, although AR and VR enhance the use of BIM 3D models on construction sites, they still need to enhance their practicality especially when it comes to the use of goggles. The construction industry needs more convenient 3D visualization tools that can be used smoothly on sites without the need to wear goggles or build special setups. Therefore, new 3D representation tools need to be developed to ensure the continuous use of generated 3D BIM models without the need to transfer the data stored in BIM to 2D plans for execution purposes.

In this regard, the aim of this study is to investigate the possible uses and benefits of holographic visualization in the AEC industry as a revolutionary medium to share construction information in 3D informative format which includes geometry and data information. The research questions tackled in this study are (1) what are the different techniques currently used to create holograms? and (2) what techniques are suitable for employment in the AEC industry based on the needed technology uses? Accordingly, the study objectives are to: (1) review the current state of the art of available 3D visualization tools currently used in the AEC industry, (2) explore available holographic display technologies and their possible uses, (3) compare holographic display technology to available BIM-based visualization tools, and (4) inform AEC companies and academics about holographic technologies and their potential uses in the construction sector. Note that this study relies on the functional features of the technologies rather than the technical aspects. Previous research into the use of holography in the AEC industry is minimal, as the technology has recently allowed for its evolvement. Thus, in addition to published studies about this topic, the authors investigate information provided by companies working to advance this field.

2. LITERATURE REVIEW

Creating and sharing information is a core activity in construction projects. Information related to project's geometry, properties, and specifications is developed and shared across the entire project's timeline. In this context, adequate representation of project's information is crucial to ensure common understanding among involved stakeholders and to avoid value loss related to data misinterpretations. Therefore, the techniques used to create and share information play a major role in directing a project towards its objective of time, cost, and quality.

Several visualization techniques have been developed to represent construction related information in the AEC industry. The issue of communicating design information; however, dates back to the Roman architect Vitruvius in the first century BC. He discussed the intrinsic value of using plans, sections, elevations, and perspectives to properly communicate the design intent (Morgan, 1960). Vitruvius work influenced the architecture profession especially in the Renaissance era, and practitioners adopted his ways to represent their design information until our days. In this regard, the use of 2D-CAD software to draft design projects is a replication of manual drafting procedures that apparently existed long before the invention of computers (Abdelmohsen, 2011).

Along with the advancement of computers, new tools started to emerge in the construction industry to model construction information. In this regard, the industry is in the midst of a technological shift towards the implementation of Building Information Modeling (BIM) as a data repository of project's information. BIM is a visual database that combines several parametric design data into central or combined local models. The proper use of BIM has proven to be beneficial to the design process as well as for the final design product (Eastman, et al., 2009, Al Hattab and Hamzeh, 2015). Since BIM is object oriented, elements used in the model hold the corresponding design information either in their graphical appearance or in the corresponding attached data. Accordingly, the major advantage in using BIM to represent construction information is the use of virtual 3D elements to represent real construction objects, which helps decrease the miss-interpretations usually encountered in the case of conventional 2D-CAD drawings.

While the use of BIM is gaining momentum, several BIM-based applications have been developed to enable new representations of construction projects. These applications help extend the potentials of BIM and are basically categorized under two main categories: "Augmented Reality" (AR) and "Virtual Reality" (VR) applications.

Augmented reality (AR), as its name indicates, is an addition to what is real or what is seen by the naked eye. In specific, augmented reality is a view of the physical real-world in real-time with its building blocks supplemented by computer-generated sensory information. The 3D reality/simulation is perceived directly through translucent eye or head-mounted displays (HMDs) or indirectly through a hand held device. The display could be complemented with audio and GPS data provided by built-in software or through their separate respective hardware. What differentiates AR from Virtual Reality (VR) is that it doesn't completely immerse the user in a synthetic environment but rather offers superimposed data and objects upon the real world (Azuma, 1997). In this regard, Azuma (1997) identifies AR as a system that satisfies the subsequent three characteristics: (1) combines real and virtual, (2) is interactive in real time, and (3) is registered in three dimensions. AR seems to have several potential uses in the AEC industry especially in 3D visualization of buildings on site, locating installed components in a building, and in supervising the compliance of constructed works to design models (Meža, Turk, & Dolenc, 2015).

Microsoft HoloLens is an example of the latest advancements in the AR field developed by Microsoft and Trimble. Microsoft HoloLens, shown in Figure 1, is an AR application that uses computer generated projections to superimpose BIM model elements over the real world. Microsoft HoloLens is a wearable, self-contained computer. It enables users to see-through generated displays and it is context aware where advanced sensors are used to map the physical environment surrounding the user. Accordingly, the device helps users interact with 3D displays projected in the real location. In this augmented reality environment, users can attach virtual displays to real physical objects and interact with data using GGV (gesture, gaze and voice) commands (Trimble White Papers, 2015). This type of mixed reality can be integrated on the construction site to foster communication between parties, offering the ability to communicate between the design office and the construction site. Thus, HoloLens has the potential to overlap field and office data by overlaying model data on real objects and capturing on field conditions through its built in camera. This can then be shared with other users who don't necessarily wear HoloLens, but use any other electronic device, so they can proceed to provide their input. However, holograms will always have the advantage that they can be viewed by several people at once during an office or field meeting without any extra eyewear.

Figure 1: Microsoft HoloLens (Trimble, n.d.)

BIM Anywhere is another example of AR applications currently in use in the construction industry. BIM Anywhere is an AR application that connects to BIM models and facilitates their use on construction sites. BIM Anywhere employs a tablet and a Quick Response (QR) code to help users reach the desired model view without the need to navigate throughout the model (bimanywhere, n.d.). The built-in QR code reader of the tablet identifies the user location and loads the corresponding model view. As the user moves or rotates the tablet, the model view changes in real time to match the area that the user is aiming at (Sawyer, 2013). This allows less skilled personnel to easily access accurate and updated project information without having to go back to the office or refer to the BIM specialists. QR location stickers are usually placed on door frames at different locations in the field. In this regard, the successful use of BIM Anywhere applications requires an adequate setup of related infrastructure to enable the application to accurately detect model views and corresponding elements.

Virtual reality is another BIM-based application that is gaining popularity due to its decreasing cost. What differentiates it from augmented reality is that it is fully immersive whereby the user is surrounded by curved screens or wears a head mounted device as shown in Figure 2. An important advantage of this technology is its role as an integrator between other systems (Issa, 1999). Indeed, it would allow CAD and other software to freely flow in the same environment while the user walks through the system visualizing it and witnessing real time simulations. Virtual reality is also a medium where cooperation between various parties may occur. The technology allows people at different locations to see the same display by which one would be using the fully immersive technology while the others use a partially immersive one (Bridgewater et al., 1994). This translates into virtual conferences and the possibility for one user to guide another geographically distant one. However one of the problems of virtual reality is that it is currently not a stand-alone application, only a medium. In addition, the degree of visualization and simulation is only as good as the quality of input into the system.

