Review and Analysis of Augmented Reality (AR) literature for Digital Fabrication in Architecture

Yang Song[a,], Richard Koeck[a], Shan Luo[b]

[a]Department of Architecture, University of Liverpool, United Kingdom
[b]Department of Computer Science, University of Liverpool, United Kingdom

Abstract

The use of Augmented Reality (AR) technologies has increased recently, due to the equipment update and the mature technology. For architectural design, especially in digital fabrication projects, more designers begin to integrate AR methods to achieve the visualization in the process. To help unskilled labors for holographic on-site previewing and instruction training, experimental and practice-based studies in AR for the architectural digital fabrication have emerged in recent years. Now, it is a great opportunity to discuss the topic of AR in architectural digital fabrication. By presenting a statistical review of AR technology in architecture projects, this literature review aims to review ongoing research and provide pathways for further research in architectural digital fabrication. This review article is based on information found in journal publications and conference papers in the fields of architecture, engineering, robotics, and digital fabrication, published to date (from 2010 to 2020). The review narrows the literature within these papers by filtering 84 articles through the keyword "Augmented Reality", "Digital Fabrication" and "Assembly". The selected articles can be categorized based on the most use of AR function in architectural digital fabrication into an order of the following three classifications with the most significant growth in the last years: (A) AR 3D holographic instruction, (B) AR data sharing, (C) AR for Human-Computer interaction. The information collected from these articles within their classifications is meant to give insight into the current state-of-the-art of AR in the architectural digital fabrication area, as well as to summarize how the topic has matured and developed over time in the research and industry literature. This article has not only analyzed the existing literature but also highlighted new emerging fields in AR research and the future trends of AR function in architectural digital fabrication.

Keywords: Augmented Reality (AR), Architecture, Digital Fabrication, Literature review

1. Context

In the past decade, digital tools such as 3D printing, robotic fabrication and other technical ways have been spread and widely used in architecture areas. From 3D printing architectural models and robotic fabrication to using Artificial Intelligence (AI) and AR within the design process, it is increasingly popular that using some kind of digital tools either for design workflow or fabrication process in architectural projects [1]. With the rise and development of AR technology, the mixed use of AR and the above digital tools has gradually increased. Digital tools combined with AR visual technology will create an easy way for human to access digital information. The interactivity and connectivity to virtual data and digital information in AR environments will be stronger than ever before [2].

Early developments in AR technology can be traced as far as the 1990s [3]. AR technology allows a person to see or otherwise sense a computer-generated virtual world integrated with the real world [4]. AR can be used to provide visual information for an existing plan in detail. More generally, AR is used as an interface between digital information and the real world. It has the ability to show the digital pre-design 3D model and fabrication guidance.

Email address: yang.song@liverpool.ac.uk (Yang Song)

The fabrication and construction processes in traditional architectural engineering are limiting the variety and complexity of architectural structures. The information found in traditional 2D drawings often has the difficulty to communicate the complexity of design. To address this problem, researchers have started to explore the sharing of 3D on-site visual information [5]. AR is seen as a tool that has developed rapidly in the last few years and has the potential to bridge the gap between real and virtual information and data, by combining holographic drawings and real-world environments [6]. Furthermore, AR is seen as being a new kind of interface between human and robot interactions during the digital fabrication process by sharing real-time simulation and information.

In this article, a new review has been proposed for AR-based digital fabrication on multiple aspects (e.g. AR 3D holographic instruction, AR data sharing, and AR for Human-Computer interaction). Since the 1990s, the concept and the research of AR have been growing significantly and new applications have been created. In the early phases of AR technology research, most articles were related to military, navigation, and industrial design [7, 8, 9]. With the continuous development and improvement of AR technology and devices, AR is more wildly applied to architectural fabrication and construction areas [10]. Especially using AR in visualizing architectural projects, Computer-generated images of a structure can be superimposed onto a local view of a property in the real world before the physical building is constructed there [11, 12].

1.1. Overview of AR in the architectural process

It has become clear that the architectural engineering industry is embracing more AR technologies to improve projects at all stages of the fabrication and construction process. This advanced technology can provide evolutionary advantages through visualization on the architectural construction area, such as allowing unskilled labor to assemble complex shape brick walls with the generating holographic construction information from parametric models in AR [13]. Different AR applications have been recommended for the architectural engineering industry by different researchers.

For manual fabrication process, Jahn proposed AR holographic instruction for the complex shape construction to solve the defects of traditional 2D documents and inefficient construction tolerance [14]. Meanwhile, Cameron and Matthew explore the potential of AR applications in the complex shape intelligent fabrication process by using on-site AR fabrication guidance [14]. Similarly, Betti developed a system with which the users can input digital parameters and change digital data by using some default gestures in the real world. The system recognizes and transforms gestures into digital commends for 3D modeling, and displays the holographic on-site model in real-time through the AR immersive design environment [15].

For robotic fabrication process, Kyjaneka investigates an AR workflow for Human-Computer collaboration which gives the possibility for unskilled users to operate robots through visual commands and simulation [16].

For on-site fabrication process, Akbari presented a workflow for the on-site fabrication by integrating design and making with uncertain material behavior through a Cyber-Physical System consisting of AR technologies [17].

These applications demonstrate the potential of AR technology for the future use in architectural fabrication process.

1.2. Originality of the review

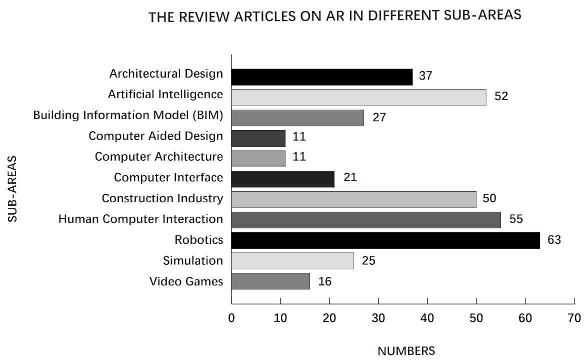

Fig. 1: The Review Articles on AR in different sub-areas. The main areas of published AR review articles with the corresponding number of published articles: Architectural Design (37 articles), Artificial Intelligence (52 articles), Building Information Model (BIM) (27 articles), Computer-Aided Design (11 articles), Computer Architecture (11 articles), Computer Interface (21 articles), Construction Industry (50 articles), Human-Computer Interaction (55 articles), Robotics (63 articles), Simulation (25 articles), and Video Games (16 articles).

