Technische Universität München

Ingenieurfakultät Bau Geo Umwelt

Lehrstuhl für Computergestützte Modellierung und Simulation

Evaluation of augmented-reality applications for BIM-based design reviews

Bachelorthesis

für den Bachelor of Science Studiengang Bauingenieurwesen

Autor:	Hedi Moalla
Matrikelnummer:	[redacted]
1. Betreuer:	Prof. Dr.-Ing. André Borrmann
2. Betreuer:	M. Sc. Jimmy Abualdenien
3.Betreuer:	M.Sc. Florian Noichl
Ausgabedatum:	07. January 2020
Abgabedatum:	09. June 202

Abstract

Architecture Engineering Construction (AEC) industry are known for their inefficient service, poor quality, delivery delay, and cost overrun. To overcome these challenges, the construction industry is adopting a new method called Building Information Modeling (BIM). This procedure uses large databases of information to characterize almost all qualities and aspects of a structure or system. BIM is currently used for projects' design phases; therefore, BIM engineers complain about the lack of relevance during on-site work. With the help of augmented reality (AR), BIM models will move to the construction site. In the first part of the thesis, two research questions will be answered:

- **What are the beneficial effects that AR brings to BIM (RQ1)?**
- **What are the limitation and challenges of adopting AR and BIM at a construction site (RQ2)?**

In the second part of the thesis, several AR and BIM applications are reviewed and explained.

Zusammenfassung

Architecture Engineering Construction (AEC) Industrie ist bekannt für ineffizienten Service, schlechte Qualität, Lieferverzögerung und Kostenüberschreitung. Um diese Herausforderungen zu bewältigen, setzt die Bauindustrie eine neue Methode ein, die als Building Information Modeling (BIM) bezeichnet wird. Dieses Verfahren verwendet große Informationsdaten, Um fast alle Eigenschaften und Aspekte einer Struktur oder eines Systems zu charakterisieren. BIM wird derzeit für die Entwurfsphasen von Projekten verwendet. Daher beschweren sich die BIM-ingenieure über die mangelnde Relevanz bei der Arbeit vor Ort. Mit hilfe von Augmented Reality (AR) werden BIM-Modelle von der Entwurfsphase auf die Baustelle verschoben. Im ersten Teil der Bachelor Arbeit werden zwei Forschungsfragen beantwortet:

- Welche positiven Auswirkungen hat AR auf BIM (RQ1)?
- Was sind die Einschränkungen und Herausforderungen bei der Einführung von AR und BIM an einer Baustelle (RQ2)?

Im zweiten Teil der Bachelor Arbeit werden verschiedene AR und BIM Anwendungen überprüft and erläutert.

Contents

List of figures

List of tables

Abbreviations

BIM	Building Information Modeling
AR	Augmented Reality
VR	Virtual Reality
HMD	Head-Mounted Display
HHD	Handheld Display
CAD	Computer Aided Design
CDE	Common Data Environment
MR	Mixed Reality
HUD	Head-Up Display
SAR	Spatial Augmented Reality
GNSS	Global Navigation Satellite System

1 Introduction

1.1 Motivation

Digitalization in Architecture Engineering Construction (AEC) has revolutionized the architectural project's design. The use of intelligent 3D models is becoming a common practice in design phases to produce digital models. This technical approach goes far beyond the abilities of conventional Computer-Aided Design (CAD), so the construction industry calls such modeling Building Information Modeling (BIM) (Borrmann, König, Koch, & Beetz, 2018). BIM is revolutionizing the way of carrying out a construction project from start to finish. It is based on an integrated functioning of work teams and the use of 3D modeling, where all the stakeholders of the project collaborate (Borrmann, König, Koch, & Beetz, 2018). By integrating three-dimensional models and allowing various typical analyzes during the construction process, this tool promises work optimization, especially in terms of costs and time (Borrmann, König, Koch, & Beetz, 2018). In addition, BIM has a new concept of project management that allows the different stakeholders to work and exchange around digital models that contain project information (Abualdenien & Borrmann, 2019).

However, BIM model's usage is limited only to the design phase (Wang, et al., 2012). It is essential to link digital to physical work to stay competitive in market. Industrialization of the construction development necessitates a high level of automation and integration of information and physical resources. Both design and planning process in construction industry work with information rather than working with physical resources (Wang, Truijens, Hou, Wang, & Zhou, 2014).

Construction industry's actors tend to lean towards implementing established and tried technologies instead of applying new technological solution like augmented reality (AR). On the other hand, the need of communication technology and standardization of information was highlighted since the workers utilize different technological tools and perhaps dissimilar datasets. Therefore, AR is a great tool to bring virtual information into the real world and to overcome problems and different challenges that the AEC industry is facing due to lacking the use of digitization (Wang, Truijens, Hou, Wang, & Zhou, 2014)

Azuma, 1997 claims that AR helps the users to combines virtual objects with real ones so they can coexist in the same space. This technique amplifies reality, instead of entirely replacing it (Gheisari, Goodman, Schmidt, Williams, & Irizarry, 2014) and its applications are increasingly versatile (Wang, et al., 2012). Indeed, AR is a perfect tool to help the AEC industry to overcome certain challenges. Possible uses can extend to all phases of a project, from property development to design, construction and even maintenance (Wang, et al., 2012). Mobile tools are perfectly suited to the application of augmented reality since the user can move to any location and superimpose the virtual on the real object through an integrated camera. (Wang, et al., 2012)

1.2 Research goal and structure

the thesis' goal is to highlight the opportunities and challenges of integrating AR with BIM as well as reviewing different AR application for BIM design.

The thesis is divided in the following chapters:

- **In chapter 2** I review at first the BIM definition. In the second part of chapter 2 I present the definition and the history of augmented reality. Then I review possible applications of AR in different fields. Next, I explain the technological principles behind augmented reality (displays, tracking system, interface). Finally, I tackle the challenges and the difficulties of using augmented reality systems. In the last part of the chapter 2 I reveal the opportunities and challenges of integrating AR with BIM by answering to two research question:
    1. **What are the beneficial effects that AR brings to BIM (RQ1)?**
    2. **What are the limitation and challenges of adopting AR and BIM at a construction site (RQ2)?**
- **In chapter 3** I will review different AR application for BIM design. Discuss their benefits as well as the challenges
- **In chapter 4** I conclude the work and give an overview about the future work.

2 Literature Review

2.1 Building Information Modeling

The US National Building Information Modeling Standard defines BIM as follows (NIBS 2012):

‘’Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle; defined as existing from earliest conception to demolition. A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder’’.

Building Information Modeling is a procedure that uses large databases of information to characterize almost all qualities and aspects of a structure or system. The information preserved in BIM is different than the information retained by traditional design systems. BIM provides the user with sets of 3D objects, for example, walls, floors, doors, windows, and ceilings, which can be digitally built up to design a 3D model of a construction project. In addition, BIM stores vast amounts of regulatory and technical specifications for various architectural projects. 3D objects in BIM are further connected to a library of semantic data points, such as technical properties, component type materials, and possible cost ranges, that allow for a fully customizable building plan. Moreover, BIM allows collaboration between project stakeholders by either allowing collaborative single model workspaces or by sharing updated model information to stakeholders over the lifetime of a project. BIM is a robust process for design, construction or renovation, building management, even for demolition. (Borrmann, König, Koch, & Beetz, 2018).

BIM models are more than geometrical representations; therefore, they can be viewed in many dimensions, from 2D to 6D. The 2D model is no more than a two-dimensional drawing. The 3D model can be easily explored and manipulated, thus facilitating the understanding of the relationships between spaces, materials, and the system of a structure. The 4D model gives temporal information by allowing users to plan jobs and visualize progress in real-time. The 5D model integrates cost estimations by calculating the corresponding building budget. Finally, BIM can be extended into nD environment, including accessibility, logistic, safety, quality, maintenance, acoustics and energy simulation. (Wang, et al., 2012).

To simplify the enormous and complex workflows associated with BIM implementation, four levels of BIM, called maturity levels, have been defined (0,1,2 and 3). Level 0 is characterized by paper drawings or by 2D computerized drawings. Level 1 is a mix of 2D and 3D computerized drawings. In Level 1, the standardized date is shared in a common environment. Workers publish and update their own data, and non-geometric data is processed separately. In Level 2, the AEC industry produces its own 3D models, which they share with other companies and workers using the Common Data Environment (CDE). Here, the goal is to unify all models into a federated model, which allows for interference and issue detection. Level 3 is based on the full implementation of BIM and is characterized by the sharing of a single, collaborative model between all parties. (Borrmann, König, Koch, & Beetz, 2018).

Although BIM has helped to improve the AEC industry, it still has some challenges to overcome. BIM models contain an enormous amount of information, which can hinder their implementation. Wang, et al., 2012 claims that BIM is currently only used for projects’ design phases, and BIM engineers therefore complain about the lack of relevance during on-site work. To transfer BIM models to the construction site the researchers suggested the use of augmented reality (Wang, et al., 2012).

2.2 Augmented Reality

2.2.1 Terminology

2.2.1.1 Definition

Augmented Reality (AR) is described as a combination of virtual and real environments by superimposing digital information on the physical world. This virtual interface interacts in real-time with the user and with the physical world and stores real and virtual elements. Carmigniani et al. (2011) describe AR as an explicit or implicit real-time image of an improved real-world environment achieved by adding information created by computers.

In 1994, Milgram proposed a taxonomy for mixed reality, illustrated in Figure 2.1 (Milgram & Kishino, 1994). He admits the assumption that there is no clear border between physical and digital environments, but with the help of a continuum called mixed reality, it can switch from one world to the next. As shown in figure 2.1, the concepts of AR and VR are integrated into this continuum and are close to the real environment and virtual environment, respectively. On the one hand, AR involves a strong presence of physical reality with a weak integration of virtual reality, whereas, on the other hand, VR makes a total abstraction for the elements of the real environment.

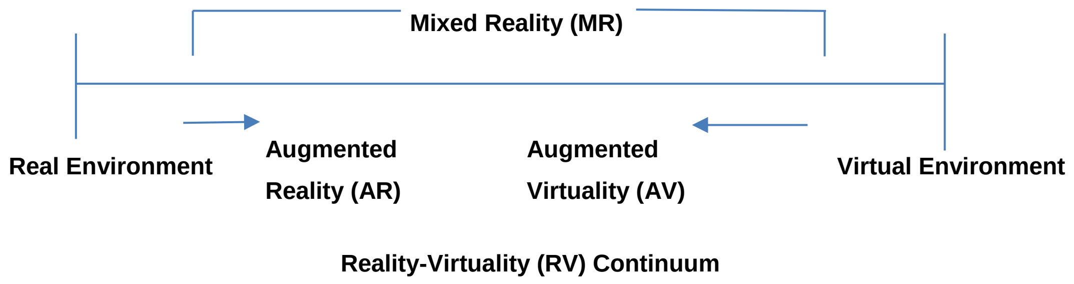

Figure 2.1: Continuum reality-virtuality according to Milgram (1994) (Milgram & Kishino, 1994)

Azuma, 1997 defined augmented reality as a system that mixed virtual objects with real ones so they can coexist in the same space. In addition, he describes that an AR system should have three features:

- Mixture of physical and virtual environments
- Interactivity in real-time
- Three-dimensional visual registration

AR purpose is to optimize the life of the user by delivering digital information not just of the surrounding environment, but also to some implicit perspectives of an actual-world related surrounding. Then, live video streaming can be included in AR. Moreover, AR increases the understanding and connection of the user with the real world. (Carmigniani, et al., 2010).

AR is not limited to some wireless technology like head-mounted displays (HMD), and it includes more senses than sight alone. AR systems can engage different senses, including smell, touch, and hearing (Carmigniani, et al., 2010). This system, therefore, offers a more interactive experience compared to virtual reality (Azuma R. , 1997). Today, several experts believe that augmented reality would gain increasing popularity compared to virtual reality due to its usability on a handheld device (mobile phones, tablets, and laptops) and its commercial use in several sectors (Carmigniani, et al., 2010)

2.2.1.2 Historical overview

Augmented reality first appeared in 1950 by Morton Heilig, who is a cinematographer. He claimed that cinema as an art should be able to pull the audience into the action on the screen. Continuing with this idea, he created a new prototype in 1962 named Sensorama, which he had proposed in ‘’The Cinema of the Future” in 1955. Then, in 1966, Ivan Sutherland created the first HMD. Two years later, he developed the prototype of the Augmented Reality system (Figure 2.2). Next, in 1975, Myron Krueger invented a video space that enabled user interaction with a virtual object. During the 1980s, the concept of Augmented Reality was mostly used in a military setting to display virtual information on aircraft windshields. In 1994, Milgram et al. defined the reality-virtuality continuum; Milgram interpreted the Augmented Reality to be included in a linear continuum that goes from real to virtual (Figure 2.1). Three years later (1997), Azuma conducted a survey of augmented reality, integrating 3D real environments with a 3D virtual environment in real-time. Then, in 2000, Bruce Thomas introduced a mobile game based on AR. In 2007 it was expanded to the medical field. After that, more AR application was created, such as the launch of the Wikitude AR Travel Guide in 2008. In the current era, it has expanded its operations and has been applied to the commercial, educational, medical, and construction industries, etc. (Carmigniani, et al., 2010)

Figure 2.2: Ivan Sutherland’s HMD (Carmigniani et al.,2011)

2.2.2 AR Application

There are many possibilities to use Augmented reality in different fields. For example, in repairs and maintenance, in the military for assisting personal, in medicine, while preparing surgeries, in Tourism and in games. This signifies the versatile uses of AR in various fields, including educational and commercial ones.