Cave systems are an example of available VR technologies. Digital caves allow the user to walk through a full scale digital BIM model. CAVE systems have been available since 1972 but interoperability issues between CAVE system applications and popular BIM software hindered their application on construction projects. However, recent efforts enabled CAVE applications to control camera locations directly from Autodesk Navisworks, which is one of the popular BIM applications, therefore eliminating interoperability issues (Kang et al., 2012). Some CAVE systems such as CornerCavern by WorldViz (n.d.) provide a more immersive VR experience by making use of 3D projectors and can even accommodate 15 people or more. The system's capacity to concurrently incorporate a whole team into the VR experience allows for an effective collaborative planning tool.

Figure 2: Screen-based (left, rug.nl) vs. Head-mounted Virtual Reality Hardware (right, en-gadget.com)

3. RESEARCH METHODOLOGY

The research methodology employed in this paper to address the research objectives consists of four modules as shown in Figure 3.

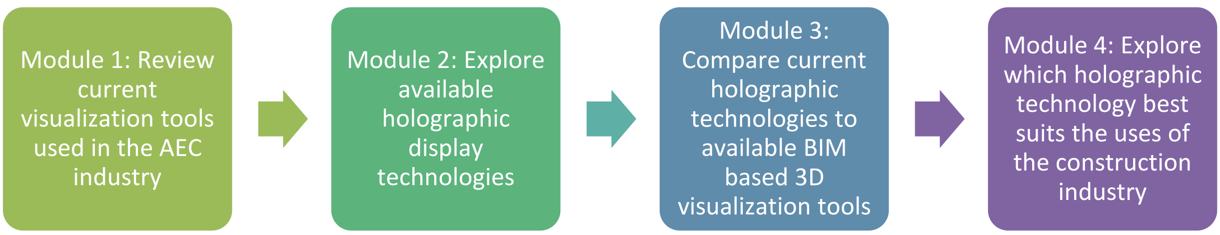

Figure 3: Research Roadmap

The first module reviews the main 3D display tools currently used in the AEC industry in conjunction with BIM where the authors reviewed material related to the topic including research papers, technical reports from specialized companies' websites, as well as technical images and videos. The first module is tackled as part of the literature review section. The second module explores available holographic display technologies and the different techniques used to create them. This module tackles the major difference among currently available holographic projection technologies and the basic features of each technique. The third module compares holographic projections technologies to currently available BIM based 3D visualization extensions such as augmented and virtual reality. This module relies on a set of criteria to compare these different 3D visualization tools. The fourth module investigates the main candidates among current holographic technologies that can, in the future, be employed in the AEC industry.

4. AVAILABLE HOLOGRAPHIC DISPLAY TECHNOLOGIES

Holography is a 3D display technology first invented in 1947 and depends on special optical setups to build images floating in midair relying on special light reflections. In this regard, holography is an optical reality not an optical illusion (realviewimaging.com). The word hologram can be used to designate almost any object that reflects light in some special way. This includes the seal of quality on an expensive product and even the ribbon or watermark on currency bills (Jääskeläinen, 2011). What differentiates holograms from other 3D renderings or photos is that the image seen by the observer depends on his/her position relative to the hologram. This enables the creation of 3D images that appear to be popping out of a 2D plane or simply hovering in mid-air. Several methods are currently used to achieve this effect; the most notable are discussed in the following sections.

Physicist Dennis Gabor conceived the theory of holography in 1947 whilst attempting to enhance the image quality of an electron microscope. He perceived that the co-presence of a coherent reference wave with scattered light from a 3D object allows for the registering of an interference pattern or in other words an image replica of the prime 3D object floating in air (Kim, 2007). This technique is called electron holography. However, optical holography did not witness significant advances until the invention of the laser in 1960 which allowed for the accurate recording of 3D objects (holography.ru). Thereon, static holograms were popularized in the 1980s and 1990s while dynamic holography was still to be developed (Khan, 2013). In 2003, researchers at the University of Texas proposed the prospect of dynamic holographic representations by processing the hologram of an object in 3D space after which the 2D digital hologram is copied onto a digital micro-mirror device (DMD) illuminated with a consistent light (Kim, 2007). From that point on, various techniques of digital holography have been created.

Successful holographic visualization depends on the realization of two basic depth cues: physical and psychological. The physical cue is achieved by several factors including binocularity, accommodation, convergence and motion parallax. The binocularity is based on the natural mechanism of the act of seeing in 3D, where each eye sees a single view of the object before being processed by the brain as a 3D view. Accommodation refers to the viewer choosing what to see by naturally controlling the eye lens. Convergence acts against the difference in viewing direction of each eye when the viewer is focusing on one point. Motion parallax depicts the movement of seen objects where a closer object appears to move faster than a farther one. Psychologically, other depth cues are important to satisfy a real like 3D visualization including texture, shading, linear perspective, knowledge, and occlusion. Texture targets the details of an object surface, and produces a feeling about the object distance and its 3D shape. The shading of an object helps the brain understand the shape and orientation of the object. Linear perspective is achieved wherever a viewer in an outer field sees two parallel lines as converging and intersecting at the horizon. Knowledge or memory provides the viewer with psychological hints to identify a certain object. Occlusion where an object partially blocking another object is understood to be closer from the viewer (Yang et al., 2016). These depth cues are important to produce realistic 3D visualizations and are not always achieved in current 3D visualization technologies. The following sections present most notable 3D visualization techniques currently used to create holograms including optical holographic prints, computer generated holograms and volumetric display technologies.

There are several types of holographic displays depending on the techniques and technology used to create them. The following paragraphs present different types of currently available holographic projections and volumetric display tools that can be possible candidates for future uses in the construction industry. Conventional techniques used to create optical holograms target the creation of holographic prints that can be reconstructed using light beams; a process that usually follows two main steps: (1) creating the hologram and (2) reconstructing it. The first step is to create the hologram on a special optical film that records the interferences and diffractions of light rays reflected by the surface of the corresponding object.

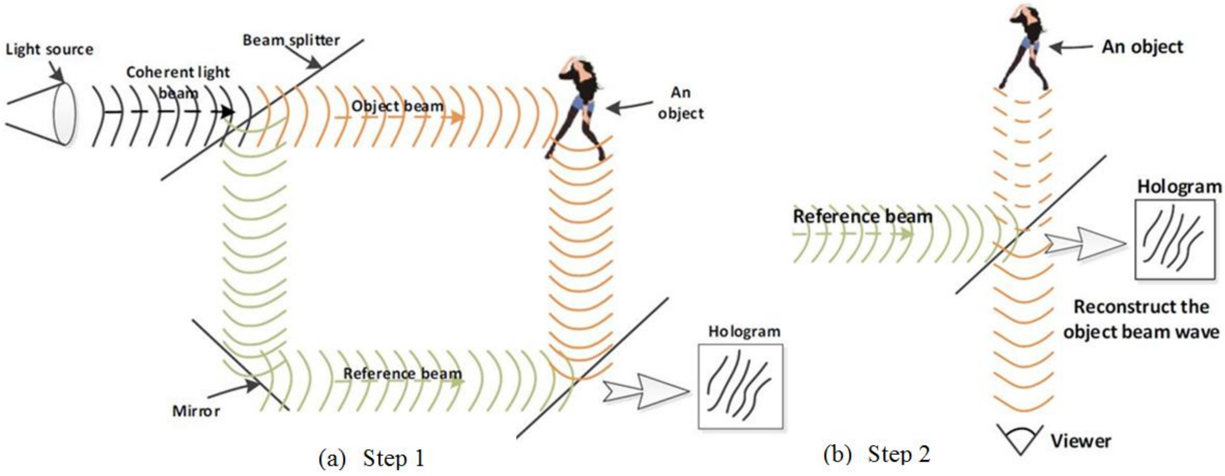

Figure. 4: Creating and Reconstructing the Hologram (*Yang et al., 2016)*

Two coherent light beams are used to create the holographic film. The first light beam is called the object beam and is used to light the object that is to be projected, while the second beam is called the reference beam (used in the second step to reconstruct the hologram) as illustrated in Figure 4-a. The reference beam hits the recording medium to generate holograms and holds the same characteristics of the object beam. Accordingly, the object's light-points information is recorded on the optical film with similar wave characteristics such as frequency and amplitude.