Between 2010 and 2020, 731 literature reviews on AR in the architecture field were published. The maximum number of review articles is 344 in the engineering area, followed by 320 in computer science and 67 in art and humanities. Most

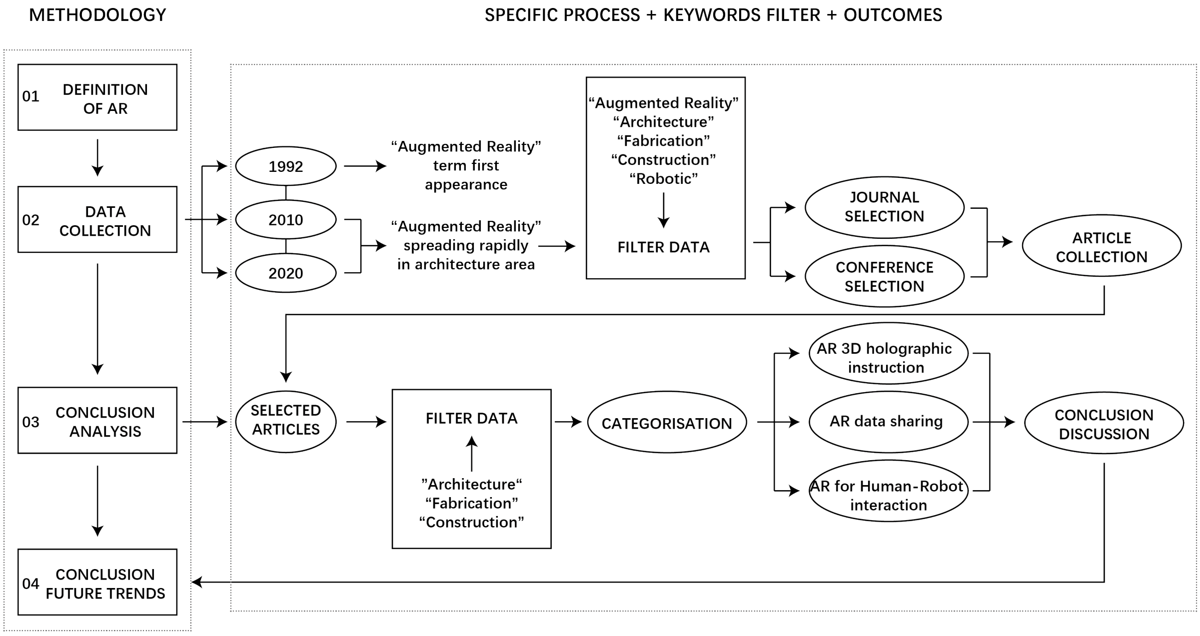

Fig. 2: The structure of the paper.
The main methodology includes: definition of AR, data collection, conclusion analysis, and conclusion future trends. In each main methodology section, there are several ways for narrowing the database, such as keywords filter, specific process, etc. The results of each section will be summarized and discussed in the last section.

of these review articles are divided into the following sub-areas including Architectural Design, Artificial Intelligence, Building Information Model (BIM), Computer-Aided Design, Computer Architecture, Computer Interface, Construction Industry, Human-Computer interaction, Robotics, Simulation, Video Games etc.(Fig.1).

For example, in 2013, Chi et al. reviewed the trends in AR application for Architecture, Engineering, Construction, and Facility Management to outline the research opportunities for applying AR in the field of AEC/FM [18]. In the same year, Kim studied AR technical options, especially in mobile devices. The article focused on the design and implementation of mobile AR and presented the direction for the further development of mobile AR [19]. In contrast to Kim, Li et al. focused on the safety of architectural construction workers. The authors reviewed the state-of-the-art of VR/AR applications in construction safety to uncover the related issues and propose possible improvements for visualizing the complex workplace situation, building up risk-preventive knowledge, and undergoing training [20].

In contrast to the above literature reviews, this review contributes to a more systematic and updates a bibliometric analysis of all published research on AR applications in architectural digital fabrication area which was not covered by previous review articles. This review is timely and detailed reviewed of related articles covering the above areas from 2010 to 2020. It is chronologically organized, giving the readers a better understanding of the evolution of AR in architectural digital fabrication area. This article provide the insight of comparing the different functions and influences of AR in digital fabrication projects, and proposing how to improve the role of AR and the future trends of AR in digital fabrication field.

After the context, the rest of the paper is structured as follows: the research methodology in detail; groups the papers into categories based on a bibliometric analysis; discussion of the contents and identification of the research gaps and future trends revealed in the literature; and the conclusions.

Throughout this review, AR technology in architecture will be categorized to simplify the understanding of the literature and permit a better analysis of trends and gaps in the research.

2. Methodology

The research methodology (Fig.2) used in this review article is divided into the following steps:

(a) Keyword search in the Scopus and CunInCAD database.
(b) Select the journals and conferences.
(c) Individual search in the database of the articles selected in the previous step.
(d) Exclusion of duplicates and articles that do not discuss AR in architectural area.
(e) Review the selected articles and define relevant categories according to the articles.
(f) Classify the articles in the defined categories.

In the first step of bibliometric analysis, the specific search has been conducted in the Scopus and CunInCAD database by using the following keywords: (a) “Augmented Reality”, (b) “Architecture”, (c) “Fabrication”, (d) “Construction”, (e) “Robotic”. The database of this review article contains the papers from related conferences and journals. In terms of conferences, it summarized the outcomes from *the Association for Computer-Aided Design in Architecture (ACADIA), the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), the Education and research in Computer-Aided Architectural Design in Europe (eCAADe), the Sociedad Iberoamericana de Grafica Digital (SIGraDi), the Arab Society for Computer-Aided Architectural Design (ASCAAD), the Computer-Aided Architectural Design (CAAD),* and *International Symposium on Automation and Robotics in Construction (ISARC)* international academic conferences. In terms of journals, the authors then refined the search in the database to only include the articles written in English and from the architecture, engineering, and computer science related fields. The outcomes have been summarized from *Automation in Construction, Robotics and Computer-Integrated Manufacturing, Visualization in Engineering, Organization Technology and Management in Construction,* and *Computer Industry.* These conferences and journals covered a wide range of databases in the architectural engineering research domain.

This article reviewed the last decade (from 2010 to 2020) to cover the most important phases of AR research, application development, and implementation from 84 articles which contain the common AR functions in architectural digital fabrication field (Fig.3). Rather than categorizing the literature based on existing research themes, the authors proposed its categories built on the articles' contents.

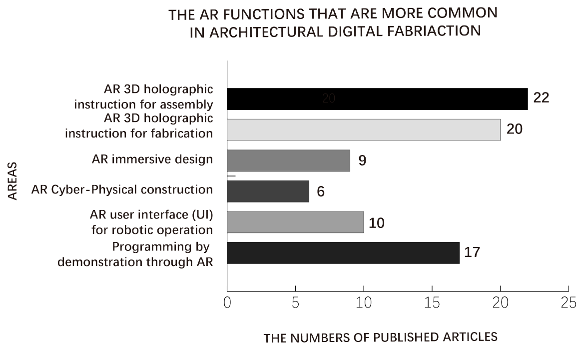

Fig. 3: The AR functions that are more common in architectural fabrication and construction in the selected articles. The maximum number of published articles is 22 in the AR 3D holographic instruction for assembly, followed by 20 in AR 3D holographic instruction for fabrication, and 17 in programming by demonstration through AR. By contrast, the number of publications in AR UI for robotic operation, AR immersive design, and AR Cyber-Physical construction has a smaller proportion of total, which are 10, 9, and 6 respectively.