2.2.2.1 Military

One of the typical application examples of augmented reality used for military purposes is the Heads-Up Display (HUD). For the pilot’s sight, the see-through display is directed. Along with critical data, the usual view to the pilot is the airspeed, the horizontal line, and the altitude. As the pilot needs not to look down on the instrumentation of aircraft for required data, so it is termed as “heads-up.” (Mekni & Lemieux, 2014) The grounded army uses the Head-Mounted Display (HMD). Through this display, the soldier can have the enemy location and other critical data in line with their sight. Moreover, HMD is used to train a soldier to make a rapid decision allowing them to participate in a multitude of the simulated mission. (Mekni & Lemieux, 2014)

2.2.2.2 Medical education

In the education field, AR presents significant advantages for learning and skill acquisition. The practical and visual aspect of this learning allows improving comprehensive skills, for example, by allowing students to view an object in all its forms. Augmented reality will help students to be more active, and it provides a particularly interesting, playful side that helps to gain their attention and their enthusiasm. (Ramos, Trilles, Torres-Sospedra, & Perales, 2018).

Augmented reality in medical education helped students to feel more comfortable with the real clinical environment they are in. AR helps to create an experience transformative learning that allows users to visualize human anatomical structure as they would in a laboratory room with the corpse. Furthermore, AR helps to simulate many medical experiences, which would be difficult to simulate (Kamphuis, Barsom, Schijven, & Christoph, 2014). In this context, Blum, Kleeberger, Bichlmeier, and Navab, 2012 created a digital mirror that represents, in 3D dimensions, a virtual human organism. This system allows a better understanding of the human body.

2.2.2.3 Medical industry

Medical industries use AR, especially in surgery. This technique reduces the risk of operations as it provides the actualized 3D representations of the patient’s body and increases the sensory perception of the surgeon. However, there are concerns about tissue movement while doing surgery. Furthermore, With the AR technology, the doctor can easily explain to the patient about complicated medical conditions through visualizations (Carmigniani, et al., 2010). Bichlmeier, Wimmer, Heining, and Navab, 2007 built an AR simulation framework on virtual anatomy through the real skin, utilizing polygonal surface models to allow for time viewing.

2.2.2.4 Tourism

Tourism and sightseeing industries make an extensive use of Augmented Reality, as it can bring life to displays through augmentation. AR has enhanced the sightseeing industry in the real outer world. Using a camera-enabled smartphone, tourists can visit historic sites and see facts and figures presented as an overlay on their live screen (Mekni & Lemieux, 2014). Fritz, Susperregui, & and Linaza, 2005 created a see-through video system called PRISMA. It is the combination of binoculars and AR systems. PRISMA was developed to help the visitors to retrieve personalized and interactive multimodal details on the landmarks and the historic city buildings. Moreover, Marimon, et al., 2010 developed a Mobil device application called MobilAR. Tourists will now be able to see a 3D model of historic Monuments as they were in the past. This allows users to experience new things rather than reading and viewing photos.

2.2.2.5 Edutainment

Edutainment in another field that uses AR. Edutainment is a new term created in the 60s by Bob Heyman that explain the connection and positive relationship between the field of education and entertainment. It helps the learner to develop their skills faster and in an enjoyable way. For example, Kaufmann, in 2004, created an application to teach mathematics and geometry called construct3D. Another application called Dimexian was developed to teach algebra games and VR-ENGAGE to teach geography (Juan, Canu, & Giménez, 2008). In the Technical University of Valencia, Juan, Canu, & Giménez, 2008 conducted a study about integrating games in education using AR applications for children. This application is based on a storytelling about the Lion King, in which the children can control how to involve the story and its ends. The children visualized the game using an HMD and a monitor. The tale had eight different endings, and It consisted of a lion video that permits the kid to follow a changed Lion King. As a result, they are almost no difference in using both visualizations devices. Carmen Juan did another study in 2009 on the same topic, but this time is about finding and learning about different exotic animals in amusement and an enjoyable way and with the help of AR system that utilize a magnet and tangible cubes and compared it to the real game. Twenty adult participants participate in this study. As a result, the adults liked the AR game more than the real game.

2.2.2.6 Entertainment

Games industries use Augmented reality to make it more real. Unlike Virtual reality (VR), that amplifies the game experience by offering the player a 360-degree vision thanks to a close glass. AR superimposes the virtual image in the environment in a natural way. Integrating AR in games will not only help the player to experience a real adventure in an amusement way but encourage young people to be active. The most popular game that uses AR is Pokemon go; it came in July 2016. It is a mobile application that combines AR and geolocalization which helps for the search and the catch of Pokemons by going outside in the street, parks, etc. (Ramos, Trilles, Torres-Sospedra, & Perales, 2018)

2.2.2.7 Advertising

Advertising companies use augmented reality to insert a 3D element in a real environment. Advertising in automotive is the first to use augmented reality. Some car companies use a unique flyer that is recognized by webcams, then a 3D image of the advertised car is shown on screen AR, which immerses the consumer in the universe of a brand. It offers a memorable and unique sense of belonging. for example, some advertising companies allows the consumer to view the product at home or even try it virtually. (Mekni & Lemieux, 2014). Some researchers of the Institute of Industrial Technologies and Automation (ITIA) of the National Council of Research (CNR) in Milan created a system to try shoes virtually. An interactive mirror that allows to try on shoes virtually by standing in front of it without having to undress. The user can as well change color, model, etc., depending on the availability of the model on the store. (Carmigniani, et al., 2010)

2.2.3 Technological principals

2.2.3.1 AR displays

Augmented Reality (AR) displays make a clear border between the consumer and the environment—a private and mobile window that fully incorporates real and virtual data such that the virtual world spatially overlay on the actual world. AR display adapts light by visual means to provide a consumer with optical (figurative or graphic) data overlay on spaces, buildings, objects, or individuals. There are three significant displays: head-mounted display, handheld display, and spatial display.

a) Head-Mounted Display (HMD)

Head-Mounted Displays (HMD) is a viewing system placed on the head that puts all views, physical and digital in the user’s world view. Two sorts of HMDs exist :

- .Optical-See-Through (OST) devices provide a direct view of the real environment on which the virtual content is overprinted (Figure 2.3). Here, virtual and real are therefore combined optically via a semi-transparent mirror.
- Video-see-through offers an indirect view of the real environment. It is seen through two cameras arranged on the headset and the virtual world being digitally superimposed on the video signal before being presented to the user via the Video see-through displays (Figure 2.4). (Carmigniani, et al., 2010)

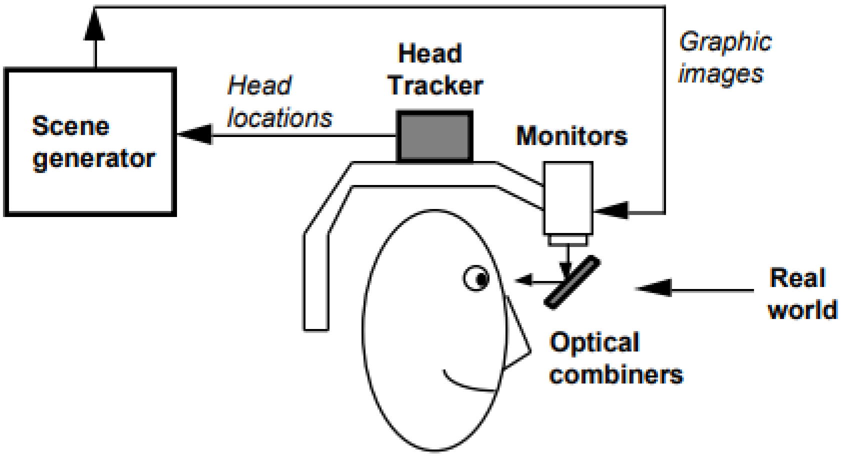

Figure 2.3: Optical see-through system by Azuma (1997)

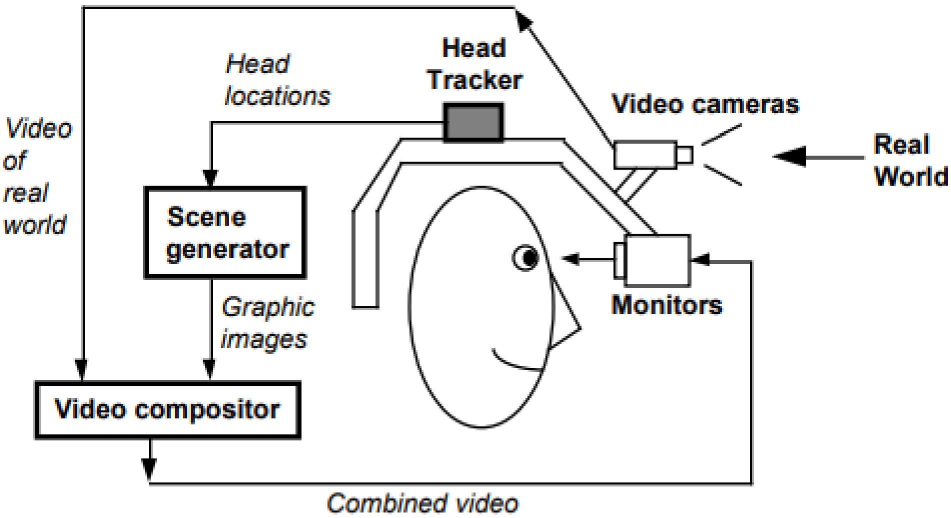

Figure 2.4: Video see-through system by Azuma (1997)

b) Handheld Display (HHD)

Handheld displays use small processing gadgets with a showcase that the client can grasp (Figure 2.5). They utilize video-transparent procedures to superimpose illustrations onto the genuine condition and utilize sensors, e.g., advanced compasses and GPS units, fiducial marker frameworks (ARToolKit), and PC vision techniques (SLAM). Smartphones, personal digital assistants (PDAs), and tablet PCs are three handheld display types. Smartphones are relatively well suited to augmented reality, as they are equipped with GPS, digital compass, a video camera, and communication devices. However, smartphones have limited computing power. Tablet PCs, unlike smartphones, have the necessary computing power for any type of augmented reality application, if they are equipped with the equipment adequate. However, it is difficult to hold the tablet with one. Moreover, their size and weight do not allow prolonged use. Finally, PDA’s are like a smartphone, but with the release of Androids and iPhones, they are becoming less used (Carmigniani, et al., 2010)

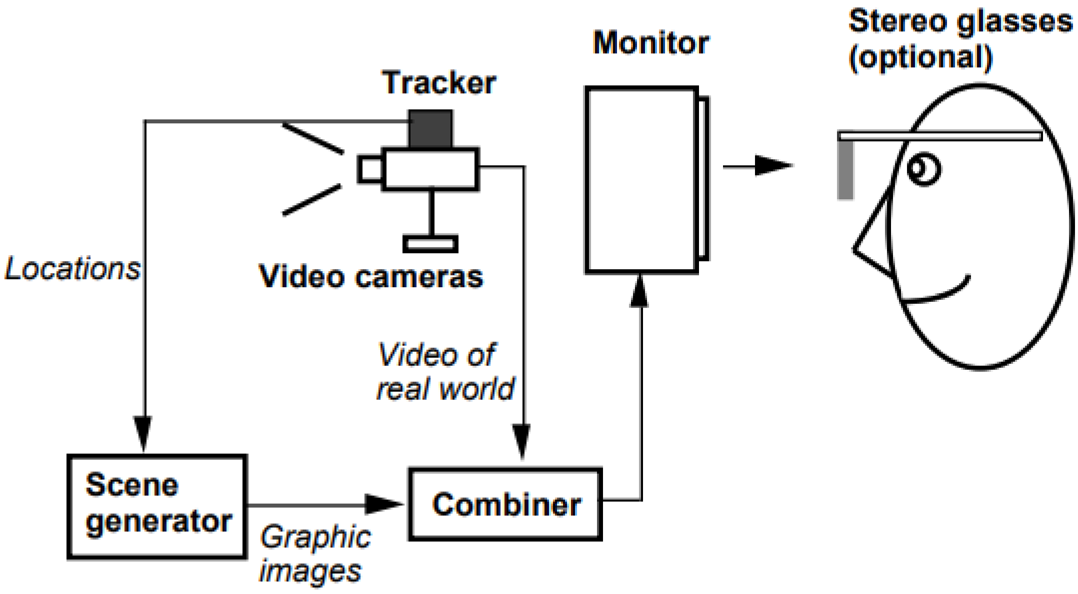

Figure 2.5: Handheld display device by Azuma (1997)

c) Spatial Display

Spatial Augmented Reality (SAR) display systems are included within the space in which the user evolves. This system offers the possibility of using several displays devices and allows multiple users to perceive the same increase within a physical environment. Spatial reality separates most of the innovation from the client and incorporates it into the surrounding environment. The spatial display can be divided into three types. First, Video-see through displays utilizes traditional monitors like screens. This type of display is easily integrated into the design of a SAR. Moreover, video monitors are affordable and allow anyone to do their own SAR installation. In addition, the use of mobiles is not necessary for this kind of display. Second, optical see-through displays which produce photos related to the real environment. Transparent screens, planar or curved mirror beam splitters, or optical holograms are examples of SAR display. Finally, Projector-based spatial displays, which are based on the concept of direct augmentation of real-world objects. A projector fixed in the environment is used and presents the digital information on the objects which are increased. (Carmigniani, et al., 2010)

d) Conclusion

All these three displays are different from each other. Handheld displays provide an interface only to one user and small-scale display. The head-mounted display provides a display to every single individual separately, but the resolution of the scene or movie is better than the handheld displays of augmented reality. However, spatial displays are different from both. They provide a direct interface to the users collectively. Every single individual does not need to use the system. It offers high resolution and better-quality displays to users than the other two types. (Table 2-1) (Carmigniani et al.,2011)

Types of displays techniques	HMD		Handheld			Spatial		
	Video-see-through	Optical-see-through	Video-see-through			Video-see-through	Optical-see-through	Direct Augmentation
			Types of Displays	HMD	Handheld			
Advantages	-Complete visualization control -Possible synchronization of the virtual and real environment	-Employs a half-silver mirror technology -more natural perception of the real environment	-Portable -widespread, -Powerful CPU -camera -accelerometer -GPS -solid-state compass	-Portable -Powerful CPU -Camera -Accelerometer -GPS -Solid state compass	-More powerful	-Cost efficient -Can be adopted using off-the-shelf hardware components and standard PC equipment	-More natural perception of the real environment	-Displays directly onto physical objects' surfaces
Disadvantages	-Requires user to wear cameras on his/her head -Requires processing of cameras video stream -Unnatural perception of the real environment	-Time lag -Jittering of the virtual image	-Small display	-Becoming less widespread -Small display	-More expensive and heavy	-do not support mobile system	-Do not support mobile system	-Not user dependent: Everybody sees the same thing (in some cases this disadvantage can also be considered to be an advantage)

Table 2-1: Comparing technologies of different types of displays (Carmigniani et al.,2011)

2.2.3.2 HMD vs. HHD devices

a) Study 1: Microsoft HoloLens vs. Google Tango tablets

Riedlinger, Leif, & Prinz, 2019 conducted a study to compare Google Tango tablets with Microsoft HoloLens. The researchers divided the study into two tasks, one for the interior design and the other for Building maintenance.