The second step in this method consists of reconstructing the hologram recorded on the film using the reference beam as illustrated in Figure 4-b. This technique allows the human eyes to perceive the same light rays as if reflected by the actual object, thus allowing them to see actual 3D visualization floating in mid-air with all depth cues satisfied theoretically (Yang et al., 2016). Note that there are several techniques to create holographic prints, yet, they all share a common basic principle: registering of a light interference pattern on the print, and reconstructing the object image. The following sections further details each of these techniques.

Denisyuk Hologram Recording is the simplest method used to create holographic prints and ranks among the most accurate methods for producing holographic prints as it requires the same laser beam to illuminate the object and record the image on the photo plate. The mechanism works first by generating a thin light beam known as the "reference beam" from a He-Ne laser, then reflecting the beam off a mirror onto a pinhole or spacial filter which spreads out the beam while enhancing its homogeneity as shown in Figure 5.

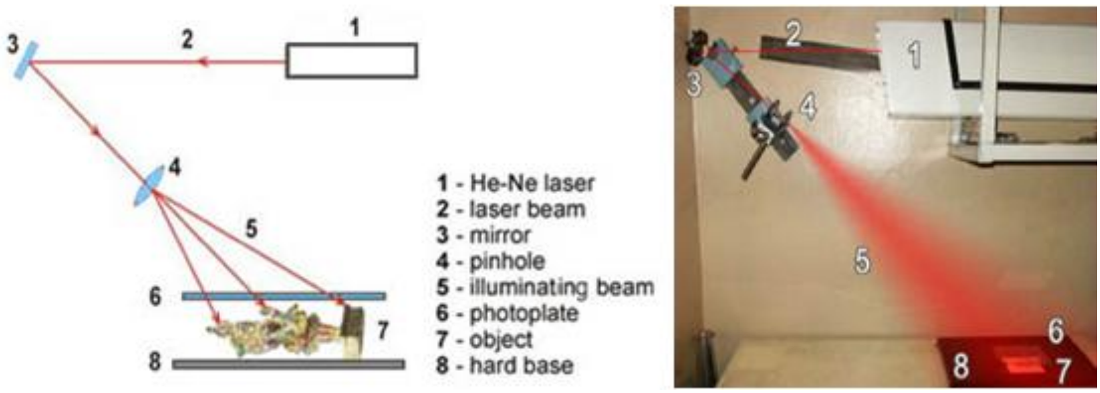

Figure 5: schematic (left) and actual (right) setup of Denisyuk's hologram recording technique (*holography, n.d.)*

The refracted set of beams pass through the transparent, high resolution photo plate and strike the object set on a firm surface. The laser beams then reflect off the object hitting the photo plate again, this time from the backside, and interconnect with the reference beams. The result is an interference pattern that shows acute variations in light intensities being recorded on the photo plate. This pattern allows for a hologram to be seen in usual white light. A drawback to this technique is that it requires complete motionlessness as any slight movement of the setup would ruin the produced hologram. In other words, holograms of moving objects cannot be created (holography, n.d.). Note that the laser beam that reflects off the object is known as the “signal beam”.

To solve the problem of mobility, the **Pulse Holographic Display** technique was developed as highlighted in Figure 6. This technique requires a complex setup of multiple and expansive equipment. Although it resolves the problem of mobility, it does force a limitation on the object size (not exceeding the size of the photo plate). The first step of the process is the laser beam being divided into a “reference beam” and a “signal beam” by a semi-transparent mirror. The “reference beam” goes on to be reflected off a mirror onto a spacial filter which expands the beam to illuminate the photo plate. The “signal beam” on the other hand, after being reflected and scattered, illuminates the object which in turn reflects the light onto the photo plate. As such, the plate records the interference pattern formed along its surface between the reference and signal beams. Then, the transmission hologram is created after the photo plate is treated with photo-chemicals. If illuminated with its corresponding reference beam while the observer looks through it, the transmission hologram creates a 3D image in the same position of the original object. As long as the transmission hologram is lit by a pulse laser, the resulting image is highly detailed and flawless. However, if illuminated by ordinary white light, a colorless 3D image of lower resolution is produced. Note that opal glasses could be used as a replacement of spatial filters for the expansion of the beams. The color of the hologram depends on the color of the laser (holography, n.d.).

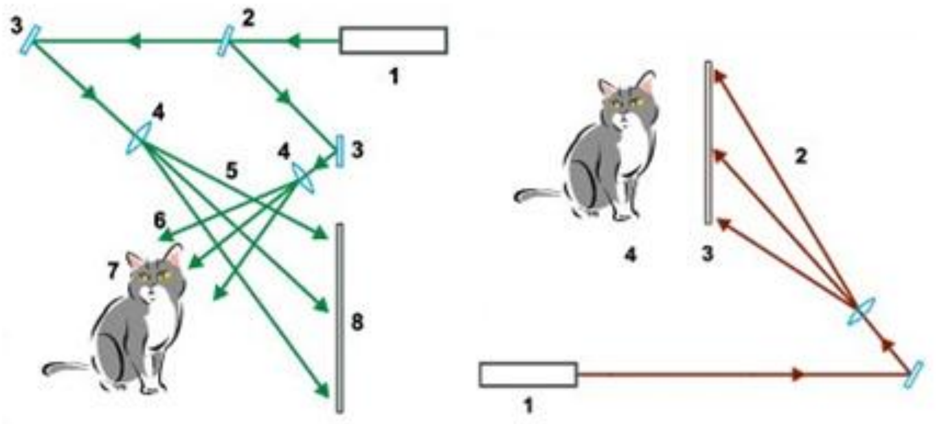

Figure 6: Creation of the transmission hologram (left) and its illumination (right) as part of the pulse laser transparent hologram recording (holography.ru, n.d.).