3. Bibliometric analysis outcomes

AR as a new and developing technology, using onsite visual holographic technology provides more research directions for architectural design. AR publications have increased significantly with the continuous upgrading and evolution of the AR device. Researchers have noticed that AR technology gives more possibilities to architectural design and more hypotheses to be studied. The bibliometric analysis shows that in the last 10 years, there has been a significant increase in published papers in the AR area from 124 in 2010 to 697 in 2020 (Fig.4) and a great increase in AR digital fabrication from 3 in 2012 to 30 in 2019 (Fig.5). Over the ten-year period under review, according to our selections criteria, the *Automation in Construction* Journal published most papers and *the Education and research in Computer-Aided Architectural Design in Europe (eCAADe)* conference published the majority of outcomes in the field of AR in architecture.

According to the content analysis, this article has been grouped into several following categories according to specific major categories after the published paper collection. This collection is based on the three most common functions of AR in architectural digital fabrication with the largest number:

(A) AR 3D holographic instruction.
(B) AR data sharing.
(C) AR for Human-Computer interaction.

Based on the above categories, the authors selected and identified the research area which is more appealing to AR fabrication and construction, because it is the field with the largest number of AR applications in architectural digital fabrication process and it is also the most representative area. Those research areas contain studies that cover the following sub-categories:

(1) AR 3D holographic instruction for assembly.
(2) AR 3D holographic instruction for fabrication.
(3) AR immersive design.
(4) AR Cyber-Physical construction.
(5) AR user interface (UI) for robotic operation.
(6) Programming by demonstration through AR.

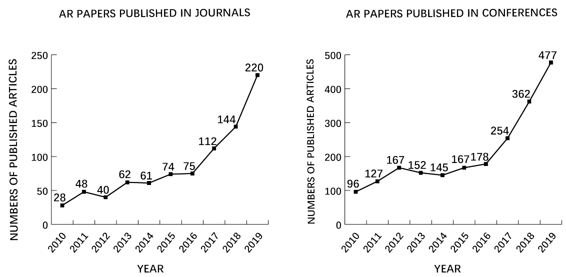

Fig. 4: AR papers published over the last decade (journal paper – left / conference paper - right).
For the articles published in journals, the number of papers increased significantly from 28 in 2010 to 220 in 2019. Similarly, for the articles published in conferences, the number of papers expanded gently from 96 in 2010 to 178 in 2016, but it soared to 477 in 2019.

4. Content analysis

AR technology is used in extensive stages and functions of architectural projects. Many architects and researchers consider that AR technology has the potential to improve the current digital fabrication process with its visual and interactive characteristics and bring automation in that process. It seems evident that AR technology has an enormous contribution to the evolutionary process in the architectural digital fabrication field to a fully visual

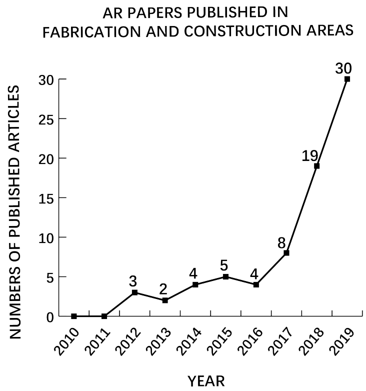

Fig. 5: AR papers published over the last decade in the digital fabrication area.
The AR research publications in the digital fabrication area started in 2012 and the number of that increased from 3 in 2012 to ten times in 2019.

automated workflow in the future. In the following, some of the most noteworthy AR applications in 3D holographic instruction, data sharing, and Human-Computer interaction will be discussed through research outcomes and the results of various research articles.

The conclusion will be highlighted, that AR in literature has increasingly focused on the following areas. Firstly, AR 3D holographic instruction, it is the virtual instruction labeled on the real physical world through AR device in the on-site construction process for the unskilled labors. Secondly, AR data sharing, is a new and convenient workflow for the designer to communicate with digital data through AR technology, including using human gestures to edit with digital data and using monitoring the material behavior to interact with digital data. Last, AR for Human-Computer interaction simplifies the traditional way to operate the robots by programming and bridges the gap between digital and physical in Human-Computer visualization interaction through the AR environment.

4.1. Category A: AR 3D holographic instruction

Computer-aided design and manufacturing have brought the potential of complex architectural structure shape and the possibility of generating construction information from design information directly [21]. However, the finite ability to interact with the digital fabrication process during the operation has limited adaptability, flexibility, and intuition for adapting the difference between the practices of design and construction [16]. The computer vision system is required for typical communication between on-site design and human construction due to the above challenges [22]. Mixed Reality environment selves well on taking physical measurements to determine the component on-site location through the holographic instruction model overlapping to the physical construction site [23].

AR 3D holographic instruction is the category with the most published papers, mainly in the past four years. It has the highest growth rate of all categories in this article. This literature review in these fields shows that several authors referred to the technical limitations of AR technology such as holographic deviation of location and virtual project drift in headset devices, which attracts more attention from researchers. AR 3D holographic instruction encompasses the following sub-categories:

(1) AR 3D holographic instruction for assembly.
(2) AR 3D holographic instruction for fabrication.

4.1.1. Sub-category 1: AR 3D holographic instruction for assembly

Meža et al. show in their study that tablet pad AR and mobile AR are the best options than other 2D drawings and 3D models for tracking and monitoring the process of construction projects. The authors also found in their research that AR technology enables them to visualize and estimate the finished work on-site with the proposed schedule of the process harmoniously and intuitively [24]. Similarly, Jahn et al. show in their research that AR technology could be used as a holographic instruction overlapping on the construction site. Their outcomes confirm that AR holographic instructions can replace traditional 2D drawings and physical templates with clear, interactive, contextual, and shared on-site information for the assembly of pre-design structures (Fig.6) [56]. By using AR 3D holographic assembly instruction, it can reduce the construction time, increase the participation of unskilled labor, and create new opportunities for training, collaboration, and skill development [13].

In contrast with the above pre-design studies without interaction, Fazel et al. present in their study an interactive multi-maker AR tool for free-form modular construction [23]. The authors also describe a way that enables the user to visualize the accurate location of designed projects in the assembly process in the real world. According to their tolerance evaluation system and comparing the physical outcome with the digital pre-design one, the authors got the result that the physical model constructed by AR can be accepted with small tolerance relative to the digital designed one. AR 3D instruction has the ability to guide and restore the digital model in the real world with high accuracy and intuitive maneuverability [23]. Similarly, Wu et al. and Lharchi et al. also showed that in the architectural assembly and construction process, AR is going to be the most used function in advanced and interactive construction projects [25, 26]. For irregular component assembly process, Wibranek et al. illustrate the possibilities to use digital fabrication techniques for additive manufacturing to guide

Fig. 6: AR 3D instruction for complex wall assembly. This figure was produced by Fologram in 2020 [56], and it summarized that the unskilled labors are assembling the complex brick wall guided by the AR 3D virtual holographic instruction through Microsoft HoloLens 1. The permission to re-use the figure has been granted by the author and the publisher.