The researchers choose 16 participants from different academic levels (Students, Professors, and research assistants), including two architects. These participants are divided into groups of two, each of them should complete four tasks (two tasks with HoloLens and surface tablet, and two with Tango tablet). In the end, each participant will answer questionnaires about the devices.

For the first part, the Participant A uses the tablet by creating two different interior design and presenting it to participant B. Then A had to sell one of them to B. After that, A chooses a place at the ceiling to build something and B checks with the tablet if that is possible. In the end, they answer the tablets questionnaire. For the second part, B wears smart glasses to check if the interior design fit the room with the aid from participant A that follows him with a surface tablet. After that, B will build something on the wall and A checks with the Microsoft HoloLens if it is possible. In the end, participants evaluate HoloLens and compare both devices. (Figure 2.6)

Figure 2.6: Participant in the left are using Tango tablet and participants in the right are using HoloLens and a surface tablet (Riedlinger, Oppermann, and Prinz (2019)

The results show that the participants favored the tango on HoloLens:

For the interior Planning part, Tango had received the maximal rating (1.0), while HoloLens had an inferior result (2.5). According to the participants, the tablet is more practical in the interior design than the smart-glasses. HoloLens has two significant problems: the first one, the connection lagged for four seconds between HoloLens and the Surface tablet. The second one, the use of the Surface tablet, is limited; it was like a Mirror.

For the Building maintenance part, Tango still has a better rate (1.875) then the HoloLens (2.375), but the results still lower than the interior planning part. The participants interpreted that there is a difficulty in measuring a plan in 3D models, sometimes there is a missing caption or additional information on the 3D design. Moreover, using the tablets is not comfortable for the arm, especially when it is pointed to the ceiling, and wearing HoloLens give only a small field of view.

b) Study 2: Google Glass vs. Tablet PC

Wille, Wischniewski, Scholl, & Laerhoven, 2014 compared a guidance system using Google Glass and Tablet PC for assembling tasks. Twenty adults aged between 18-67 years participated in this study using the head-mounted displays (HMDs), and ten adults aged between 21-59 years used the handheld display. The researcher divided the study into two tasks. Each participant had to perform the two tasks at the same time, as quickly and precisely as possible.

On the one hand, participants were given a toy car base on the Lego Technik to assemble, where they were given step by step graphic instructions by researchers. The difficulty of the task was increased by adding several construction bricks in every step. Then, the performance was measured by the number of the lego assembled.

On the other hand, the participants were required to observe and note the monitoring task. The assembled slides in the step were presented parallel to this task. Three bars changed their length every 94.45 seconds and changed color between red and blue every 106.44 seconds (Figure 2.7). Every time the longest bar position changed, the user of Google glass said, “bar changed,” and the user of the tablet double tapped on the screen.

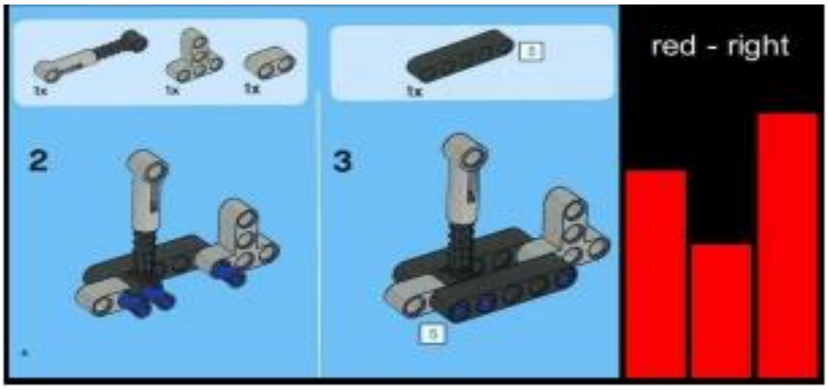

Figure 2.7: Assembly task on the right and monitoring task on the left (Wille, Wischniewski, Scholl, & Laerhoven, 2014)

As a result, there is no significant difference between the two devices. However, the participants using the tablets have a higher number of processed slides than the one using Google Glass. Head-mounted displays (HMDs) are theoretically perfect for workers as it allows the worker to do manual tasks while using the device. Though, while using this device, participants experienced a higher level of mental fatigue, and they had some visibility problems after continuously using it for multiple hours.

c) Study 3: Google Glass vs. Google Nexus 7 tablet

Johnson, Gibson, & Mutlu, February 2015 carried out extensive research on comparing Google Glass with Google nexus 7 tablet. In this study, 66 participants were selected to build a toy car using either an HMD or Handheld device. The work done in pairs, one participant took the role of ‘’ the worker’’ to do all construction work guided and assisted by the other participant ‘’ the helper’’, who has the detailed plan of the car. The worker used either of the two devices, Google glass or Google Nexus 7 tablet, for this experiment, whereas the helper had to use a computer that had a camera and microphone to make it easier for him to communicate with the worker mentioned above.

Two tasks were randomly given: a dynamic task (a high level of mobility) and a static task (a lower level of mobility). For the static part, the elements required to construct the entity were distributed into three different groups located at the worker’s desktop. But, three different desktops were used for the dynamic part of the task, and the important elements in this part were placed on them (Figure 2.8). The worker was only permitted to transfer pieces from the desktop if the elements were already attached or else if only one piece was being carried by the worker. The researcher focused on this study on collaborative behavior, collaborative performance, and collaborative perceptions.

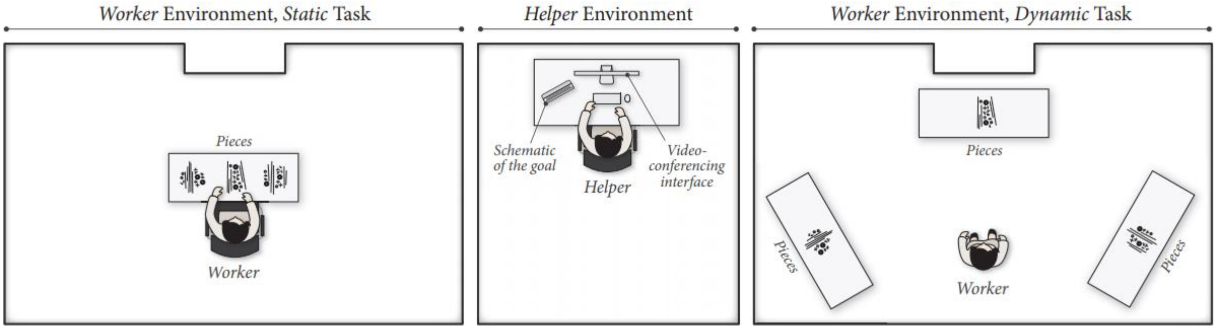

Figure 2.8: Static task (left), the helper's room (center), and dynamic task (right). (Johnson, Gibson, & Mutlu, February 2015)

As a result, the use of Google Glass in the dynamic part allowed the helper to give more frequent commands and provide support, leading to finishing the task faster. In the static part, the helper had a higher collaboration with the worker, when the last uses the tablets instead of the HMD, due to the wide view that the tablet can offer. The use of tablets aided to transfer the information that was visually sophisticated. As a result of this, a variation was observed in the views of helpers and workers about the devices and how they devoted their success.

d) Conclusion

According to the previous studies, both devices have advantages and disadvantages (see the table 2-2 below):

	Head-Mounted Display	Handheld devices
Previous studies	+Combination of virtual and real world +More enjoyable +More comfortable +natural view-point selection - heavy on the eye - Small wide angle of view -complicated GUI interaction with gesture and clicking -Mental fatigue -Energy problem (the device gets warm fast)	+easier to use +better field of view +more comfortable to share with other +Less distracting + The ability to point at the screen -Display size -More arm works -Tracking stability -less immersive

Table 2-2: Summarizing both the advantages (+) and disadvantages (-) of HMD and HHD

2.2.3.3 AR interface

AR interface permit to the users to interact with digital information using the appropriate techniques. AR interfaces types are Tangible interface, Collaborative interface, Hybrid interface, and Multimodal interface

a) Tangible Interface AR

The development of various tangible AR interfaces are supported by the invention of novel sensing and display development. Using surfaces such as tables and walls, these systems offer a tangible correspondence between the input and the projection of the technological surface. Moreover, they allow a direct interaction of the user with the information by touch and hand gesture (Mistry, Maes, & Chang, 2009). An example of a tangible AR interface is Oblon’s g-speak system. This system is a touch-independent collaborative computing program supporting a wide range of freehand gestures.

Carmigniani, et al., 2010 found that tangible interfaces mainly advocate for direct relationships with the real enviroment through the exploitation of the real, corporeal entities and instruments. VOMAR is a critical example of tangible AR interface systems established by Kato et al. VOMAR enables the individual to select as well as reshuffle the furniture within AR spacing by use of a real physical paddle. (Carmigniani, et al., 2010).

b) Collaborative Interface AR

Being able to collaborate remotely with other people can provide valuable capabilities to perform tasks that need multiple users. In addition, Augmented reality technologies are interesting tools for developing new types of applications offering more natural interactions and possibilities of perception compared to conventional systems. A group of researchers used the AR collaborative application on a tennis game. Two players used their phone camera by pointing them to the ARToolkit markers. Then they saw a virtual tennis stadium overlaid on the actual world. The players hit each other virtual balls with the use of their phones. Every time the virtual ball hit the phone, the players could hear a sound and feel a vibration (Zhou, Duh, & Billinghurst, September 2008).

c) Hybrid Interface AR

Hybrid AR interfaces integrate different but complementary interfaces into a single system. These interfaces interact via a broad spectrum of interaction devices. As a result, they offer a flexible program for unplanned daily interactions. (Carmigniani, et al., 2010) Emmie is an example of a hybrid user interface. It helps the user to share 3D virtual space and to manipulate virtual items using computers, displays, and devices. It helps to complement and exchange information between different displays (Zhou, Duh, & Billinghurst, September 2008).

d) Multimodal Interface AR

The multimodal interface combines several methods of communication between the user and the machine, such as hand gesture, speech, gaze, or touch. Irawati, Green, Billinghurst, Duenser, & Ko, 2006 have investigated the scheme then evaluated the augmented multimodal interface applying to both speech and paddle gestures. The interface depicted some interaction of visual materials in the actual environments of the world and the virtual environments. The study focuses on the assessment of the effectiveness of multimodal interaction/interface within the augmented reality environment. Media Room was the first multimodal interface that combined speech and gesture recognition (Carmigniani, et al., 2010). The Media Room was importantly advocated for the interaction of the users and computers by the use of voices, gestures, and sight. In the same context, (Irawati, Green, Billinghurst, Duenser, & Ko, 2006) have found that multimodal interfaces are intuitive since the strength of the voice input is complimenting the restrictions of gesture interaction and vice-versa. The speech interfaces suitably fit into the descriptive approach, and gestural communication is sufficient for the undeviating influence of objects (Zhou, Duh, & Billinghurst, September 2008). Therefore, when they are applied together, combined speech, as well as gesture input, they create a more robust interface.

2.2.3.4 Augmented Reality Tracking systems

AR needs accurate position as well as orientation tracking systems to align and register digital data with the real world that are supposed to be annotated. Azuma R., 1997 noted that the outdoor augmented reality Systems should track precisely and make decisions accordingly. A survey of different tracking techniques by Rabbi & Ullah, 2013 reveals that a large amount of work has been done to find out viable and most efficient tracking mechanisms. These are various tracking techniques used in AR, including optical tracking system, sensor-based tracking, magnetic tracking, inertial tracking, acoustic tracking, hybrid tracking, vision-based tracking, maker-based tracking, and markerless tracking, etc. (Figure 2.9) (Rabbi & Ullah, 2013)