While the **Pulse Holographic Display** technique solves the problem of object mobility, it imposes restrictions on the illuminating beam where only pulse lasers are suitable. In this context, **Transmission Hologram Copying** is developed to solve two problems at once: to make the image visible in normal white light and to allow the position of the image can to change with respect to the photo-plate. Figure 7 outlines this process as the laser beam is first divided into two beams by a semi-transparent mirror. The reconstruction beam is directed from the mirror to a special filter. Afterwards the enlarged beam falls on the transmission hologram from the side of the glass substrate and restores the real image. By adjusting the distance between the transmission hologram and the photo-plate, the position of the reconstruction images changes. The object and the reference beam land on the photo-plate from different sides meaning that the three dimensional image is visible in white light. The copied hologram should then be adjusted in function of the photo-plate position, the alignment of the optical paths of both beams, the ratio between the latter, and the hologram exposure time (holography, n.d.).

The previous methods rely mainly on optical setups to print the holograms on specific recording films and to reconstruct them by special illumination. Another technique to create holograms is to employ advanced computational methods using computers. **Computer Generated Holograms (CGH)** are used to substitute the first step in conventional holographic prints by digitally creating the hologram. A specialized software and hardware design is used to create the 3D object using Computer Aided Design software (CAD). In this technique, the object is 3D modeled using CAD, the object beam is designed with a specific direction to light up the object, and the reference beam is designed to facilitate diffraction with the object beam where the computer calculates the different interferences scenarios. The resulting hologram is more flexible to reconstruct where original chemical processes used in optical holography are no more required. However, several hardware and algorithm restrictions face CGHs resulting in imperfect holographic display especially at low viewing angles. CGHs are expected to perform better in the future with the advancement of computers and may become very popular due to their direct linkage to CAD software, their flexibility, and convenience for customers (Yang et al., 2016).

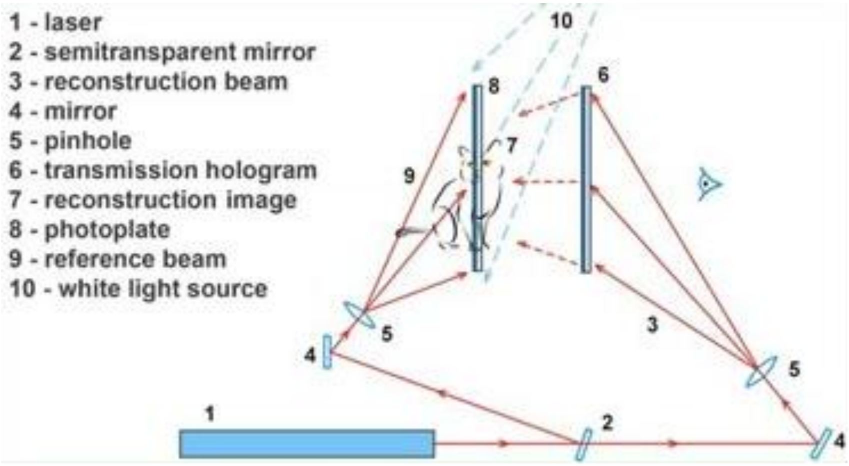

Figure 7: Schematization of transmission hologram copying (holography, n.d.)

Several companies are already using CGHs to create holograms. "Zebra Imaging" for instance is a company that creates holograms out of computer models. The process adopted by Zebra is a modification/enhancement of the original technique of pulse laser transparent hologram recording which was discussed in previous paragraphs. Instead of creating a hologram from a real object, this technique creates holograms from virtual 3D data modeled on a computer. A rendering engine breaks down the 3D model and calculates the information that needs to be transcribed onto each division of the print known as a hogel (a three dimensional pixel). The 3D image sections are then recorded on each hogel as an interference pattern between two laser beams, the reference beam and the signal beam. However, the signal beam in this process is created by an LCD screen that holds the 3D data and a converging lens. With the interference pattern established on each of the thousands of hogels that make up the photo polymer film, the holographic print is ready for display if illuminated by the same reference beam. In other words, with the interference pattern recreated by the reference beam light source, each hogel acts as a point source of light forming together a 3D image floating in space (zebraimaging, n.d.). Figure 8 visually describes Zebra's process. Note that the sources of 3D graphic information include computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAM), medical imaging technologies, LIDAR, aerial photography, and radar and laser scans.

Among the shortcomings of CGHs is the need for complex computational methods and high computer capabilities that may complicate the creation of the holograms. A different technique to create holograms from digital input sources is Digital holography that uses a Charge-Coupled Device (CCD) instead of special media in traditional optical holography. This technique allows for receiving holograms in digital format without requiring complex computing capabilities as needed in CGHs. Therefore, this method can be seen as a compromise between conventional optical holography and CGHs to allow user to create holograms from digital input without requiring advanced computing technologies. However, these techniques suffer from complex optical circuits, environment limitations, and bounded flexibility (Yang et al., 2016).

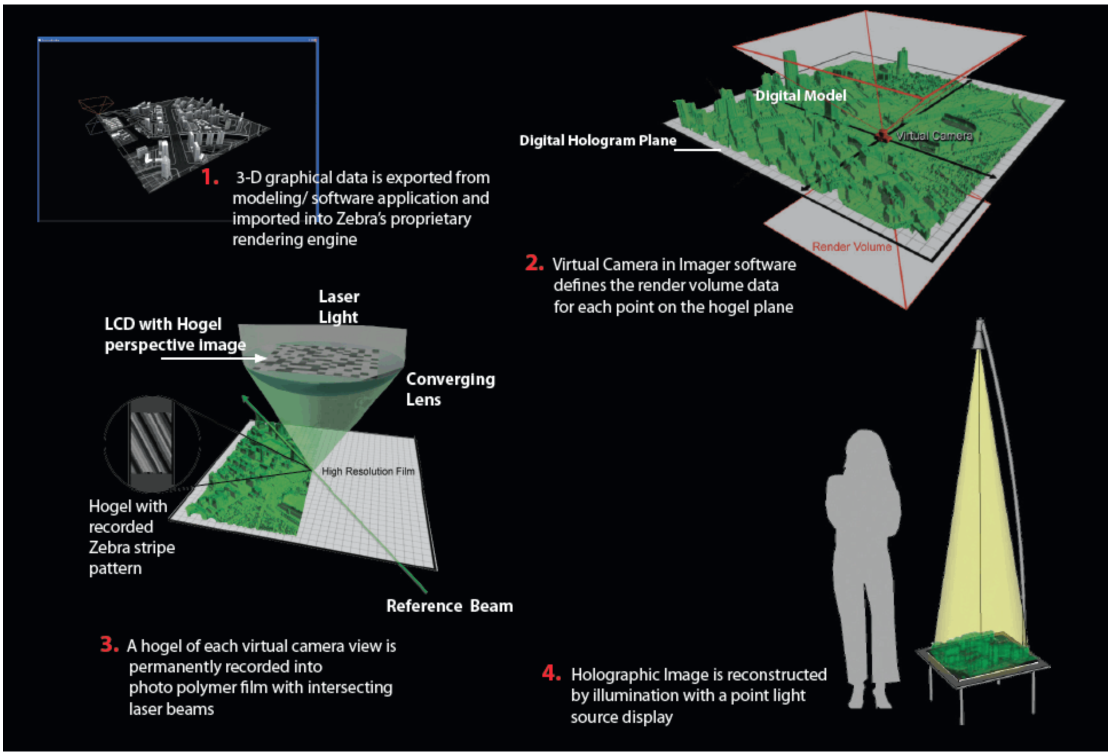

Figure 8: Zebra imaging's holographic prints process (zebraimaging, n.d.)