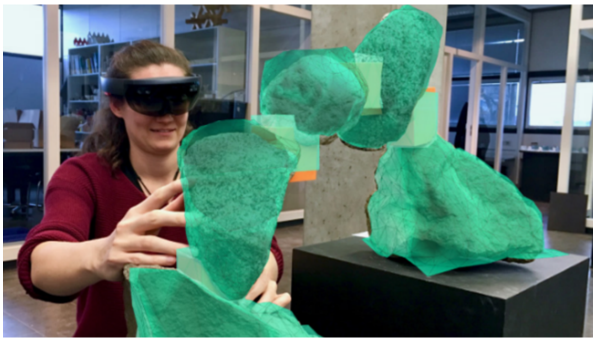

Fig. 7: Irregular shape assembly in AR. This figure was produced by B.Wibranek and O.Tessmann in Technique University Darmstadt, DDU(Digital Design Unit) in 2019 [27], and it summarized the AR setup allowed users to switch parts on and off depending on the stage of assembly. The permission to re-use the figure has been granted by the author and the publisher.

users during assembly and provide a connection between the physical objects with irregular shape for construction (Fig.7) [27].

4.1.2. Sub-category 2: AR 3D holographic instruction for fabrication

Andrew et al. illustrate in their research that it is possible to create an AR holographic fabrication instruction system by using simple and easy manufacturing toolsets for the fabrication of extremely complex forms with high levels of precision in short time frames [28]. In this study, the authors prove that using AR can relieve the fabrication process from the requirements of expensive molds or equipment in the traditional fabrication process (Fig.8) [57]. The authors speculate in their study for extending handcraft-based practices using intelligent, precise, and interactive holographic instruction communication through the AR environment [28].

In contrast, Jahn et al. focus more on components design than toolsets design. The authors note the use of AR technology for the component fabrication process as an efficient way for the majority of different shapes components fabrication [14]. The authors demonstrate that fabrication within AR holographic environments can enable unskilled labor to fabricate numerous, different shapes, and complex structures in short time frames with minimal tolerance (Fig.9) [14]. The authors also demonstrate that using traditional methods would be excessively tedious and time-consuming in a huge number of different shape measurements. AR holographic fabrication instruction can also reduce the requirements to switch attention from machine and material to 2D drawings or documents [14].

4.1.3. Future trends of AR 3D holographic instruction

AR 3D holographic instruction provides new methods for the assembly of complex structures in the digital fabrication process and offers more advanced production modes for replacing the intricate traditional handicrafts. However, the existing problems of AR holographic instruction have prompted the future development and research.

First, the systems and methods above require users to have access to a laptop running Grasshopper plug-in in Rhino to promote a real-time exchange for data and models, which are not practical on most construction sites. For the future trends, it aims to address this issue by allowing users to

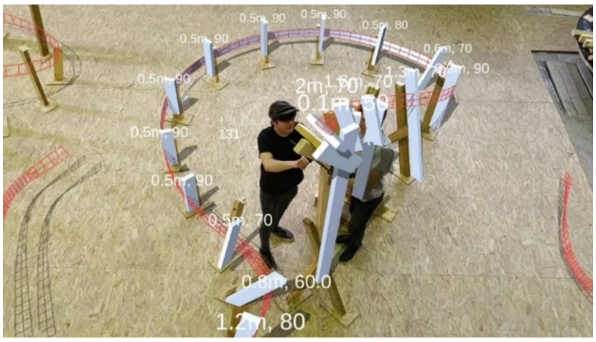

Fig. 8: Steam bending timber in AR.
This figure was produced by S.Hahm in 2019 [57], and it summarized the AR composite placed on top of the completed steam-bent panel. The permission to re-use the figure has been granted by the author and the publisher.

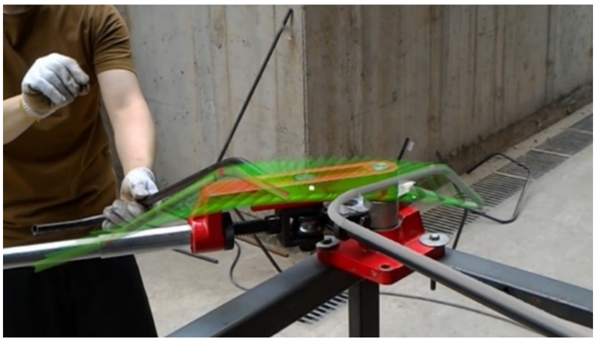

Fig. 9: AR holographic fabrication guidance.
This figure was produced by G.Jahn et al. in 2109 [14], and it summarized calibrating holographic guidance in AR for fabrication. The permission to re-use the figure has been granted by the author and the publisher.

export interactive holographic instruction to run as an independent application on AR headset such as HoloLens and to bring this portable AR instruction system to more construction sites.

Second, due to the technical limitation of current AR devices, the holographic instruction will drift during the assembly process. The AR headset device is expensive, the workflow of reading AR instruction by a person and transmitting the order to the partners is very common during the assembly process which leads to errors during the information transformations. In the next decade, this problem will be improved by devices and technology upgrades. In this way, the holographic instruction system can improve the accuracy by reducing the virtual projects drift and the times of proofreading target coordinates.

Last, this AR instruction system enables high precision when the physical and digital components are aligned but does not provide the same precision when the material has unexpected behave, alignment will be lost, and models cannot be validated by eye. For future trends, more researches will be applied to the materials with irregular shapes or natural property behaviors. That will expand the usage and construction site selection of AR holographic instruction.

4.2. Category B: AR data sharing

It is seen in digital art and medicine practice projects that tracking human motoric skills including speech, gesture, and touch into machine-code to get remote support from experts [29, 30]. This multimodal interface has been in use for the gaming industry and this fully operational AR-based multimodal system prototype seems to have potential in immersive on-site fabrication process [31].

As the technology is just getting started, AR data sharing has the minimal published outcomes in the last years and has more possibilities to be developed (Fig.5). This domain has the potential to become one of the most popular topics for the computer to share digital data to human according to generative calculation, algorism simulation, human interaction, and material behavior through the AR environment. AR data sharing field is also a new trend in terms of research and study, to improve the interaction with the designer, material, and digital data. The sub-categories has been identified as the following:

(1) AR immersive design.
(2) AR Cyber-Physical construction.

4.2.1. Sub-category 1: AR immersive design

Betti et al. show in their research that AR technology can play in promoting collaborative design. The authors designed an AR representation and multimodal interface, which shows the potential in the inclusion of non-professional in architectural design and fabrication process, especially in on-site multi-participant immersive design [15]. The structure shape will generate in real-time according to the control points located in the AR interface (Fig.10) [15]. The use of a holographic interface confirmed that AR has the possibility of in-suit immersive design, fabrication, and assembly [15]. Equally, Forren et al. start in their study to present a design method that building through gestures in the AR environment. In their AR system, the user can view structural implications of stand position in real-time and adjust them interactively by tracking the movement and location of the structure control points in AR (Fig.11) [32]. The authors confirmed that this AR immersive design method which breaks the rote design method, gives the possibility for experts and non-experts to exchange ideas, to build through gestures, and to interact with virtual models in real-time [32].