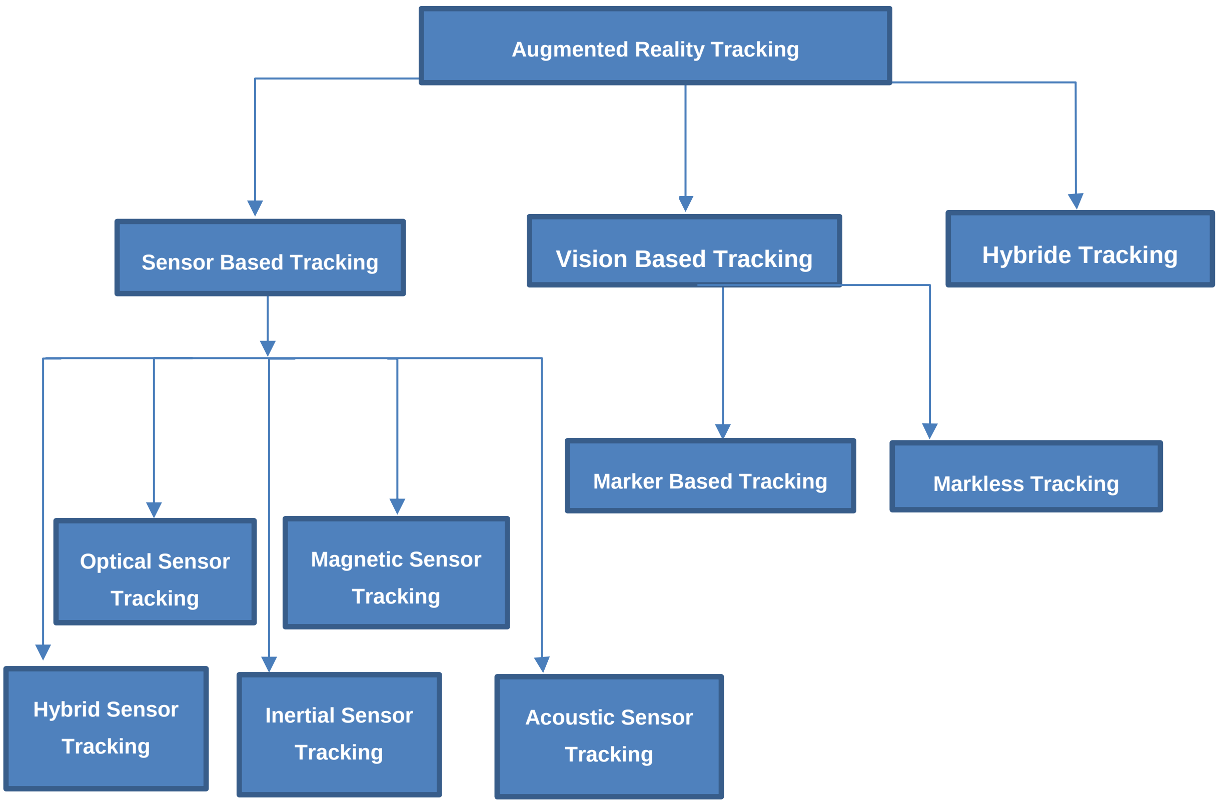

Figure 2.9: Augmented Reality Tracking systems (Rabbi & Ullah, 2013)

a) Sensor-Based Tracking

There are many types of Sensor-based tracking, such as optical, magnetic, inertial, acoustic, and hybrid sensors (Rabbi and Ullah,2013). The selection of the sensor used depends on various considerations such as accuracy, calibrations, expensiveness, range, resolutions, and environmental conditions like temperature and pressure. For example, magnetic sensors are used because of their high update rate and light. However, accuracy can easily be disabled due to the presence of a Metall. (DiVerdi and Hollerer, 2007).

Ullah, 2011 have studied the optical tracking system in detail. In this type of sensing, visible light or infrared radiations are employed to sense the object position. It was noted that using one camera provides a two-dimensional view, while two or more cameras give a three-dimensional view of the target object. The cameras are installed at varying angles. The position of the object is determined by the coordinates of these cameras and helps in the process of decision making.

Another example is the inertial sensor-based tracking systems. In this type of tracking, a mechanical gyroscope or an accelerometer is used and the principal of conservation of the angular momentum is put to work. For example, changes in position are calculated through a double integration of productions of the accelerometers using their acknowledged alignments (Rabbi & Ullah, 2013). In the acoustic tracking system, Ullah, 2011 noted that the ultrasound transmitter and sound sensor are employed. The time taken by the sound from the object to the sensor is measured, and the position is calculated by them.

Hybrid tracking technique is a combination of different sensors to develop hybrid sensor tracking system. For instance, the inertial and magnetic tracking system can be combined in one tracking system (DiVerdi & Hoellerer, 2007). In this system, magnetic monitoring has been applied to offer a reliable approximation of both position and orientation, which is manipulated in real-time by optical tracking. These approximations lead to a faster and dependable tracking system compared to the optical tracker and the magnetic tracker. Rabbi & Ullah, 2013 claim that AR application computer vision in standalone cannot offer firm tracking solutions. As a result, hybrid methods have been created, combining various sensing technologies.

b) Vision-Based Tracking

Zhou, Duh, & Billinghurst, September 2008 have noted that vision-based tracking is widely popular in today's industry. Vision-based tracking uses the vision methods of the computing device to measure the position of the object. It can be divided into marker-based tracking and markerless tracking. Papagiannakis, Singh, & Magnenat-Thalmann, 2008 have noted marker base tracking are widely used in AR. These markers are black and white and consist of a simple pattern surrounded by a black border (Fig 2.10). A virtual object can be inserted into this repository local then projected on the display screen according to the user field of view. The markers must, however, be presented at all times in the field view of the camera. Vision markerless-based tracking is a visual tracking algorithm providing realistic real-time camera tracking based on a number of metho such as edge detection, planar strategies, and natural feature detection. However, markless tracking system demands a large amount of power to process, thus producing challenges on the additional augmented reality rendering activities (DiVerdi & Hoellerer, 2007)

Figure 2.10: Examples of Marker Based Tracking (Rabbi & Ullah, 2013)

c) Hybrid Tracking System

Combining several sensing and tracking techniques, some researchers suggested a hybrid tracking system that is more helpful in obtaining accurate and precise results. Azuma, et al., 1998, emphasized that out of a large number of tracking techniques, not a single technique can give a complete solution. The better idea is to use a hybrid tracking technique to ensure the efficiency of the overall tracking system. For example, combining inertial sensor with vision based to obtain a hybrid system. Inertial sensor track stereo images and a camera orientation to create a reliable tracking device, while the vision-based is utilized to measure the location and the orientation of the camera by tracking markers in the real world. (Rabbi & Ullah, 2013)

2.2.3.5 Augmented Reality Challenges

Aside from the enormous potential of AR technologies, there are some challenges that the AR system still needs to overcome. Several scholars studied the problems associated with Augmented Reality. As stated by (Rabbi & Ullah, 2013), five challenges augmented reality systems need to overcome:

- **Performance challenges:** Consist of real-time computing, reacting, and progressing with the change of real-world environment.
- **Alignment challenges:** AR systems should permanently align the virtual object on the real object. It should know the user's location and orientation to adjust the information displayed according to the field of view. Technically alignment problems lead to registration problems and tracking problems. A tracking system with a lack of precision induces an alignment instability of the virtual on the real object.
- **Interaction challenges:** represents the user's interaction simultaneously, with real and virtual objects. The interaction adopts several interfaces that could be tangible, acoustic, gaze, haptic, or text-based. It permits the user to interact with digital objects; this can lead to different interaction problems.
- **Mobility challenges:** The portability of Augmented Reality systems represent one of the mobility challenges. As being small and light, these systems could be used anywhere. Thus, being portable outside a controlled environment characterize the best Augmented Reality systems.
- **Visualization Challenges:** Current AR Display struggle from several problems, for example, resolution, field of view, contrast, and brightness. Additionally, AR devices suffer from poor occlusion. it is defined as the "process which determines which surface or its part are not visible from a certain viewpoint." Therefore, virtual objects can have a realistic view by having a similar occlusion as the real object. Moreover, real and virtual objects should have the same illumination.

Apart from these challenges, Mekni & Lemieux, 2014, and Papagiannakis, Singh, & Magnenat-Thalmann, 2008 stated that social acceptance and social privacy should also be taken into consideration when it comes to the growth of AR application in a different field.

2.2.4 Integrating Augmented Reality with Building Information Modeling

2.2.4.1 AR and BIM

Integrating AR with BIM has helped the Architecture Engineering Construction (AEC) industry to plan projects more efficiently and effectively. The integration is examined in different scientific studies relevant to engineering, construction architecture, inspections, construction and maintenance, training and education (Wang, et al., 2012)

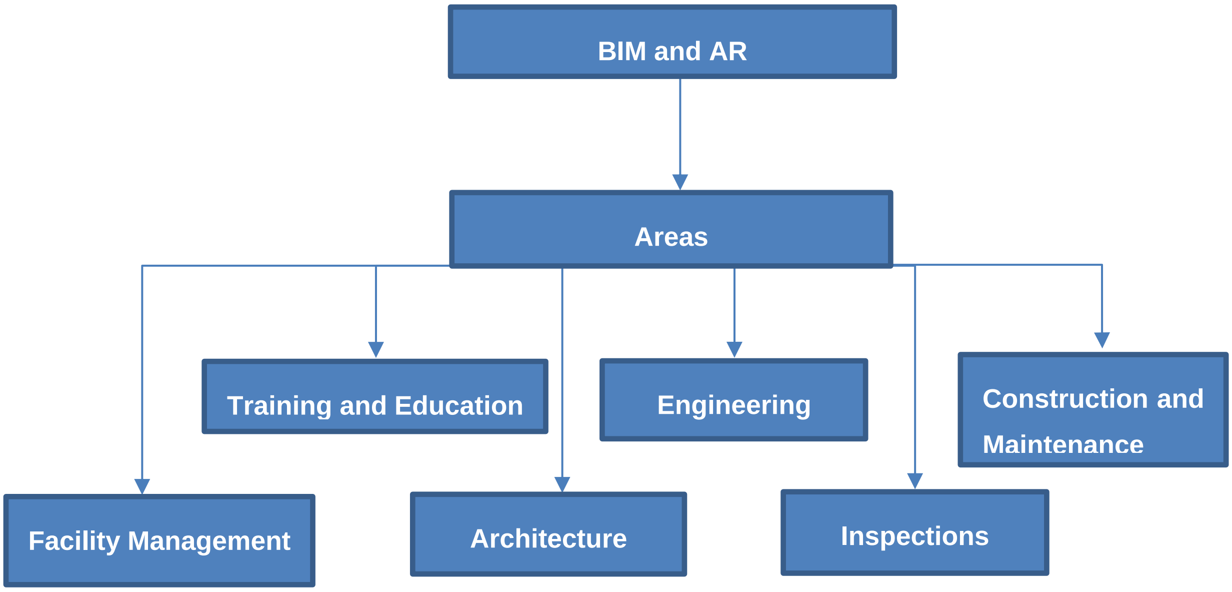

Figure 2.11: Application domain AR with BIM (Wang, et al., 2012)

Wang, et al., 2012 conducted a study about mixing AR with BIM. They examined how to integrate AR with BIM to visualize each construction task by giving it a physical context. According to their study, although BIM aids the design coordination by improving its efficiency and making it more effective, it fails to calculate uncertainty that is related to changes in design and rework. This situation prevails during construction, especially for complex projects (Wang, et al., 2012). The study further suggests that AR and BIM can give contractors a complete three-dimensional (3-D) interactive solid model, providing a visual understanding of the design's details (Wang, et al., 2012). Augmented Reality in BIM can present the data on-site, which gives a real-time dynamic and active planning environment for site managers. Moreover, the information in AR provides on-site workers with a better understanding of the building sequencing (Wang, et al., 2012).

Wang, Truijens, Hou, Wang, & Zhou, 2014 conducted an additional study about the use of AR in the construction of a liquefied natural gas (LNG) industry plant. The researchers discussed the requirement of a structured methodology for entirely incorporating AR technology in BIM. BIM-based navigation technology, along with AR, can be used to find out the exact location of a component's presence in a construction site or a warehouse (Wang, Truijens, Hou, Wang, & Zhou, 2014). AR-based visualization of information in BIM gives an improved and better understanding of on-site work, which ultimately leads to increased productivity. Furthermore, the use of the AR-based on-site assembly in BIM can help workers efficiently recognizing the interdependency of every installation stage. This, in turn, minimizes the errors and rework that result by using the wrong component, installation sequence, or installation path (Wang, Truijens, Hou, Wang, & Zhou, 2014). The study suggests that BIM must be information critical, context-aware, and intellectual for it to be integrated with Augmented Reality on-site in a better way (Wang, Truijens, Hou, Wang, & Zhou, 2014). Their study lacks the use of 4D and 5D in BIM + AR in the construction of the LNG plant.

Architectural visualization is used in balancing constraints and requirements to make the interactions between the owners and designers flow easily (Abualdenien & Borrmann, 2020). Wang, Wang, Shou, & Xu, 2014 conducted a study on the use of BIM and AR for architectural visualization. The researchers stated that traditional practice of architectural visualization, like static pictures or three-dimensional scale models, is tedious, extensive, and time-consuming (Wang, Wang, Shou, & Xu, 2014). Moreover, 2D and 3D models are expensive and are not adaptable as one would have to do all the work manually to make minor changes. The 3D scale model does not give any practical guide to help in the construction but is only used in providing the architectural appearance of the structure (Wang, Wang, Shou, & Xu, 2014). However, BIM and AR are a system of integration that provides a further intuitive and immersive environment that alleviates the stakeholders' mental burden (Wang, Wang, Shou, & Xu, 2014). BAAVS (BIM and AR for Architectural Visualization System) improves work productivity, reduces its production cost and provides an improved level of architectural visualization. It allows the designers to place a digital building scheme in a real environment. The users can get a unique experience, which lets the property sellers efficiently and professionally communicate with their customers (Wang, Wang, Shou, & Xu, 2014). Although this system is quite efficient, it still has some drawbacks that make it less practical for use. Creating augmented reality scenes, updating information, and converting the texture is a time-consuming, and laborious (Wang, Wang, Shou, & Xu, 2014)

Office managers are required, on a regular basis, to connect physical articles to database information. Therefore, AR makes a decent method to support them with their normal tasks, as their live perspective on space could further be enhanced by the database information they need and all in one interface (Gheisari & Irizarry, 2016). Gheisari , Goodman, Schmidt, Williams, & Irizarry, 2014 have developed a conceptual framework to enable maintenance workers to conduct routine on-site research, incorporating models of information and realistic indicators for AR-related maintenance assistance.

Furthermore, Koch, Neges, König, & Abramovici, 2014 integrated the innovative methods of BIM, including Augmented Reality (AR), which has provided facility administrators an accessible and easy way to communicate the information they need from BIM models. A detailed and thorough BIM system that integrates the needed information along with a 3D structure of overall items in the facility possibly will be used as a server, which is combined with an Augmented Reality solution to include an immersive intellectual atmosphere for facility administrators.