Another ambitious technique to create holograms is known as 3D Volumetric Display. The technique behind creating volumetric 3D displays differs from creating holographic prints. Instead of printing holograms and reconstructing them, volumetric display technologies create virtual 3D holograms in space using mirrors or LED panels. Accordingly, volumetric display devices reconstruct the light field of an object in mid-air using special methods that theoretically satisfy all depth cues and viewing ranges. The first method consists of lighting up specific points in space with different colors and intensities to produce a true 3D image. A self-luminous or light-reflecting medium that occupies the volume in which the hologram is to be displayed is required so that the image can be seen. This medium commonly consists of one of the following: (1) a rapidly rotating screen on which layered images are projected from different directions, (2) a stack of several screens each displaying a 2D image of the hologram at a different depth (Sullivan, 2005) or (3) a fluorescent gas that can be excited by intersecting rays of infrared light (Pastoor and Wöpking, 1997). In most of the literature, products that use this method are called volumetric displays and are sometimes considered as a different branch of technology from holographic displays.

Another 3D Volumetric Display method uses a different approach to produce the volumetric display relying on the fact that what observers (or a cameras) see is only due to the light rays that enters through their pupils (or lenses). Therefore, instead of trying to light up specific points in space, this method focuses on reproducing the time-varying light field that would have been perceived by an observer at a specific location if the actual object was actually there (Onural et al., 2011). This is commonly achieved by using: (1) Screens where every pixel (hogel) emits lights rays of different color and intensity in different directions (holografika, n.d.), (2) Spacial Light Modulators (SLM) that can digitally shape light to converge and focus in specific locations in space (realviewimaging.com, seereal.com) and (3) Tracking the observer's position relative to the display and optimizing the image accordingly (zspace, n.d.). Some companies use a combination of the last two techniques, For example, SeeReal uses SLMs coupled with observer tracking to avoid displaying wasted information and therefore enable faster processing and clearer images. At any time, only the essential information (or sub-hologram) is displayed as shown in Figure 9.

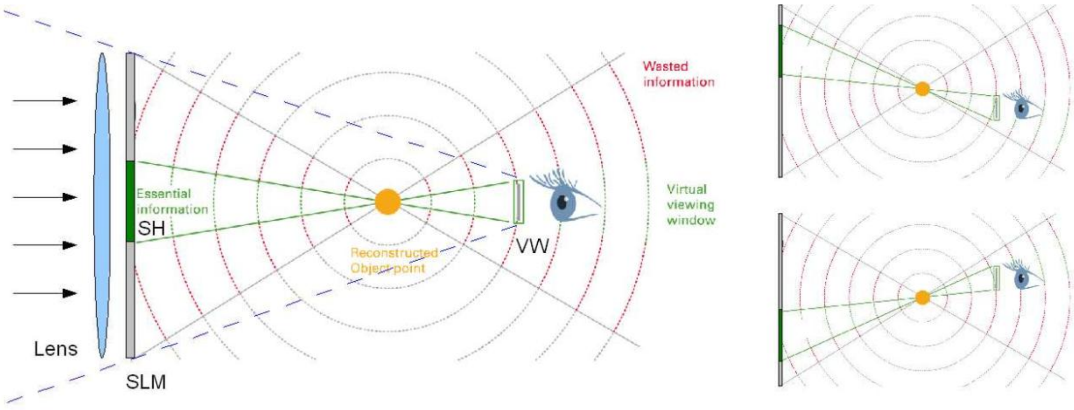

Figure 8: Side of the hologram display mechanism using an SLM, the green part represents the portion of the screen that emits the light field which is useful to the observer in different positions (Häussler et al., 2009).

3D Volumetric Display is a technology that can be used to create interactive 3D holographic display with an interface system (realviewimaging, n.d.). The method adopted consists of using a Spatial Light Modulator (SLM) that digitally shapes light to converge into focused points of light in specific locations in free air. This technology allows the user to manually interact with realistic 3D holograms using hand gestures to rotate and resize the hologram, and a special pen to highlight or even draw lines on the hologram (video demonstrations available at www.realviewimaging.com). In October 2013, the first study on the use of live 3D holography in interventional cardiology was completed. The study involved successfully using the technology coupled with X-ray and cardiac ultrasounds systems to guide minimally invasive structural heart disease procedures on eight patients (Philips news center, 2013).

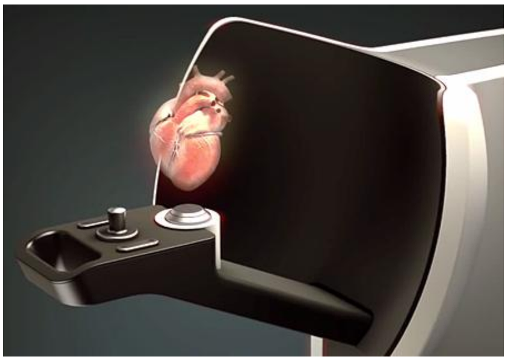

Figure 9: 3D holographic display (RealviewImaging.com)

5. COMPARING AVAILABLE 3D DISPLAY TECHNOLOGIES

Several technologies are used to create 3D visual displays; however, they do have the same maturity. While technologies like holographic prints are already developed and used in the industry, other technologies are still in their initial period of development. In this regard, the Gartner Hype Cycle of 2017, presented in Figure 11, is used to assess the maturity of currently developing 3D display technologies. It is noted that Virtual Reality is the most mature technology right now heading to reach the plateau in 2 to 5 years. However, Augmented Reality stands behind Virtual Reality where it needs 5 to 10 more years to reach its corresponding plateau. As for the volumetric displays, which include holography, they are still rising towards the peak of inflated expectations and need more than 10 years to reach the plateau.

Since current 3D display technologies are not on the same maturity level, this section tries to compare them based on a set of criteria summarized in Table 1. The first criterion that differentiates among current available technologies is the need to wear special equipment. In this context, some AR and VR technologies require the user to wear special goggles to see in 3D while holographic prints and volumetric 3D display allows the users to see objects floating in mid-air using their naked eyes.

Another important criterion that differentiates among available technologies is their ability to satisfy visual depth cues. Note that satisfying depth cues is very important to experience a realistic 3D display without causing discomfort to the user. Optical Holographic Prints allow the human eyes to perceive the same light rays as if reflected by the actual object, thus allowing them to see actual 3D visualization floating in mid-air with all depth cues satisfied theoretically (Yang et al., 2016). As for Computer Generated Holographic (CGH) prints, several hardware and algorithm restrictions result in imperfect holographic display especially at low viewing angles (Yang et al., 2016). Volumetric display devices theoretically satisfy all depth cues by reconstructing the light field of an object in mid-air using special methods (Häussler et al., 2009). As for Augmented Reality and Virtual Reality applications, the quality of corresponding 3D visualization highly depends on corresponding computer renderings that significantly affect the realization of visual depth cues (Berning et al., 2014; Gerig et al., 2018).