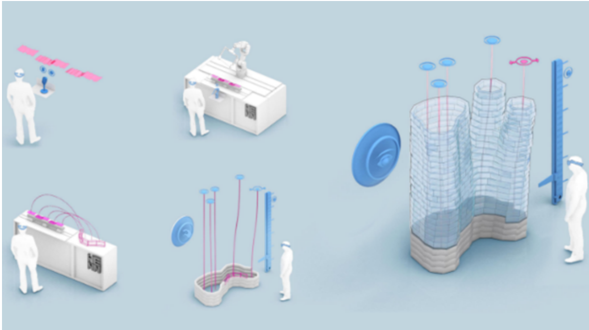

Fig. 10: The diagram of immersive design.
This figure was produced by G.Bitti et al. in 2018 [15], and it summarized the various interaction elements of the holographic interface in AR immersive design process. It shows the icons of the holographic interface and their activation. The permission to re-use the figure has been granted by the author and the publisher.

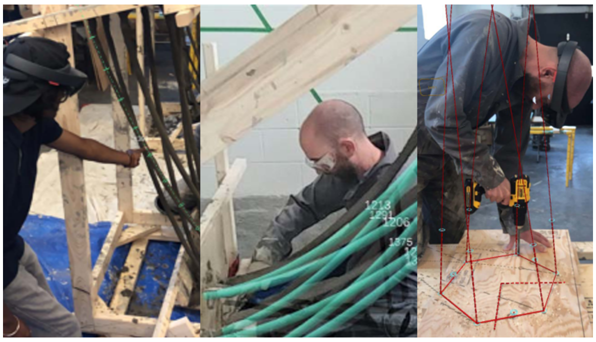

Fig. 11: Real-time adjustment in AR.
This figure was produced by J.Forren et al. in 2019 [32], and it summarized the immersive design interface and process with dynamic structural simulation data. The three-dimensional diagram was rationalized into discrete architectural components which were prefabricated in a wooden three-dimensional frame. This holographic model and instruction will change with the real-time adjustment. The permission to re-use the figure has been granted by the author and the publisher.

In the same way, Hahm et al. and Song illus-

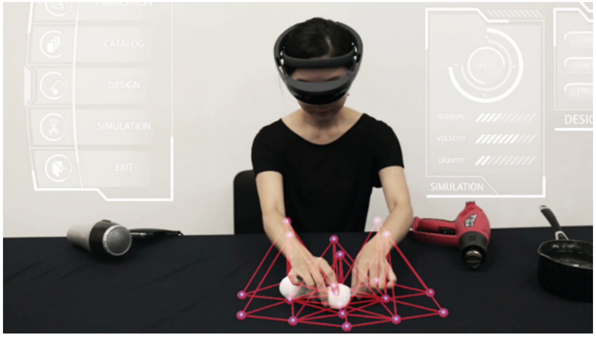

Fig. 12: Immersive design with real-time calculation. This figure was produced by S.Hahm et al. in 2019 [33], and it summarized the real-time calculation and an immersive design process which shows that a quite simple hologram that guides a maker is sufficient rather than deploying all of the details of the 3D model. The permission to re-use the figure has been granted by the author and the publisher.

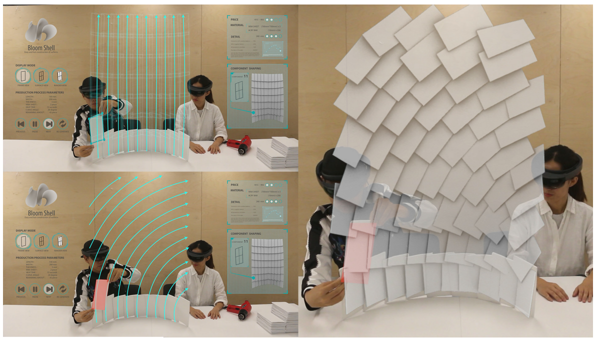

Fig. 13: Immersive design with real-time calculation. This figure was produced by Y.Song in 2020 [58], and it summarized the evolution scheme calculated by computer after human-made change has been detected by Microsoft HoloLens in AR. The permission to re-use the figure has been granted by the author and the publisher.

trate in their research respectively that AR immersive design method shows great potential for gesture recognition during the design process, and influences digital simulation through hand gestures (Fig.12, Fig.13) [33, 58]. The authors prove that using the AR immersive design can generate more reasonable outcomes related to the location of physical components placed by the designer, hand gestures, and material behavior in real-time on-site locations [33, 58]. By way of contrast, Goepel et al. focus on the physical model scanning and the assembly of nonstandard prefabricated elements based on the optimized parametric structure through the AR environment. This method gives the possibility to designers to combine the tolerance within the construction stage into the design through the real-time feedback loop between the real and digital. This AR immersive design is based on the scanning of the physical model and structural calculation in real-time. The authors confirm that fixing errors in real-time AR environments is much easier, cheaper, and faster than the execution of precision by a perfect system [34].

4.2.2. Sub-category 2: AR Cyber-Physical construction

The robotic fabrication is design for controlled factory environments. In the contrary, digital fabrication systems can hardly provide the flexibility of manual fabrication dealing with the uncertain on-site place [35]. Traditional manual on-site fabrication can solve the accumulative errors in freeform building perfectly [36]. On-site builders will have AR visual guidance about the current operation on the real object to solve the uncertainties and improve the performance of manual operations [37, 38].

Sun et al. propose a freeform building process with high on-site flexibility and acceptable accumulative error through AR visualization [36]. The authors note that human builders are more flexible in dealing with on-site uncertainties than a computer, the computer is more effective in calculating the acceptable structure. AR as a virtual bridge between human builders and computer, gives the condition for approaching human flexibility upon on-site uncertainties and the computer's accuracy (Fig.14) [36]. The design will update itself according to the parametric generative model and the results made by human in real-time through the holographic illustration in AR. The authors confirmed that AR cyber-physical construction works well with reducing the on-site limitation, accumulative tolerance, increasing the flexibility of dealing with uncertainties, and error acceptance [36].

Similarly, according to the uncertain natural material behaviors, Akbari recommended a new workflow for on-site fabrication by fabricating the performance of natural material and generating the following design through a cyber-physical system in the AR environment [17]. This system is composed of 3D scanning sensor and computational calculating software to optimize the architectural construction process. These "dynamic blueprints" are visualized through AR as an updated fabrication model based on the feedback of material behavior and the structural-reasonable of design (Fig.15) [17]. This workflow associates virtual design information with the physical environment and opens a new communication through the AR environment which can transform traditional practices within the building construction industry deeply. The author presents that this AR cyber-physical construction system will enable architects to integrate new architecture techniques with the advanced and complex computational design which can lead to new forms of construction and transform traditional practices within the architectural construction industry [17].

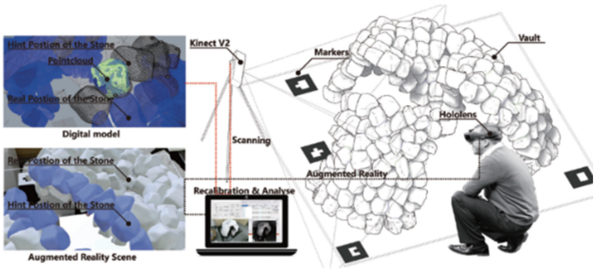

Fig. 14: Cyber-physical system with irregular foam bricks. This figure was produced by C.Y.Sun et al. in 2018 [36], and it summarized a scenario of a hybrid fabrication freeform pavilion with irregular foam bricks in AR. The permission to re-use the figure has been granted by the author and the publisher.