Williams, Gheisari, Chen, & Irizarry, 2015 developed a Mobile Augmented Reality (MAR) application and integrated with BIM called BIM2MAR. As reported by the researchers, integrating BIM with a MAR system would be a “transparent window” that will offer the required information to the system managers or the target users to perform their tasks successfully. To work, there are several steps to be followed. The first requirement for this system is to generate geographic location and properties of the target objects, which can later be used to define the location of the user. Then, to utilize BIM in a MAR, a couple of exchange formats are used to discrete geometry and data property sets. However, the idea of implementing such a model completely still faces a few challenges, and there is still room for improvement. As this study suggests that once an entirely automated BIM2MAR system is configured, the system will automatically use the instantaneous information and its results produced to update the changes made in the Building Information Model. (Williams, Gheisari, Chen, & Irizarry, 2015)

2.2.4.2 Challenges of Integrating AR with BIM

A survey of previous papers reveals that some pertinent issues tend to be a major stumbling block in the integration of AR with BIM. These issues can be categorized as technical, operational, material, and logistics challenges.

As for the technical challenges, an issue was encountered by almost all the experiments and pilot studies while integrating AR with BIM was the drift problem. As mentioned by Williams, Gheisari, Chen, & Irizarry, 2015, the drift appears as the result of a misalignment of the virtual augmentation from the real object. Resultantly, the users do not trust the measurements taken by AR and tend to take their own set of measurement values to analyze. In the same study, they found that the subjects were leaning back from their standing place to observe the augmented information. Secondly, the results were found based on partial processing of the information, beginning from the color of the target to their geometric properties. It was also noted that after a little acquaintance with the apparatus, the users were able to translate the differences in the values that were arisen due to drift.

As for the material challenges, it was seen that the inaccuracies of measurement are the result of the use of consumer-grade materials in the construction of accelerometers and gyroscopes along with other instruments. Williams, Gheisari, & Irizarry, 2014 highlighted a difference of several centimeters when these materials are used. To rectify this error, real-time measurements are taken, and the values are fed to CAD, which is a long and time-consuming process.

Williams, Gheisari, Chen, & Irizarry, 2015 have studied BIM2MAR workflow implementation. They found that this implantation poses many technical and logistical problems that are needed to be addressed. For one, BIM is not taken as a comprehensive, standard package with all the solutions available for the construction industry. Instead, it is only considered as the solution for specific problems and is used at certain phases of the construction project. For other phases, the practitioners prefer other tools like CAD. The utilization of BIM promises to reduce measurement mistakes and so, it must be available in the form of a standard package for all phases. If BIM is improved in such a way to compete with other tools as well, its applications will give birth to more innovations in the AEC industry. Two, the alignment of a virtual camera and a real camera is not accurate when it comes to the use of BIM. If these problems are solved, the integration of AR with BIM can go hand in hand for a long time, and phenomenal progress will be noticed.

Not only this, but Williams, Gheisari, Chen, & Irizarry, 2015 also noted that further research is necessary to be focused on the design requirements for the application of AR in AECO. More efforts is required to make the system more realistic and competitive in the individual stages of the building cycle.

As for operational challenges, Williams, Gheisari, & Irizarry, 2014 have found that the BIM software is quite different as compared to other construction management software already used by the construction managers. Resultantly, they face certain difficulties in recording and assigning the routine tasks for the team. Moreover, there is no facility to customize the software as per the practices of the facility managers in the construction industry. These limitations in the software are because of the lack of family structure in Revit which is the user-oriented software of the BIM.

2.2.5 Conclusion

BIM technology has led the AEC industry to digitalization. It provides a 3D model representation, containing all the elements of the projects and shares platform for information exchange and communication between projects. Moreover, BIM technology has reduced the reputation of bad service, poor quality, delivery delay, and cost overrun that the construction industry obtains.

However, BIM technologies are only used in the design phase. The operational and integration of information development in BIM during design with construction site is challenging. With AR entering the AEC industry, it will help them to overcome these challenges. This is because AR has proven its efficacy and efficiency in other domains, e.g., military, medicine, advertising, tourism, entertainment, etc.

Based on the findings mentioned above, two main research questions (RQ) are answered in the table below.

- **What are the beneficial effects that AR brings to BIM (RQ1)?**
- **What are the limitation and challenges of adopting AR and BIM at a construction site (RQ2)?**

RQ1	RQ2
-Real-time visualization of the design (Wang, et al., 2012) (Wang, Truijens, Hou, Wang, & Zhou, 2014)	-Misalignment virtual object with a real object. (Williams, Gheisari, Chen, & Irizarry, 2015)
-Improve understanding of the concept (Wang, Wang, Shou, & Xu, 2014) (Wang, Truijens, Hou, Wang, and Zhou, 2014)	-Acceptance (Williams, Gheisari, & Irizarry, 2014)
-Improve communication (Wang, Wang, Zhou, and Xu, 2014)	-Weak tracking system (Wang, Wang, Shou, & Xu, 2014)
-Cost reduction (Wang, Wang, Shou, & Xu, 2014) (Wang, Truijens, Hou, Wang, & Zhou, 2014)	-Lack of powerful AR device (Wang, Wang, Shou, & Xu, 2014)
-increase productivity (Wang, Wang, Shou, & Xu, 2014)	-Requires engagement of the entire working team (Williams, Gheisari, & Irizarry, 2014)
-Reduce the number of errors and flaws (Wang, Truijens, Hou, Wang, & Zhou, 2014)	-Lack of standardization of information and communication technology (ICT) tools (Wang, Truijens, Hou, Wang, & Zhou, 2014)

Table 2-3: Summary of the opportunities and challenges of integrating AR with BIM

3 Market Analysis

In this chapter, several AR and BIM applications are reviewed. I will highlight the application features, challenges, and limitations. Every application is tested with an iOS device (iPhone XS) in 20cm² room.

3.1 Gamma AR

Gamma AR is an application that uses AR technology to overlay 3D models using smartphones or tablets for construction industry. It helps the users to compare the real work with the planning information contained in the project. Moreover, Gamma AR connects the construction site and the office via a portal. This platform enables the user to access any annotation, photos, issues, reports at any time. Gamma AR features include:

- Avoid errors.
- Monitor the progress.
- Precise commentaries on the object with audio registration or with writing as well as taking pictures.
- Avoid interpreting the 2D plan.
- Combine multiple models.
- Tabletop presentation.
- Connecting the construction site and the office via a portal.

Comments:

Gamma AR provides a trial period with a demo model as illustrated in the Figure below. (Figure 3.1)

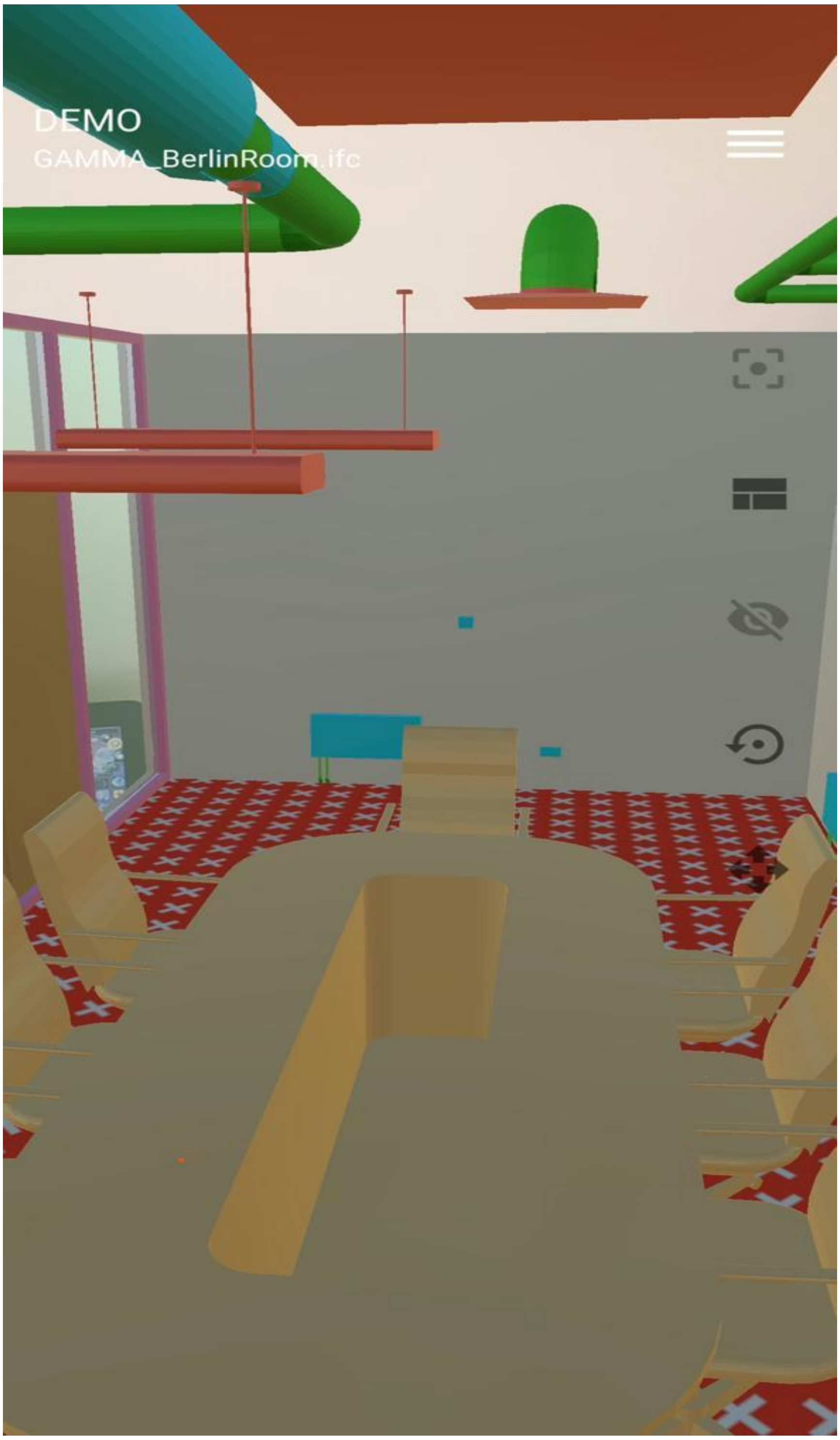

Figure 3.1: Demo model from Gamma AR

3.2 ARki

Sarah Fikouhi founded the design studio Darf Design in 2012. The studio combines designers, engineers, and developers, all working together to create innovative AR experience. The company has succeeded to create AR applications in a different field, such as gaming and architectural industries. For example, ARki is an AR visualization for architecture models. It allows the architects to create mixed-reality visualizations and produce engaging presentations that can better communicate the design process between teams. ARki features include:

- Uses markerless vision-based Tracking systems
- Light estimation (uses the camera sensor to estimate the amount of light available and applies the correct lighting to virtual objects)
- Create multiple layers in 3D
- Create interactive presentations
- Record videos
- Create and save unlimited projects
- Import FBX files directly from Gdrive, Dropbox, and Onedrive

Comments:

- ARki application provides some trial models see the Figures (3.2, 3.3) below.
- These models are only for visualization.
- The user must be subscribed to use all the application features.
- I tested this application with a high and low lightness room. In the low lightness room, the phone could not detect a surface where the model will be overlaid.
- The application is only available on iOS devices, and virtual models cannot be calibrated every time the application is launched.