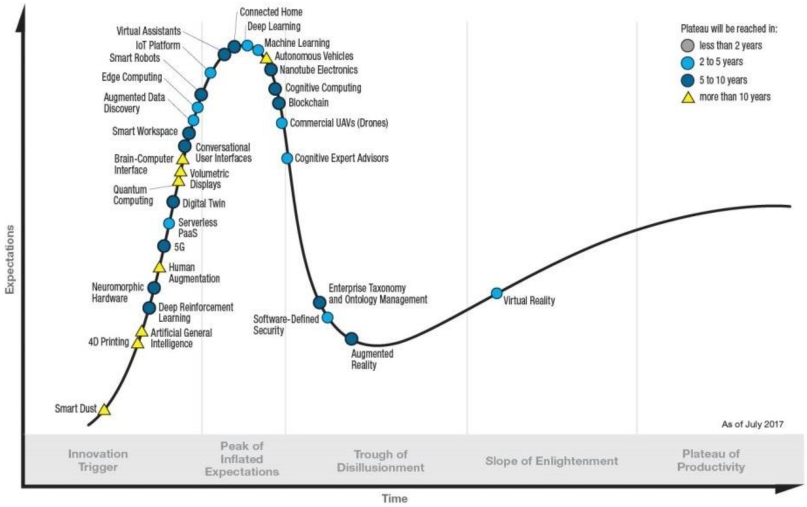

Figure 10: Gartner Hype Cycle for emerging technologies 2017 (Gartner Hype Cycle, 2017)

The available 3D display technologies also differ in the way users can interact with them. While optical and computer holographic prints do not allow users to interact with the corresponding 3D visualization, volumetric displays as well as AR and VR do allow users to directly interact with the generated 3D displays with the possibility of editing and modification. Nonetheless, these technologies differ in the way they interact with their surroundings. It is interesting that only augmented reality technologies can detect their environment either by special cameras or sensors. Therefore, these technologies are considered to be context aware where they can understand and decipher the environment surrounding them.

Table 1: Comparison between available technologies

Criteria	Optical holographic prints	Computer generated holographic prints	Volumetric 3D display	Augmented Reality	Virtual Reality
Need for Goggles	No	No	No	Depends on technology	Depends on technology
Satisfy Depth Cues	Satisfactory	Satisfactory	Good	Good	Satisfactory
Interactive with user	No	No	Yes	Yes	Yes
Context Aware	No	No	No	Yes	No
Easy to Update	No	No	Yes	Yes	Yes

The ease to update the generated holograms is another major parameter that differentiates among these technologies. Optical and computer generated Holographic Prints do not allow users to update the holograms at hand unless they re-generate the whole process from the beginning by reconstructing the hologram using the updated object; however, Volumetric Displays as well as AR and VR enable the user to directly update the displayed visualization by updating the corresponding CAD file. In this context, the use of Volumetric Displays, AR, and VR technologies look more convenient for the AEC industry where stakeholders continuously need to make changes and adjust their designs.

6. DISCUSSION

This paper investigates the major 3D display technologies that are applicable to the AEC industry and explores the possible uses of holography as a revolutionary medium to display and share construction information among stakeholders. Several types of holographic projections are studied and differentiated in correspondence to the technology being used. In this context, three major holographic display technologies are studied: optical holographic prints, computer generated holograms (CGHs), and volumetric 3D displays.

Although optical holographic prints are already available with several techniques to create them, for fixed or mobile objects, they require the existence of the object that needs to be projected. For instance, if a hologram of a small statue needs to be projected, the statue needs to physically exist first. In this context, this technique seems to be the least convenient for the AEC industry where the building or construction component that needs to be projected may not be physically built yet. Even if built, creating optical holographic prints for a large scale object is not available currently.

The other available technology used to create holographic prints is computer generated holograms (CGHs). This technique does not require the physical existence of the object but a digital model of the object that needs to be projected. Accordingly, this technique is a possible candidate for the AEC industry if holographic prints are to be constructed. In this context, once the digital model of the building or part of it is developed, a computer generated hologram can be created. A CGH can substitute the conventional use of 2D drawings especially if the complexity and cost of creating CGHs are minimized. Nonetheless, the CGHs are recorded on a photo polymer film that can be easily used on sites instead of 2D documents such as A0 and A1 papers. If successfully used, a CGH print can be used by constructors as a digital 3D construction document that enables the representation of the height dimension which is missing in conventional 2D paper plans. Thus, with a holographic CGH print, constructors and workers are more likely to understand the 3D shape of the elements they are building especially in the case of complex geometrical shapes.

Although CGH prints can be of significant value if employed as 3D digital documents, they have several shortcomings that may hinder their use. First, CGHs cannot be updated nor changed where any modifications to the model requires the creation of new CGH prints. This can increase the cost of this type of digital documents and can act against their employment. Second, CGH prints are not interactive with users; they only serve as 3D representation of models without the possibility of navigating the holograms like showing some parts or turning off some others. This fact can reduce their value as an efficient medium for interactive coordination and development. Third, CGH prints face some hardware and algorithm restrictions which can result in imperfect holographic display especially at low viewing angles.

In this regard, volumetric 3D display technologies present several advantages over CGH prints. The most important is that volumetric displays are not holographic prints, and therefore, their modification and update are possible. Moreover, volumetric display is an interactive technology that allows the user to freely navigate the model. For instance, volumetric display developed in the medical field allows doctors to handle the holograms with hand gestures, which allows them to rotate the model, select elements to be displayed, and even get dimensions directly from the displayed hologram. This technology therefore presents several advantages to the AEC industry if successfully employed whether during the design or construction phases. The ability to navigate the hologram and freely selecting what to show and what to hide enhances the usability of holograms created following the volumetric 3D display technology. In this regard, volumetric display can be used as an interactive medium to represent and share construction information among stakeholders which enhances coordination and shared understanding on construction projects.

It can be inferred that CGHs can be used in the execution phase of the project as 3D digital documents to share 3D geometry to constructors and workers on site. However, volumetric display technologies are more suitable to the design phase of the project where participants need to navigate the model and coordinate their work in a shared environment. The current barrier to volumetric displays is the small size of created holograms which can reduce their value as 3D visual representation tools for the AEC users. However, this may change in the future.

In this regard, the development of real size holographic projection, as schematically highlighted in Figure 12-d, promises to ensure the continuity of 3D data representation from design to construction phases. Nonetheless, the use of one-to-one holographic projections is very convenient to workers on site where no goggles or pads are needed. Accordingly, the design intent of designers is directly shared with constructors by a real size hologram. Therefore, workers can directly understand the corresponding design without the need of 2D plans or the BIM model. This fact minimizes the loss of value that usually occurs at the design-construction interface due to the misinterpretation of design information, thus minimizing construction errors and rework.

Moreover, the use of real size holograms can dramatically enhance the management of the construction process at several levels. At the level of constructing planning, planners can sequence the holographic display on site in a way to match the construction plan. Therefore, this sequential holographic display that conforms to the sequence of the schedule can be used to manage resources on site and to direct the corresponding workflows. At the level of tracking progress, managers can instantly track the progress of the project by comparing the executed works and the projected holograms. For instance, once a column is poured, an automatic notice can be generated signaling the finishing of this specific task. Nonetheless, the use of to-scale holographic projections can enhance the quality of executed works. So at the level of quality control and building alignment, managers can use special sensors and applications to ensure that installed elements fit exactly to their intended positions.