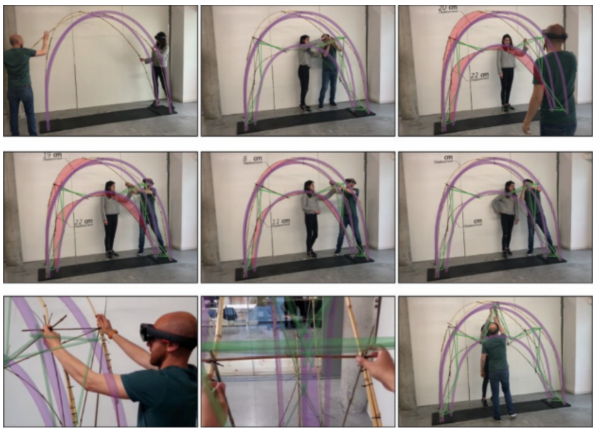

Fig. 15: Cyber-physical construction process in AR. This figure was produced by A.Akbari from IAAC programme Master in Advanced Architecture in 2018 [36], and it summarized that during the fabrication, the differences between 3D virtual blueprints and the physical structure are constantly monitored and the user tried to follow the virtual guide as much as uncertain behavior of the material allows in AR. The permission to re-use the figure has been granted by the author and the publisher.

4.2.3. Future trends in AR data sharing

AR data sharing offers a dynamic communication between human thought, digital data, computer calculation, and material behavior. The elements of this real-time system interact and restrict each other relevantly. Due to the existing limitation, there are still many possibilities to be studied in AR data sharing areas.

First, the methods using above, such as assessing by eye and using the single sensor system, will cause tolerance and unexpected situation which is difficult for the system to identify. It will be the future trend to complete a rigorous process by improving the accuracy of scanning sensors and the diversification of data sharing. Providing clearer feedback to users on construction accuracy and project performance may be achieved by combining the AR data sharing system with third party photogrammetry tools and depth scanners in the future works to improve on what researchers have established can be achieved by eye alone.

Second, there are still some phenomena that need to be discussed, such as the difference between passive deviations caused by human operation and active adjustments. That will be a trend to distinguish the different kinds of inputs and filter the error interferences from positive inputs. This selection will be a key for AR data sharing.

Last, future work will explore the utility of these possible improvements as the users continue to apply the AR data sharing system to the challenges of larger structures.

4.3. Category C: AR for Human-Computer interaction

AR for Human-Computer interaction in robotic operation is the second-largest category in the past three years (Fig.5). This domain makes a huge contribution to AR digital fabrication. Because manipulating the robotic arms is kinds of dangerous for architects who have little or no practical experience, especially during the real robotic trajectory operation process. Apart from this, using a programming language to control the robotics is not an easy task for architects. Manipulating and operating robots with intractable user interface (UI) and demonstration in 3D holographic during digital fabrication process through AR environment can solve the above difficulties. The 3D robot hologram overlapping on the real machine in the AR environment will demonstrate the trajectory simulation animation virtually to remind the operator about collision warnings and reduce the danger in operations. The sub-categories have been identified as:

(1) AR UI for robotic operation.
(2) Programming by demonstration through AR.

4.3.1. Sub-category 1: AR UI for robotic operation

The UI for industrial robots is gradually being developed, which is not as perfect as the UI in other similar systems such as mobile phones and computers [39]. Therefore, it is a key motivation for allowing robots to infiltrate more in the architectural digital fabrication process by increasing the possibility for non-programmer designers to operate and interact with the robots [40]. AR technology has the ability to overlay digital information on the real-world projects as well as the ability to interact in real-time using physical gestures and virtual controls. These characteristics give the prototype and necessary conditions for developing an AR UI to operate robots.

Johns et al. use object interaction and projection-based AR environments to design and transform material systems out of melting wax robotically [41]. The authors state in the conclusion that using AR technology can benefit the robotic operating system [41]. On the contrary, with the improvement of AR equipment, headset devices like Microsoft HoloLens provide more convenience for manipulating robots. Kyjanek et al. design a workflow for the Human-Computer interaction through AR in the production and assembly of an architectural scale wooden construction system (Fig.16) [16]. The authors proposed an interactive fabrication process that construction worker can plan the robotic trajectories, influence assembly sequencing, view and activate robotic operations through AR user interface in order to solve the disadvantage of adapting robots in construction, and enhance the non-programmer worker participation in Human-Computer interaction to reduce the risk of manipulating and debugging real robots [16]. In the same way, Danielsson et al. show in their research that AR instructions can give information for untrained workers to the assembly in collaboration with a robot, and the AR user interface can make robot interaction more dynamic and efficient without creating risk for human (Fig.17) [16].

In contrast, not limited to simple robotics manipulation, Olar et al. and Jasche et al. start their research in controlling a robotic arm with AR UI and appropriating 3D printers with AR UI respectively [43, 44]. They both declare that the AR UI gives the possibility for non-professor to get easier access to the robotic machines and devices which used to need high-tech operators [43, 44]. Similarly, Peng et al. design a project to achieve interactive fabrication with an AR UI and a robotic 3D printer which enhanced a fast, precise, hands-on, and in-situ modeling experience through the digital fabrication system [45]. They present that this research project simplifies the traditional design method by using a mouse and a keyboard and improve the Human-Computer operation through the AR UI to open up new interaction opportunities between designers and the robotic arms [45].

Fig. 16: Robotic operation setup in AR.
This figure was produced by O.Kyjanek et al. in 2019 [16], and it summarized the robotic demonstration setup with the wood structure assembly pedestal in the AR environment. The permission to re-use the figure has been granted by the author and the publisher.

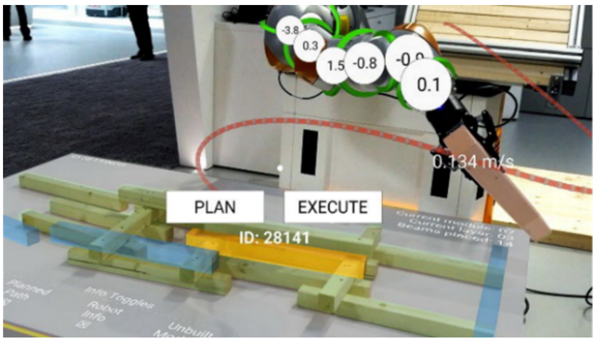

Fig. 17: AR UI for previewing path and operating robots.
This figure was produced by O.Kyjanek et al. in 2019 [16], and it summarized the AR view visualizing buttons for selecting, planning, and executing robotic instructions as well as superimposed diagnostic feedback data. The permission to re-use the figure has been granted by the author and the publisher.