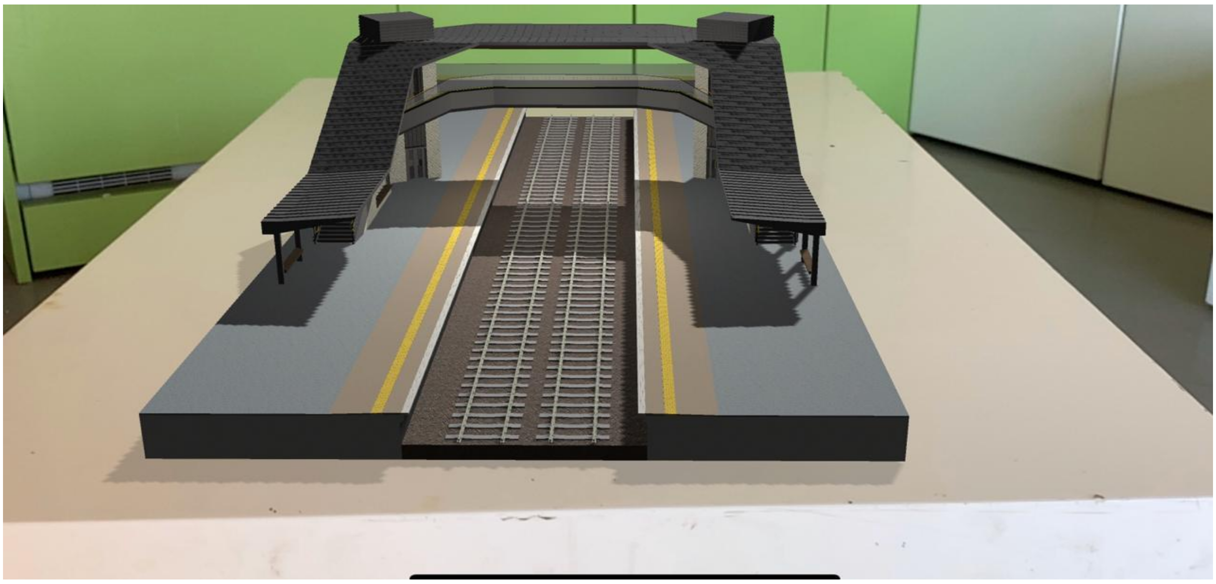

Figure 3.2: Trial model from ARki

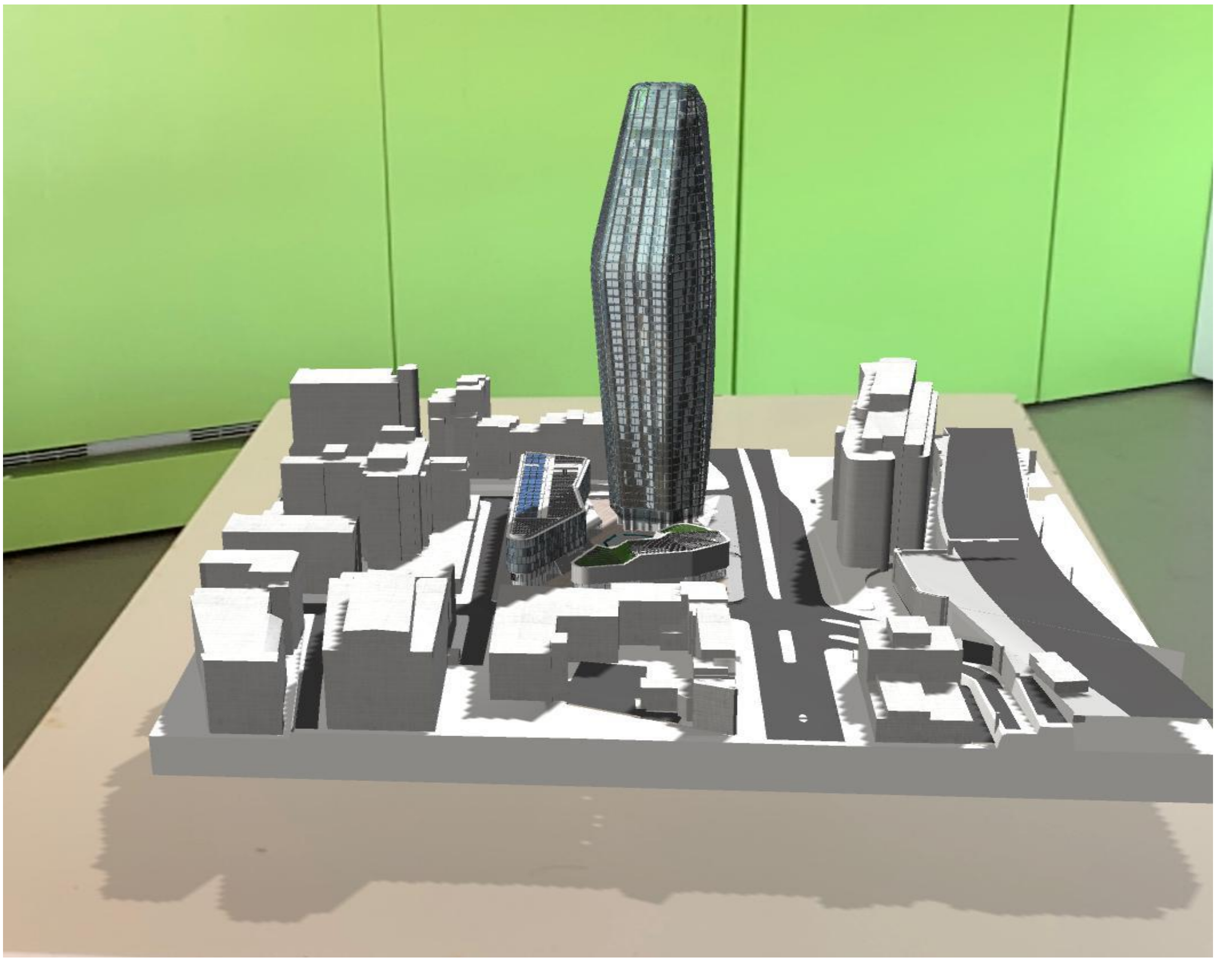

Figure 3.3: Trial model from ARki

3.3 DAQRI

DAQRI is an American augmented reality company, which was founded by Brian Mullins and Gaia Dempsey, in 2010. DAQRI is the leader in Professional Grade AR that enables workers to be more involved and to connect digital content to the real-world to improve productivity. Innovative developers, application builders, and professional services companies like Amazon Web Services, Oracle construction, SAP, IBM, and Autodesk are working with DAQRI to build professional-grade augmented reality solutions. DAQRI features include:

- **DAQRI Show:** is a natural combination of video. Voice and 3D visualization also enable observers to direct real-time view with digital tools.
- **DAQRI Tag**: it helps in managing operations visually and linking live data.
- **DAQRI Scan**: it captures realistic photos, shareable 3D models using the Autodesk platform.
- **DAQRI Model**: transforms high-resolution 3D models from Autodesk BIM Docs.
- **DAQRI Smart Glass**: they are portable and lightweight wearable for workers having ultra-low latency rendering to display complex workloads, for indoor and outdoor use.

Comments:

- This application uses only an HMD device. Therefore, there is no application available to download on the apple store or google play.

Figure 3.4: DAQRI application (extracted from DAQRI website https://daqri.com/partners/)

3.4 Dalux Viewer

Dalux is a Danish company created in 2005. The company tried to make the construction industry more efficient and smarter. They developed at first a BIM viewer application that allows the user to have access to the BIM model and sheets using smartphones or tablets. Moreover, to erase the boundaries between the real and digital environment, the Danish company developed a new technology tool called TwinBIM. It is based on Augmented Reality. With the help of smartphones and tablets, TwinBIM merges the BIM model with the physical world. Dalux application includes the following features:

- **Dalux BIM Viewer:** is free access application. It shares BIM models and drawings. Using Navisworks plugin and combining 2D drawings and 3D models.
- **Dalux Box:** is a BIM documentation coordinator with having unlimited storage and mobile access. Integrated with BIM 3D viewer, documentation, hyperlinks, public markups, comparing sheets as well as having BIM server
- **Dalux Field:** this field include features all in one, gaining access to the projects and responding simply by using the application
- **DaluxFM:** it is one of the most user-friendly systems which are integrated with BIM. its Supports 2D and 3D BIM on iOS as well as Android
- **TwinBIM:** this feature uses augmented reality to merge BIM models with the physical world with the help form smartphones or tablets. It has offline accessibility to make the use of TwinBIM in construction sites more manageable, and it helps to discover flows and issues as well as the collaboration with all members.

Comments:

- After contacting the company, they provided me with full access to the application along with a project.
- Dalux is a BIM-viewer application that provides 3D models on a smartphone. The user can choose between the architecture model, installations model, or structural model (Figure 14). Moreover, by clicking on the AR button (Figure 15), the user can view the model in AR.

- There is no AR figure taken because of the large space needed to overlay the project.

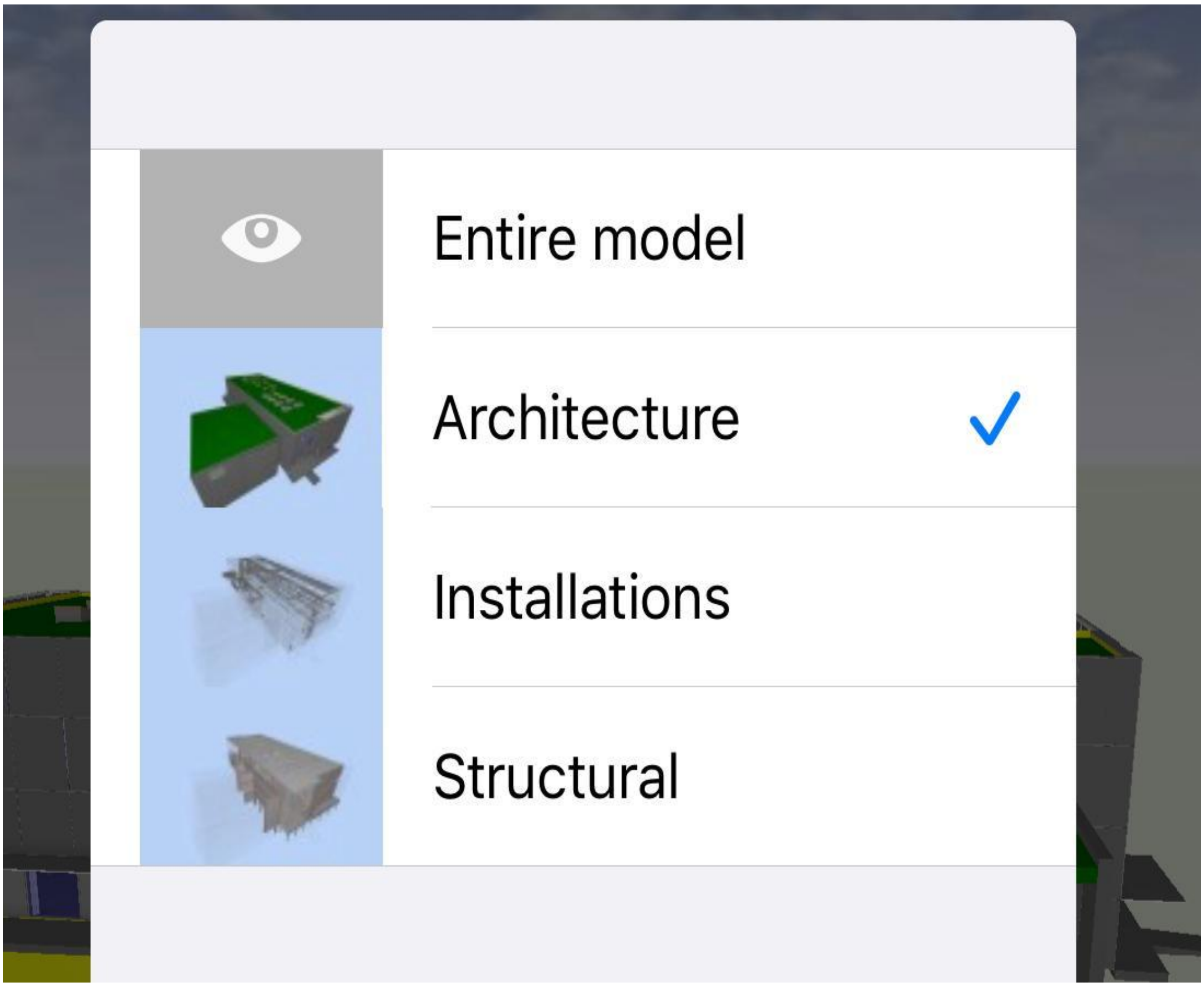

Figure 3.5: Dalux Menu

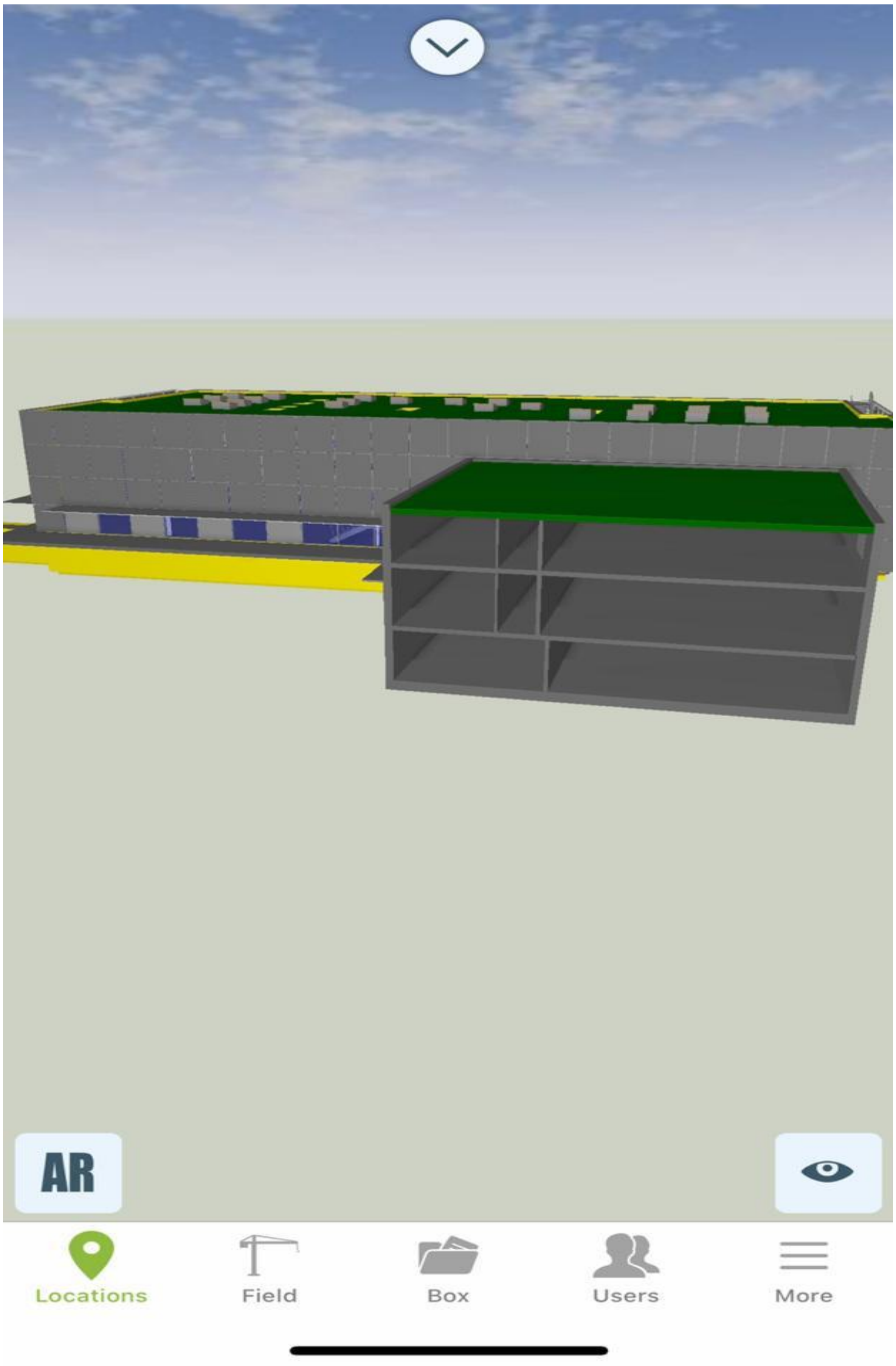

Figure 3.6: Dalux BIM viewer

3.5 Fologram

Gwyllim, Cameron and Nick are the founders of the application Fologram. Fologram is a collection of applications and plugins that run in mixed reality devices and tend to integrate with Rhino and Grasshopper. In Fologram, geometry, layers and grasshopper parameter can be modified in real-time to create powerful tools for design, communication, collaboration, and fabrication using Smart-glasses or mobile devices

Features:

- Create fabrication instruction (help to build a complex structure by giving the correct instruction)
- View and modify the geometry of Rhino and Grasshopper in real-time
- Architectural drawings and presentation
- Change layers, geometry, and materials in real-time
- Create or track Aruco maker or QR code
- Create a shared experience with multiple devices

Comments:

The application has a free feature as well as paid features. I have access only to free features. Therefore, my feedbacks are limited.