Also in the design phase of construction projects, the use of real size holograms to share design intents is of great value to all involved stakeholders, especially for owners. For instance, the ability to project an architectural BIM model on the specified construction site can help the owner better understand and visualize the final shape and position of the corresponding building. In this scenario, owners can tell if the designed building satisfies their values by directly seeing the building in its actual environment before being constructed. Therefore, the use of holograms in the design phase can play a major role towards realizing owner's value, while avoiding surprises resulting from the designers' miss-alignment with owner's needs.

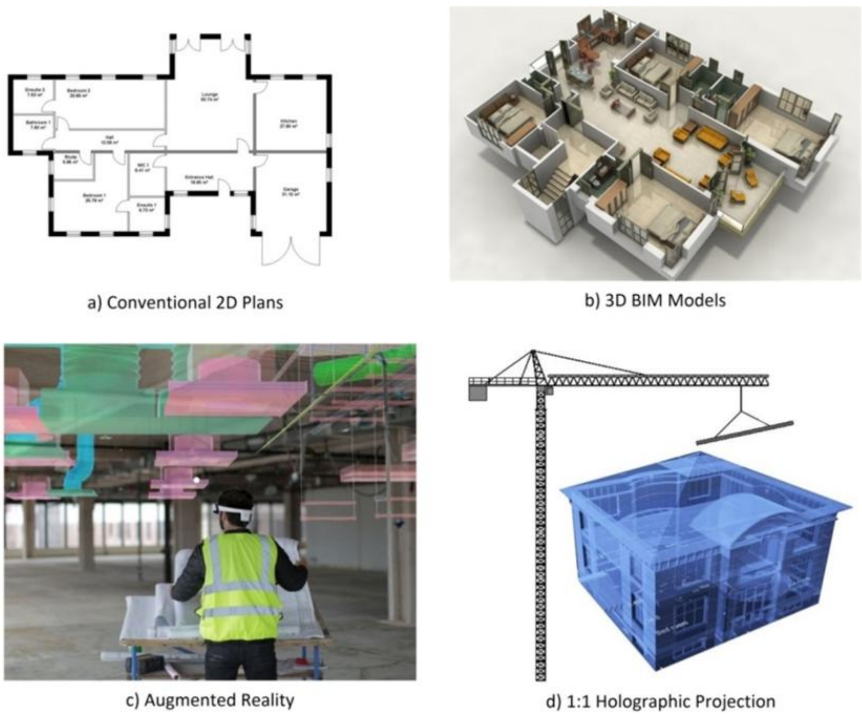

Figure 11: Progress of Information Display Technologies and Future Use of Holograms

Scaled holograms (1 to n) can also be used in the design phase for the purpose of collaboration among design teams. So instead of having the teams surrounding a screen or a tablet to discuss design conflicts, they may be surrounding a holographic display where all disciplines are projected. In this regard, the clash detection process can be performed live at the presence of all related parties. The convenience of holograms to display design information can enhance the resolution of design conflicts where faster interpretations and explanation can be achieved. Nonetheless, with interactive holographic displays, designers can instantly suggest and implement corresponding changes, take confirmations from other disciplines, and proceed to continue the design development.

7. CONCLUSIONS

Information display in the AEC industry have witnessed several developmental stages starting with 2D plans that are still used in today's practices, to Building Information Modeling (BIM), to reach virtual and augmented reality applications. This study explores the use of holograms as a revolutionary medium to share construction related information among stakeholders. Holographic technologies are assessed for possible use in the AEC industry.

Several technologies used to create holographic displays are investigated and compared in this study, where each technology is investigated against the needed uses in the AEC industry. The main two candidates that can be used in the AEC industry are computer generated holograms (CGHs) and volumetric 3D displays. CGHs can be used as 3D display documents instead of conventional paper plans. Accordingly, CGHs can serve as 3D construction documents that show the height dimension of building elements that is missing in conventional 2D paper plans. Thus, CGHs can help reduce the errors resulting from the misinterpretation of 2D plans by showing the entire 3D representation of building elements. In this regard, current technologies used to create CGHs allow AEC users to share the geometry of their model in a holographic format; however, data stored within the BIM model cannot be shared using current available technologies.

Volumetric 3D displays present advanced holographic display features where created holograms are interactive with users. In this context, users can navigate the hologram using hand gestures, select what elements to show and what to hide, as well as zoom and scale the projected hologram. These features provide AEC users with more flexibility to navigate their projected BIM models; thus, allowing them to use holograms for coordination and shared understanding. Nonetheless, volumetric displays can be used to share the data stored in the BIM model not just its 3D shape. The current barrier to volumetric displays is their small size that may reduce their value as possible 3D representation tools in the AEC industry.

Using holography in the AEC industry highly depends on the advancements of holographic projections technologies. In this regard, future studies can, on one hand, target the technical advancement of CGHs and Volumetric Displays, and on the other hand focus on the needed properties of holographic projections to be used in the AEC industry whether in the design or execution phases. The successful development of holograms and their employment in the AEC industry is expected to be a game changer in the way construction information is generated, developed, and shared among different AEC stakeholders.

REFERENCES

Abdelmohsen , S. (2011). *An Ethnographically Informed Analysis of Design Intent Communication in BIM-Enabled Architectural Practice.* Atlanta, USA: Georgia Institute of Technology.

AIA/AGC. (2018). *AIA/AGC Recommended Practices.* American Institute of Architects and Associated General Contractors. Retrieved from https://www.agchouston.org/AGCH/About/Publications/AIA-AGC-Recommended-Practices/AGCH/About/Pubs/AIA_AGC_Recommended_Practices.aspx?hkey=525527cd-e4c9-42e9-99c7-e7d141f27ae6

Al Hattab, M., & Hamzeh, F. (2015). Using social network theory and simulation to compare traditional versus BIM-lean practice for design error management. *Automation in Construction, 52*, 59-69. doi:10.1016/j.autcon.2015.02.014

Azhar, S., Nadeem, A., Mok, J., & Leung, B. (2008). Building Information Modeling (BIM): A new paradigm for visual interactive modeling and simulation for construction projects. *Proc., First International Conference on Construction in Developing Coutries,* (pp. 435-446).

Azuma, R. (2006). A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments, 6*(4), 355-385. doi:10.1162/pres.1997.6.4.355

Berning, M., Kleinert, D., Riedel, T., & Beigl, M. (2014). A study of depth perception in hand-held augmented reality using autostereoscopic displays. *IEEE International Symposium on Mixed and Augmented Reality (ISMAR).* IEEE. doi:10.1109/ISMAR.2014.6948413

bimanywhere. (n.d.). *bimanywhere.com/*. Retrieved March 11, 2019, from https://bimanywhere.com/

Blinn, N., Tayeh, R., & Issa, R. (2018). Visualizing Construction Projects Using Holography. *Construction Research Congress.* New Orleans, Louisiana: American Society of Civil Engineers. doi:10.1061/9780784481264.044

Bridgewater, C., Griffinb, M., & Retikc, A. (1994). Use of Virtual Reality in Scheduling and Design of Construction Projects. *Proceedings of the 11th International Symposium on Automation and Robotics in Construction* (pp. 249-256). Automation and Robotics in Construction Xi, Elsevier. doi:10.1016/B978-0-444-82044-0.50037-0

Côté, S., Trudel, P., Desbiens, M.-A., Giguère, M., & Snyder, R. (2013). Live Mobile Panoramic High Accuracy Augmented Reality for Engineering and Construction. *International Conference on Construction Applications of Virtual Reality.* London.