4.3.2. Sub-category 2: Programming by demonstration through AR

Programming by demonstration is a programming method that incorporates the users' manual demonstration and leaves the robots to observe follow or replicate the task in real-time [46]. Recent research on robot programming shows a trend of moving towards multimodal interfaces [47]. Gestures, voices, etc., are beginning to be used as high-level inputs to control the industrial robotic system for the architectural industry [48, 49]. The various applications of AR provide the unskilled user with intuitive simulation options in robotic path planning and translate human actions directly and visually into a robot programming language [50].

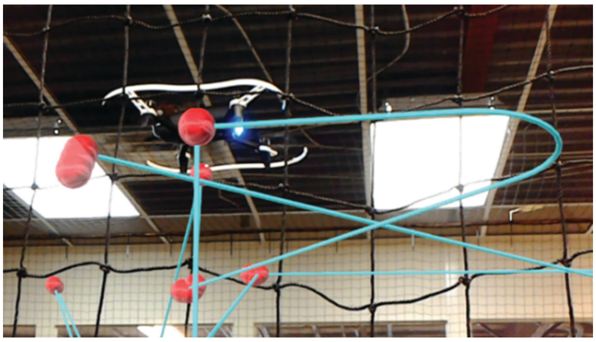

Fig. 18: AR-robot visualization programming. This figure was produced by JN.A.Dackiw et al. in 2019 [51], and it summarized the waypoint navigation interface for drones through AR. The permission to re-use the figure has been granted by the author and the publisher.

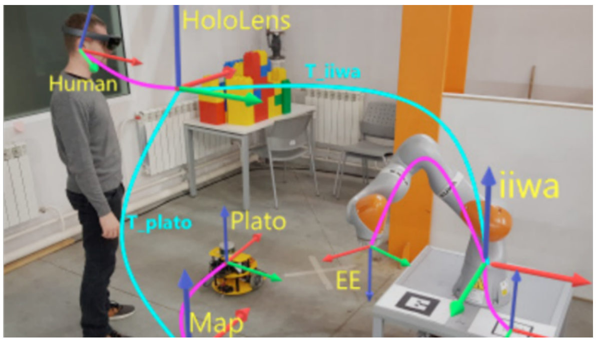

Fig. 19: Programming robots by demonstration through AR. This figure was produced by M.Ostanin et al. in 2019 [54], and it summarized the principal frames and transformations of the system in AR demonstration programming. The permission to re-use the figure has been granted by the author and the publisher.

Fang et al. present an AR-based system for robot programming and trajectory planning as well as Dackiw et al. present an AR interface for programming drone operation and navigation (Fig.18) [51]. They provided an AR environment that the user can preview the simulated motion, find out any possible errors, and resolve discrepancies between the planned and simulated trajectory. By AR simulation, the user can plan, operate, and evaluate the robot path intuitively. Robot programming using AR is developed to assist the users in robot task and path planning using a virtual robot in the real working environment [52]. In a similar way, Blankemeyer et al. and Ostanin et al. also show that simply the programming process through AR can rise the efficiency and flexibility of robot operation and give the operator an easy assembly process [53, 54]. Their research shows that the AR interactive programming of the different robots is an unskilled user-friendly, more intuitive, and safer robot path programming and visualizing method (Fig.19) [54]. This method can define and manipulate the robot in the on-site area with virtual simulation through AR instead of traditional programming and improve the robot control efficiency without physical collision [55].

4.3.3. Future trends in AR for Human-Computer interaction

AR for Human-Computer interaction field is at the very beginning step of study and research, with the technical limitations and many issues to be solved. With the popularity of industrial robots in the architectural digital fabrication process, it has become a challenge for non-programming skilled architects that how to control the robotic arms reasonably and efficiently. Different with the original digital fabrication in architecture, AR technology provides architects a way for manipulating robot trajectory with intractable UI and demonstrating robotic operation with 3D holograms. It reduces the requirements for architects to write code in computer science language and improves the safety for no practical experience operators during the digital fabrication process. AR environment for Human-Computer interaction offers a suitable method for facing the challenge in the future.

First, the Human-Computer interactions in robotic operations that have been achieved above are only simple operations such as picking, moving, and placing. Due to the complexity and diversity of operations in architectural digital fabrication, it will be the future trend to study and apply multiple complex operations for industry robotic arms in the AR environment to satisfy the requirements of different architectural structures and forms.

Second, the AR Human-Computer interaction systems above are working with one robotic arm. This system serves well as the initial research prototype tests. But for large scale components and structures, this system needs to be improved. Multiple participations and multiple collaborative robotic arms need to be added and identified in the AR environment for large scale explorations. Future trend has also be highlighted that it is moving towards using AR technology for large scale of architectural fabrication and construction with multi-robot interaction methods.

5. Conclusion and Future trends

This study of AR for architectural digital fabrication has shown that in the last ten years, the most widely developed and researched direction in architectural digital fabrication is AR 3D holographic instruction. Unlike traditional 2D drawings, holographic instruction provides contextual, scaled, and tangible descriptions of intuitive target for on-site projects. But there are still some shortcomings that need to be improved in the future. AR technologies promoted the non-expert participation in architectural fabrication and construction processes especially in immersive design, construction guidance, and robotic operation. From the recent research, there is a small number of projects related to the AR immersive design, Human-Computer interaction through AR including operating and programming. These researchers achieved interactive adjustments, interaction with gestures, and programming through the real world in the visualization environment. But they are still in the initial exploration stage. The simple interactive control method, the lack and the tolerance of gesture recognition through AR device, the single and easy robot command, and the lack of a multi-operation system are the problems that need to be solved and developed more in architectural digital fabrication.

Many researchers believe that all the shortcomings and limitations will be solved by the upcoming generations soon in the future. The multidisciplinary research is also the essential power for AR technology innovations.

Five trends of future development are anticipated:

(a) High-precision AR devices and systems will be used to track human voice, movement, gestures, and other input information during immersive design in the AR environment.

(b) The body of knowledge on the multi-robot system in Human-Computer interaction will contribute to more possibilities to support AR methods or tools for architectural construction.

(c) The multi-operator participation for a more in-depth exchange of opinions, experience sharing, and trainings will be more widely used in AR technologies.

(d) Real-time scanning of the constructed on-site structure and the dynamic information and suggestion between computer calculation and human thought will be better in communication and presentation through an AR environment during the architectural fabrication and construction process.

(e) The feedback system based on the uncertain shape performance of natural materials and the suggestion given by real-time generation will be the future AR construction system for manual fabrication in the architectural construction process.

It has been implied that these trends will have potential significance for the development of the architectural digital fabrication area. The higher precision AR device and sensor will reduce the gesture recognition errors during the immersive design and data interaction process. This could improve the digital data interaction process between material behavior, designer, computer, and robotic to avoid tolerance during data sharing in digital and physical. This could mean also that the aforementioned developments will also provide the possibility of AR technology for large scale architectural construction projects, which need multi-operator participation and multi-robot interaction through AR real-time communication and presentation environment.

Based on this review, it seems evident that AR technologies have a future in the architectural digital fabrication area. That future is possibly very meaningful for the entire building industry. The rapid development of research and applications in AR technologies for the architectural engineering sector points also towards another research finding. AR seems the have indeed the potential capabilities to solve the traditional construction problems and fabrication difficulties, by overlapping holographic instructions to on-site projects in the real world.