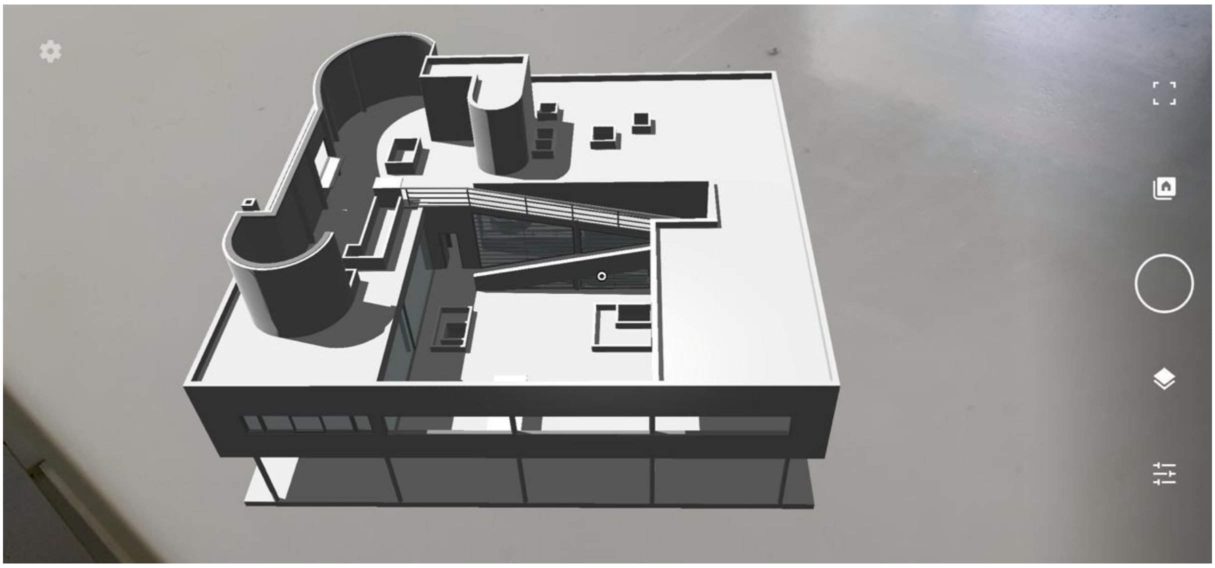

Figure 3.7: Fologram model

3.6 AR Mapper

AR Mapper is an application that was developed by Immotef Company. Immotef is an international technology company that grew out of the mobile application world as well as for the construction sector. It was founded in 2018. AR Mapper is an application that makes the use of 2D prints on construction sites unnecessary and eliminates human errors. With the help of AR Mapper technology and its application, the site manager, contractors, or subcontractors can follow work precisely and digitally. Following are the features of AR Mapper:

- AR Mapper can allow 3D protection of an entire project based on every layer; either its plumbing, insulation, electrical or any other technical installation
- Report work on a daily basis and implement comments, including follow up and communication, it also allows making annotations
- The work uploaded is precisely stored in a server, where the information is easily accessible through authorized personnel
- Measuring and Planning
- It can display plans in AR on a designated location
- It tends to check the installation with the help of holographic overlay, which is collaborated with 3D

Comments:

- There no application available to run some tests.

Figure 3.8: Examples of AR Mapper applications (extracted from the AR Mapper website: https://www.immotef.com/ar-mapper)

3.7 Smart Reality

Smart Reality application is developed by JBKNOWLEDGE Company, providing technology for construction and insurance. This company was founded out of Texas A&M University by James Benham, Jim Benham and, Sebastian costa in 2001. Smart Reality app is there latest and profound development in construction technology. It is based on augmented reality using a mobile device and other wearable devices. Following are the features of Smart Reality application:

- Real-time visualization
- Smart Reality app simplifies paper plans to facilitate incredible levels of association and cooperation in the field as well as in the office
- Allows users to walk around BIM models detailed in 3D virtual reality
- It could transform any company's plan file viewing and construction projects for the future

Comments:

There is no application available to run some tests.

Figure 3.9: Example of SmartReality application(Extracted from: https://www.youtube.com/watch?v=tNYBmkLZmaY)

3.8 Visual Vocal

Visual Vocal was founded by John San Giovanni and Sean B House in 2015, and it is headquartered in Seattle, Washington DC. Visual Vocal is currently in use by large scale universal construction companies Like McKinstry, Walter P Moore, GLY as well as well-known global architecture organizations, including NBBJ, Perkins Will, HOK, and many others. Visual Vocal is a revolutionary platform for virtual reality as well as augmented reality communication, documentation, and training. It is a breakthrough new communication system designed for the near future of ubiquitous AR. Complex construction and engineering projects waste billions due to decades-old communication technologies. Still, now with Visual Vocal's technology, Construction and Engineering projects can be accomplished excitingly on a large target market. Following are the features of Visual Vocal:

- Visual Vocal's unique system enables the rapid creation, sharing, and consumption of augmented reality as well as virtual reality content.
- The content created by Visual Vocal can be easily and safely stored in the cloud.
- Construction teams can create high-resolution experiences using Visual Vocal in under two minutes using any iOS or Android devices.

- Visual Vocal's interface is ideal for hastening decision making for intricate construction and engineering projects.
- It allows users to use mobile virtual reality to recapitulate information with fast voice annotation. Its workflow can power into a real-time meeting that may comprise of local or remote as well as circulated messaging for later viewing.

Comments:

- The application does not provide a trial period.
- Need a code to test the features of the application.
- An interesting feature of Visual Vocal is the combination of AR and VR with BIM. The user of AR and the user of VR can collaborate simultaneously on the same work.

Figure 3.10: AR user (extract from the website of Visual Vocal)

Figure 3.11: VR user (extract from the website of Visual Vocal)

3.9 Storyboard VR

Storyboard VR application is designed by Artifact, which was founded in 2006 by Rob Girling and Gavin Kelly, headquarters in Washington, US. Storyboard VR is a tool that was developed for Architects, artists, and creators across industries. Artifact develops this tool to eliminate hindrances in creativity and making the impossible real. Following are the features of Storyboard VR:

- create and produce a VR experience, save time and money early in the development process
- Storyboard VR help to transform communication also in creating and experiencing content
- Contains pre-loaded 3D sphere maps and planes
- Upload transparent images, like PNG files
- The menu gives users the ability to control and let the user access to the storyboard story progression and make adjustments.

Comments:

The application uses virtual reality. Therefore, there is no application available in the Apple store or google play. In the figure below, you can see how the user can create a new plane, sphere, cylinder, etc. by using a paddle and wearing an HMD (Figure 3.12)

Figure 3.12: StoryBoard VR (extract from the website of StoryBoard VR: https://www.artefact-group.com/case-studies/storyboard-vr/)

3.10 Trimble

Trimble company was initiated in November 1978 by Charles Trimble. It is a service technology company based in Sunnyvale, California. The company offers facilities global businesses in Agriculture, Transportation and Logistics, Building Design, Construction and Operation, Natural Resources, Utilities and Government, Geospatial, Survey and Engineering, Civil and Site Construction and Engineering, Optical and Laser Construction Tools, Mapping and GIS, and Software.

Trimble allows connecting with HMD or HHD device, which operates with mixed reality for site efficiency, effectively by providing detailed arrangements for holographic information on the worksite. That permits employees to evaluate their different models overlapped in the framework of their physical situation. Trimble applications include:

- **Trimble SiteVision (see Figure 3.12)**: Helps to visualize the models using HHD in the real world with GPS enabled augmented reality. It includes the following feature
  -Field Reporting

-Pre-Construction

- Measure position using GNSS

-Collaboration: share, communicate, and collectively interact in real-time

Trimble Connect for HoloLens and Trimble XR10 with HoloLens 2 (Figure 3.13): Connect the project data directly to the field so the user can directly explore and interact with the BIM model. It includes the following feature:

-Optimize coordination

-Real-time visualization

-Coordination: Enhanced coordination to improve workflow

-Step by step guidance

-Support for.SKP,.IFC., RVT, DWG, .DXF and more

- Multiple model overlay

- track issues

Comments:

- The application is only available on Android devices
- Trimble XR10 with HoloLens 2 is an advanced version of Trimble Connect for HoloLens.

Figure 3.13: Example of Trimble SiteVision (Extracted from:https://sitevision.trimble.com/)

Figure 3.14: Example of Trimble XR10 with HoloLens (Extracted from https://mixedreality.trimble.com/)

3.11 Conclusion

The following table compares every application in the technology they use, the areas and the displays

Application	Technology			Areas				Displays
	BIM viewer	AR	VR	Inspec-tions	Architec-ture	Construction and mainte-nance	Facility manage-ment	HMD /HHD
Gamma AR		✓		✓		✓		HHD
ARki		✓			✓			HHD
DAQRI		✓		✓		✓	✓	HMD
Dalux viewer	✓	✓		✓	✓	✓		HHD
Fologram		✓			✓	✓		Both
AR Map-per		✓	✓	✓		✓		HHD
Smart Re-ality		✓			✓			HHD
Visual Vo-cal		✓	✓	✓		✓	✓	HHD
StoryBoard VR			✓		✓			HMD
Trimble		✓			✓	✓	✓	Both

Table 3-1: Comparing the application

Common features:

Most of the applications share many common features:

- Architecture visualization
- Writing notes on elements
- Discover flaws and issues
- Collaboration
- Captures realistic photos
- Measuring and Planning
- Reduce material consumption

Personal comments:

Every application has its own technology and purpose in the AEC industry. In my personal view, Visual Vocal and Fologram are two promising applications. The first has combined AR and VR with BIM. That means the user in the construction site uses AR in collaboration with another user that follows him using VR to do the work. The second application help to build a complex structure by giving the correct instruction.

My feedback about the applications is limited, due to (1) the lack of the correct area to overlay the projects, (2) limited features in the trial period, and (3) the availability of the applications.

4 Conclusion and Future work

The design of a building is today revolutionized with the BIM process. Construction engineers base their studies on making a 3D digital model containing all the elements of the projects. The implementation of the BIM process is complicated in construction companies. The models contain a lot of information. They are hardly viewable and manipulated. This thesis work proposes to support them using AR technologies. AR brings virtual information onto the real world using HHD or HMD. It has also proven its efficiency and efficacity in many other industries such as medical, advertising, entertainment, tourism, military, etc.

According to the study's mention in 2.2.4, AR+BIM system tends to optimize the design to provide support for the construction phase by providing real-time visualization of the design which has led to a better understanding of the concept, increase of the productivity, improve communication between the workers as well as reduce the number of errors. But still, AR+BIM system has difficulties to overcome such as misalignment virtual with a real object, stronger tracking systems, and AR devices as well as the acceptance of the AR.

In the third chapter, I tested and highlighted some features of the AR BIM application. The applications are used in different areas such as architectural visualization, construction, maintenance, inspection, and facility management. My feedback is limited because of the need for the right area to overlay the project, the availability of the application, and the limited features in the trial period.

4.1 Future work

AR and BIM integration are a recent topic. Researchers are working on a different aspect to optimize their integration. They are exploring distinct features of this integration so that they improve it effectively in the future. Future work includes:

- Adding a new tool to compare and register the as-built situation or the progress of the designs plan and make the control of geometric quality parameters more efficient by improving a stable and accurate positioning of the AR platform.

- The use of cloud-based systems that store, process, and synthesize all design data as a result of the concept, design, development, construction, renovation, and demolition. AR and BIM will be significantly affected and will benefit from other technological advances, from cradle to cradle construction projects that include wireless sensor technology and big data and will collect and use information throughout the life of the building.
- Integrating time and cost change (4D and 5D) in BIM+AR to display construction site information in real-time and provide practical simulation.
- Improve the efficiency of the information transfer about the progress of work through real-time visualization.
- Working on Synergy of technologies that will apply in the construction industry. Such integration will present 3D scanning and mixed reality model in conjunction with big data, smart homes, and smart cities.
- Examine how AR affects work performance in terms of quality, implementation, reduction of losses, and increasing human resources productivity.

5 Bibliography

Azuma, R. (1997, August). A Survey of Augmented Reality. *In Presence: Teleoperators and Virtual Environments 6, 4*, 355-385. Retrieved from https://www.cs.unc.edu/~azuma/ARpresence.pdf

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., & Macintyre, B. (2001, November). Recent advances in augmented reality. *IEEE Computer Graphics and Applications*, pp.34-47. Retrieved from https://ieeexplore-ieee-org.eaccess.ub.tum.de/document/963459/authors#authors

Abualdenien, J., & Borrmann, A. (2019). A meta-model approach for formal specification and consistent management of multi-LOD building models. Advanced Engineering Informatics, 40, 135-153.

Abualdenien, J., & Borrmann, A. (2020). Vagueness visualization in building models across different design stages. Advanced Engineering Informatics, 45, 101107.