CURT. (2004). *Construction Project Controls: Cost, Schedule, and Change Management Construction.* Construction Users Round Table UP-201.

Eadie, R., Millar, P., & Grant, R. (2013). PFI/PPP, private sector perspectives of UK transport and healthcare. *Built Environment Project and Asset Management, 3*(1), 89-104. doi:10.1108/BEPAM-02-2012-0005

Eastman, C., Lee, J., Jeong , Y., & Lee, J. (2009). Automatic Rule-Based Checking of Building Designs. *Elsevier, Automation in Construction, 18*, 1011-1033. doi:10.1016/j.autcon.2009.07.002

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2008). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors.* John Wiley & Sons Inc.

Gartner's Hype Cycle. (2017). *Gartner's Hype Cycle.* Gartner. Retrieved March 11, 2019, from https://www.gartner.com/en/newsroom/press-releases/2017-08-15-gartner-identifies-three-megatrends-that-will-drive-digital-business-into-the-next-decade

Gerig, N., Mayo, J., Baur, K., Wittmann, F., Riener, R., & Wolf, P. (2018). Missing depth cues in virtual reality limit performance and quality of three dimensional reaching movements. *PLOS ONE, 13*(1). doi:10.1371/journal.pone.0189275

Gu, N., & London, K. (2010). Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction, 19*(8), 988-999. doi:10.1016/j.autcon.2010.09.002

Häussler , R., Reichelt , S., Leister , N., Zschau , E., Missbach, R., & Schwerdtner, A. (2009). Large real-time holographic displays: from prototypes to a consumer product. *Proceedings Volume 7237, Stereoscopic Displays and Applications XX; 72370S*. doi:10.1117/12.805873

holografika. (n.d.). *holografika*. Retrieved March 11, 2019, from holografika.com

Holography. (n.d.). *Holography*. Retrieved March 11, 2019, from http://holography.ru/holoflat.htm

Issa, R. (1999). Virtual Reality: A Solution To Seamless Technology Integration In The AEC Industry. *Construction Congress VI* (pp. 1007-1013). Orlando, Florida: American Society of Civil Engineers. doi:10.1061/40475(278)107

Jääskeläinen , J. (2011). *Holographic print from an architectural model.* Helsinki: Helsinki Metropolia University of Applied Sciences.

Kang , J., Ganapathi , A., & Nseir , H. (2012). Computer aided immersive virtual environment for BIM. *Proceedings of the 14th International Conference on Computing in Civil and Building Engineering*, (pp. 27–29). Moscow, Russia.

Khan, J. (2013). *Holographic volumetric 3d displays.* Association of Engineering Doctorates. Retrieved from http://www.aengd.org.uk/files/5213/8659/3616/EngD_Writer_of_the_year_-_Holoxica_final.pdf

Kim, E. (2007). Emerging 3D display technologies: holographic 3D, volumetric 3D and spacial 3D displays. *Korea IT Times*(200710(#4420)).

Ku, K., Pollalis, S., Fischer , M., & Shelden, D. (2008). 3D Model-Based Collaboration in Design Development and Construction of Complex Shaped Buildings. *Journal of Information Technology in Construction (ITcon), 13*(Special issue Case studies of BIM use), 258-285. Retrieved from www.itcon.org/2008/19

Meadati, P. (2009). BIM extension into later stages of project lifecycle. *Associated Schools of Construction 45th Annual International Conference*, (pp. 121-129).

Meža, S., Turk, Ž., & Dolenc, M. (2015). Measuring the potential of augmented reality in civil engineering. *Advances in Engineering Software, 90*, 1-10. doi:10.1016/j.advengsoft.2015.06.005

Migilinskas, D., Popov, V., Juocevicius, V., & Ustinovichius, L. (2013). The Benefits, Obstacles and Problems of Practical Bim Implementation. *Procedia Engineering, 57*, 767 – 774. doi:10.1016/j.proeng.2013.04.097

Morgan, M. (1960). *Vitruvius – The Ten Books of Architecture.* New York: Dover Press.

NBIMS. (2007). *National Building Information Modeling Standard.* National Institute of Building Sciences.

Onural, L., Yaras, F., & Kang, H. (2011). Digital Holographic Three-Dimensional Video Displays. *Proceedings of the IEEE, 99*(4). doi:10.1109/JPROC.2010.2098430

Pastoor, S., & Wöpking, M. (1997). 3-D displays: A review of current technologies. *Displays, 17*(10), 100-110. doi:10.1016/S0141-9382(96)01040-2

Philips News Center. (2013). *Philips*. Retrieved March 11, 2019, from http://www.newscenter.philips.com/main/standard/news/press/2013/20131028-philips-and-realview-imaging-conclude-worlds-first-study-to-evaluate-live-3d-holographic-imaging-in-interventional-cardiology.wpd#.VPaQFPnF-xU

RealView Imaging. (n.d.). *RealView Imaging*. Retrieved March 11, 2019, from http://realviewimaging.com/

Sawyer , T. (2013). *bimanywhere.* Retrieved from BIMAnywhere: http://www.bimanywhere.com/img/6-3-13-ENR.pdf

Sheppard, L. (2004). Virtual building for construction projects. *Computer Graphics and Applications, 24*(1), 6-12. doi:10.1109/MCG.2004.1255800

Sullivan , A. (2005). 3-Deep: new displays render images you can almost reach out and touch. *IEEE Spectrum, 42*(4), 30-35. doi: 10.1109/MSPEC.2005.1413728

Trimble . (2015). *Trimble White Paper.* Trimble. doi:https://community.trimble.com/docs/DOC-1923

worldviz. (n.d.). *worldviz*. Retrieved March 11, 2019, from www.worldviz.com

Yan, H., & Demian , P. (2008). Benefits and barriers of building information modelling. *Ren, A., Ma, Z. and Lu, X. Proceedings of the 12th International Conference on Computing in Civil and Building Engineering (ICCCBE XII) & 2008 International Conference on Information Technology in Construction (INCITE 2008).* Beijing.

Yang, L., Dong, H., Alelaiwi2, A., & El Saddik, A. (2016). See in 3D: state of the art of 3D display technologies. *Multimedia Tools and Applications, 75*(24), 17121–17155. doi:10.1007/s11042-015-2981-y

Zebraimaging. (n.d.). *Zebraimaging*. Retrieved February 5, 2016, from zebraimaging.com

Zspace. (n.d.). *Zspace*. Retrieved March 11, 2019, from zspace.com