Bichlmeier, C., Wimmer, F., Heining, S. M., & Navab, N. (2007). Contextual Anatomic Mimesis Hybrid In-Situ Visualization Method for Improving Multi-Sensory Depth Perception in Medical Augmented Reality. *2007 6th IEEE and ACM International Symposium on Mixed and Augmented reality*, (pp. pp.129-138). Nara, Japan. Retrieved from https://ieeexplore-ieee-org.eaccess.ub.tum.de/document/4538837/authors#authors

Blum, T., Kleeberger, V., Bichlmeier, C., & Navab, N. (2012). Mirracle: An augmented reality magic mirror system for anatomy education. *Virtual Reality Short Papers and Posters (VRW), 2012 IEEE.* Retrieved from https://www.researchgate.net/publication/261308641_Mirracle_An_augmented_reality_magic_mirror_system_for_anatomy_education

Borrmann, A., König, M., Koch, C., & Beetz, J. (2018). *Building Information Modeling : Technology Foundations and Industry Practice.* Springer. Retrieved from https://ebookcentral-proquest-com.eaccess.ub.tum.de/lib/munchentech/detail.action?docID=5520323

Brian Mullins, G. D. (2012). DAQRI. Los Angeles, CA. Retrieved from https://daqri.com/about/resources/

Cameron Newnham, N. v. (2018). Fologram. Retrieved from https://fologram.com/

Carmigniani, J., Furht, B., Anisetti, M., Ceravolo, P., Damiani, E., & Ivkovic, a. M. (2010). Augmented reality technologies, systems and applications. *Multimedia Tools and Applications*, 341–377. Retrieved from https://link-springer-com.eaccess.ub.tum.de/article/10.1007/s11042-010-0660-6

Chionna, F., Argese , F., Palmieri, V., Spada, I., & Colizzi, L. (2015). Integrating Building Information Modeling and Augmented Reality to Improve Investigation of Historical Buildings. *Conservation Science in Cultural Heritage*, p. 16. Retrieved from https://doaj.org/article/51ae226b933c4a199e43a141a2a59081

Company, I. (2018). AR Mapper. Warsaw/ Ostend , Poland / Belgium. Retrieved from https://www.immotef.com/ar-mapper

Dalux. (2005). Dalux TwinBIM. Ole Maaløes vej 3, København N, 2200, DK, Danish. Retrieved from https://www.dalux.com/

DiVerdi, S., & Hoellerer, T. (2007). GroundCam: A Tracking Modality for Mobile Mixed Reality. *Virtual Reality Conference, VR '07. IEEE*, (pp. 75-82). Charlotte, Noth Carolina, USA. Retrieved from https://www.researchgate.net/publication/224698789_GroundCam_A_Tracking_Modality_for_Mobile_Mixed_Reality

Fikouhi, S. (2012). ARki. London , United Kingdom. Von https://www.darfdesign.com/ abgerufen

Fritz, F., Susperregui, A., & and Linaza, M. (2005). Enhancing Cultural Tourism experiences with Augmented. *The 6th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST (2005).* Spain. Retrieved from https://s3.amazonaws.com/academia.edu.documents/30925830/short2005.pdf?response-content-disposition=inline%3B%20filename%3DEnhancing_Cultural_Tourism_experiences_w.pdf&X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Credential=ASIATUSBJ6BAFPWKYOBS%2F20200503%2Fus-

Gheisari, M., & Irizarry, J. (2016). Investigating human and technological requirements for successful implementation of a BIM-based mobile augmented reality environment in facility management practices. *Facilities, Vol. 34 Iss 1/2*, pp. 69 - 84. Retrieved from https://www.researchgate.net/publication/291377453_Investigating_human_and_technological_requirements_for_successful_implementation_of_a_BIM-based_mobile_augmented_reality_environment_in_facility_management_practices

Gheisari, M., Goodman, S., Schmidt, J., Williams, G., & Irizarry, a. J. (2014). Exploring BIM and Mobile Augmented Reality Use in Facilities Management. *Construction Research Congress 2014*, (pp. 1941-1950). Retrieved from https://www.researchgate.net/publication/269047977_Exploring_BIM_and_Mobile_Augmented_Reality_Use_in_Facilities_Management

House, J. S. (2015). Visual Vocal. Seattle, Washington DC. Von https://www.visualvocal.com/ abgerufen

Irawati, S., Green, S., Billinghurst, M., Duenser, A., & Ko, a. H. (2006). An Evaluation of an Augmented Reality Multimodal Interface Using Speech and Paddle Gestures. *16th International Conference on Artificial Reality and Telexistence, ICAT 2006,* (pp. pp 272-283). Hangzhou, China: Springer. Retrieved from https://ir.canterbury.ac.nz/bitstream/handle/10092/2310/12603298_2006-ICAT-ARUsingSpeechPaddleGestures.pdf?sequence=1

James benham, J. B. (2001). Smart reality. Bryan, TX. Retrieved from https://jbknowledge.com/introducing-our-new-application-smartreality

Johnson, S., Gibson, M., & Mutlu, a. B. (February 2015). Handheld or Handsfree?: Remote Collaboration via Lightweight Head-Mounted Displays and Handheld Devices. *CSCW '15: Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social*, (pp. p. 1825–1836). Vancouver BC Canada. Retrieved from http://pages.cs.wisc.edu/~bilge/pubs/2015/CSCW15-Johnson.pdf

Juan, C. (2009). *Augmented Reality and Tangible Interfaces for Learning.* Valencia, Spain. Retrieved from https://www.researchgate.net/publication/221906240_Augmented_Reality_and_Tangible_Interfaces_for_Learning

Juan, C., Canu, R., & Giménez, a. M. (2008). Augmented Reality Interactive Storytelling Systems Using Tangible Cubes for Edutainment. *2008 Eighth IEEE International Conference on Advanced Learning Technologies*, (pp. pp.233-

235). Santander, Cantabria, Spain. Retrieved from https://www.researchgate.net/publication/4352441_Augmented_Reality_Interactive_Storytelling_Systems_Using_Tangible_Cubes_for_Edutainment

Kamphuis, C., Barsom, E., Schijven, M., & Christoph, a. N. (2014, September). Augmented reality in medical education? In *Perspectives on Medical Education?* (pp. 300-311). Springer. Retrieved from https://link.springer.com/article/10.1007/s40037-013-0107-7

kelly, R. G. (2006). StoryBoard VR. Washington, US. Retrieved from https://www.artefactgroup.com/case-studies/storyboard-vr/

Koch, C., Neges, H.-M., König, M., & Abramovici, M. (2014). BIM-based Augmented Reality for Facility Maintenance using Natural Markers. *Australasian Journal of Construction Economics and Building Conference Series, 2 (1)*, 23-34. Retrieved from https://epress.lib.uts.edu.au/index.php/AJCEB-Conference-Series/article/view/3767

Lup, F. H., Santhanam, A. P., Imielinska, C., Meeks, S., & P, R. j. (2007). Distributed Augmented Reality With 3-D Lung Dynamics—A Planning Tool Concept. *IEEE Transactions on Information Technology in Biomedicine*, 1-6.

Marimon, D., Sarasua, C., Carrasco, P., Álvarez, R., Montesa, J., Adamek, T., . . . Gascó, a. P. (2010, January). MobiAR: Tourist Experiences through Mobile Augmented Reality. Retrieved from https://www.researchgate.net/publication/228979424_MobiAR_Tourist_Experiences_through_Mobile_Augmented_Reality

Mekni, M., & Lemieux, a. A. (2014). Augmented Reality : Applications , Challenges and Future Trends. *Computer Science*, 205-214. Retrieved from https://pdfs.semanticscholar.org/a77e/78e46a0cdfdc191e732e23da3deac57fd366.pdf

Milgram, P., & Kishino, a. F. (1994, December). A Taxonomy of Mixed Reality Visual Displays. *EICE Transactions on Information Systems, Vol E77-D, No.12 December 1994.*, 1-15. Retrieved from https://www.researchgate.net/publication/231514051_A_Taxonomy_of_Mixed_Reality_Visual_Displays

Mistry, P., Maes, P., & Chang, a. L. (2009). WUW - Wear Ur World - A Wearable. *Proceedings of the 27th international conference extended.* Boston, MA, USA: Association for Computing Machinery / Special Interest Group on. Retrieved from https://dspace.mit.edu/bitstream/handle/1721.1/61366/Maes_WUW%20Wear.pdf?sequence=1&isAllowed=y

NIBS. (2019). *National BIM standard United States version 3*. Retrieved from National Institute of Building Sciences: https://www.nationalbimstandard.org/

NIBS, C. o. (2008). Commitee of the National Institute of Building Sciences.

Papagiannakis, G., Singh, G., & Magnenat-Thalmann, a. N. (2008). A Survey of Mobile and Wireless Technologies for Augmented Reality Systems (Preprint). *Computer Animation and Virtual Worlds 19(1)*, 3-22. Retrieved from https://www.researchgate.net/publication/216813780_A_Survey_of_Mobile_and_Wireless_Technologies_for_Augmented_Reality_Systems_Preprint

Paul Milgram, H. T. (1994). Augmented reality: A class of displays on the reality-virtuality continuum., (S. Proceedings of SPIE - The International Society for Optical Engineering 2351). Kyoto, Japan. Von https://www.researchgate.net/publication/228537162_Augmented_reality_A_class_of_displays_on_the_reality-virtuality_continuum abgerufen

r.l., G. T. (n.d.). GAMMA AR. Luxembourg. Retrieved from https://gamma-ar.com/

Rabbi, I., & Ullah, S. (2013). A Survey of Augmented Reality Challenges and Tracking. *Acta graphica: znanstveni časopis za tiskarstvo i grafičke komunikacije*, 29–46. Retrieved from https://www.researchgate.net/publication/236461845_A_Survey_of_Augmented_Reality_Challenges_and_Tracking

Ramos, F., Trilles, S., Torres-Sospedra, J., & Perales, a. F. (2018, December). New Trends in Using Augmented Reality Apps for Smart City Contexts. *ISPRS International Journal of Geo-Information*, 1-23. Retrieved from https://www.researchgate.net/publication/329663405_New_Trends_in_Using_Augmented_Reality_Apps_for_Smart_City_Contexts

Riedlinger, U., L. O., & Prinz, a. W. (2019, April). Tango vs. HoloLens: A Comparison of Collaborative Indoor AR Visualisations Using Hand-Held and Hands-Free

Devices. *Multimodal Technologies and Interaction*, 1-15. Retrieved from https://doaj.org/article/ee471e612e154e05a30599a852c95604

sciences, N. I. (2019). Retrieved from National BIM standard United States version: https://www.nationalbimstandard.org/

Trimble. (2020). *Mixed Reality*. Von Trimble: https://mixedreality.trimble.com/ abgerufen

Ullah, S. (2011, January). Multi-modal Interaction in Collaborative Virtual Environments: Study and analysis of performance in collaborative work. Université d'Evry-Val d'Essonne. Retrieved from https://www.researchgate.net/publication/281532188_Multi-modal_Interaction_in_Collaborative_Virtual_Environments_Study_and_analysis_of_performance_in_collaborative_work

Wang, J., Wang, X., Shou, W., & Xu, B. (2014, September 30). Integrating BIM and augmented reality for interactive architectural visualisation. *Construction Innovation*, pp. 453-476. Retrieved from https://www-emerald-com.eaccess.ub.tum.de/insight/content/doi/10.1108/CI-03-2014-0019/full/html#loginreload

Wang, X., E.D.Love, P., Kim, M. J., Park, C.-S., Sing, C.-P., & Hou, L. (2012, December 9). A conceptual framework for integrating building information modeling with augmented reality. *Automation in construction*, pp. 37-44. Retrieved from https://www-sciencedirect-com.eaccess.ub.tum.de/science/article/pii/S0926580512001793#!

Wang, X., Truijens, M., Hou, L., Wang, Y., & Zhou, Y. (2014, February 12). Integrating Augmented Reality with Building Information Modeling: On-site construction process controlling for liquefied natural gas industry. *Automation in construction*, pp. 96-105. Retrieved from https://www-sciencedirect-com.eaccess.ub.tum.de/science/article/pii/S092658051300215X#!

Wille, M., Wischniewski, S., Scholl, P. M., & Laerhoven, a. K. (2014). Comparing Google Glass with Tablet-PC as Guidance System for Assembling Tasks. *2014 11th International Conference on Wearable and Implantable Body Sensor Networks Workshops*, (pp. 38-41). Zurich, Switzerland. Retrieved from https://www.researchgate.net/publication/286650979_Comparing_Google_Glass_with_Tablet-PC_as_Guidance_System_for_Assembling_Tasks

Williams, G., Gheisari, M., & Irizarry, J. (2014). Issues of Translating BIM for Mobile Augmented Reality (MAR) Environments. *Construction Research Congress 2014*, (pp. 100-109). Retrieved from https://www.researchgate.net/publication/269047503_Issues_of_Translating_BIM_for_Mobile_Augmented_Reality_MAR_Environments

Williams, G., Gheisari, M., Chen, P.-J., & Irizarry, J. (2015, January 1). BIM2MAR: An efficient BIM translation to mobile augmented reality applications. *Journal of Management in Engineering*, pp. 1-8. Retrieved from https://www.researchgate.net/publication/270844716_BIM2MAR_An_efficient_BIM_translation_to_mobile_augmented_reality_applications

Zhou, F., Duh, H. B.-L., & Billinghurst, a. M. (September 2008). Trends in Augmented Reality Tracking, Interaction and Display: A Review of Ten Years of ISMAR. *7th IEEE and ACM International Symposium on Mixed and Augmented Reality, ISMAR 2008, Cambridge, UK, 15-18th September 2008*, (pp. 193-202). Cambridge, UK. Retrieved from https://www.researchgate.net/publication/216814064_Trends_in_Augmented_Reality_Tracking_Interaction_and_Display_A_Review_of_Ten_Years_of_ISMAR

Zlatanova, S. (2002). *Augmented Reality Technology.* Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Geodesy, Section GIS Technology. Retrieved from https://www.researchgate.net/publication/27344741_Augmented_Reality_Technology

Erklärung

Hiermit erkläre ich, dass ich die vorliegende Bachelor-Thesis selbstständig angefertigt habe. Es wurden nur die in der Arbeit ausdrücklich benannten Quellen und Hilfsmittel benutzt. Wörtlich oder sinngemäß übernommenes Gedankengut habe ich als solches kenntlich gemacht.

Ich versichere außerdem, dass die vorliegende Arbeit noch nicht einem anderen Prüfungsverfahren zugrunde gelegen hat.

München, 15. June 2020 Hedi Moalla

Vorname Nachname