Having this said, however, a degree of skepticism and caution is prudent. Most of the outcomes and systems found in the literature to date are demonstrations. They are developed for a specific purpose and research direction. It seems clear that some new systems offer valuable features and provide competitive advantages. As AR technology is evolving rapidly, it is recommended for the fabrication and construction participants to catch this development closely in order to get the latest update. Assuming that AR technologies will improve with safety, efficiency, visualization, and workforce, it is far nearly sure that such technologies will play more important roles in the architectural digital fabrication areas for future years.

References

[1] M.Claypool, 2020, The Digital in Architecture: Then, Now and in the Future, https://space10.com/project/digital-in-architecture.

[2] S.Hahm, I.Pantic, 2016, Hybrid design workflows of digital crafting and material computation, International peer reviewed conference, aae 2016 Research Based Education, London: The Bartlett School of Architecture, UCL.

[3] L.Rosenberg, 1992, The Use of Virtual Fixtures as Perceptual Overlays to Enhance Operator Performance in Remote Environments, Stanford Univ Ca Center for Design Research, AL/CF-TR-1994-0089.

[4] B.X.Chen, 2009, If You're Not Seeing Data, You're Not Seeing, https://www.wired.com/2009/08/augmented-reality.

[5] J.Steuer, 1992, Defining virtual reality: Dimensions determining telepresence, Journal of Communication, 42, pp.73-93.

[6] S.Mann, S.Feiner, S.Harner, M.A.Ali, R.Janzen, J.Hansen, S.Baldassi, Wearable computing, 3d Aug* Reality, photographic/videographic gesture sensing, and veillance, Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction, 2015, pp.497-500.

[7] S.Noelle, 2002, Stereo augmentation of simulation results on a projection wall by combining two basic ARVIKA systems, International Symposium on Mixed and Augmented Reality (ISMAR), Darmstadt, Germany: IEEE, DOI: 10.1109/ISMAR.2002.1115108.

[8] M.Abernathy, J.Houchard, M.Puccetti, J.Lambert, Debris Correlation Using the Rockwell WorldView System. Proceedings of 1993 Space Surveillance Workshop, 1993, pp.189-195.

[9] F.J.Delgado, M.F.Abernathy, J.White, W.H.Lowrey, Real-time 3D flight guidance with terrain for the X-38, Enhanced and Synthetic Vision 1999, 1999, International Society for Optics and Photonics, pp.149-156.

[10] D.Divecha, 2011, Augmented Reality (AR) used in architecture and design, https://www.middleeastarchitect.com/inspiration/augmented-reality-ar-part-architecture-design.

[11] V.Meeuwen, 2012, Architectural dreams in augmented reality, http://www.news.uwa.edu.au/201203054410/events/architectural-dreams-augmented-reality, the university of western Australia.

[12] A.Keoghan, 2008, Outdoor AR: Using augmented reality and GPS tracking to overlay 3D content on to the outside world, HIT Lab NZ Trimble, https://www.youtube.com/watch?v=jL3C-OVQKWU.

[13] G.Jahn, C.Newnham, N.Van Den Berg, M.Iraheta, J.Wells, Holographic Construction, Design Modelling Symposium Berlin, 2019, Springer, pp.314-324.

[14] G.Jahn, C.Newnham, M.Beanland, 2018, Making in Mixed Reality: Holographic design, fabrication, assembly and analysis of woven steel structures, Proceeding of 2018 ACADIA, Mexico City, pp.88-97.

[15] G.Betti, S.Aziz, G.Ron, 2019, Pop Up Factory: Collaborative Design in Mixed Rality, Interactive live installation of the makeCity festival, Proceeding of eCAADe 2019, Berlin, pp.115-124.

[16] O.Kyjanek, B.A.Bahar, L.Vasey, B.Wannemacher, A.Menges, Implementation of an augmented reality AR workflow for human robot collaboration in timber prefabrication, Proceedings of the 36th International Symposium on Automation and Robotics in Construction, 2019, Volume 36.

[17] A.Akbari, 2018, Cyber-Physical Construction: Negotiating design and making through Augmented Reality, http://www.iaacblog.com/programs/cyber-physical-construction, Institute for advanced architecture of Catalonia.

[18] H.L.Chi, S.C.Kang, X.Wang, 2013, Research trends and opportunities of augmented reality applications in architecture, engineering, and construction, Automation in Construction, 33, pp.116-122.

[19] M.J.Kim, 2013, A framework for context immersion in mobile augmented reality, Automation in Construction, 33, pp.79-85.

[20] X.Li, W.Yi, H.L.Chi, X.Wang, A.P.Chan, 2018, A critical review of virtual and augmented reality (VR/AR) applications in construction safety, Automation in Construction, 86, pp.150-162.

[21] B.Kolarevic, 2004, Architecture in the digital age: design and manufacturing, taylor Franci, pp.17-45.

[22] K.Dörfler, T.Sandy, M.Giftthaler, F.Gramazio, M.Kohler, J.Buchli, 2016, Mobile robotic brickwork: Robotic Fabrication in Architecture, Art and Design 2016, Springer, pp.205-218.

[23] A.Fazel, A.Izadi, 2018, An interactive augmented reality tool for constructing free-form modular surfaces, Automation in Construction, 85, pp.135-145.

[24] S.Meza, Z.Turk, M.Dolenc, 2015, Measuring the potential of augmented reality in civil engineering. Advances in Engineering Software, 90, pp.1-10.

[25] N.H.Wu, M.Dimopoulou, H.H.Hsieh, C.Chatzakis, 2019, Rawbot A digital system for AR fabrication of bamboo structures through the discrete digitization of bamboo, Proceeding of eCAADe 37/SIGraDi 23, pp.161-170.

[26] A.Lharchi, M.R.Thomsen, M.Tamke, 2019, Towards Assembly Information Modeling (AIM), 2019 SimAUD, 51, pp.1-6.

[27] B.Wibranek, O.Tessmann, 2019, Digital Rubble Compression-Only Structures with Irregular Rock and 3D Printed Connectors. Proceedings of IASS Annual Symposia, 2019 International Association for Shell and Spatial Structures (IASS), pp.1-8.

[28] G.Jahn, A.J.Wit, J.P.Samara, 2019, [BENT] Holographic handcraft in large-scale steam-bent timber structures, ACADIA 2019, Austin, Texas, pp.1-11.

[29] I.Hacmun, D.Regev, R.Salomon, 2018, The principles of art therapy in virtual reality, Frontiers in Psychology, 9, 2082, pp.1-8.

[30] J.Bodner, F.Augustin, H.Wykypiel, J.Fish, G.Muehlmann, G.Wetscher, T.Schmid, 2005, The da Vinci robotic system for general surgical applications: a critical interim appraisal, Swiss Medical Weekly, pp.674-679.

[31] Z.Syed, J.Z.Arshad, S.Berkovsky, F.Chen, 2017, Human-In-The-Loop Machine Learning with Intelligent Multimodal Interfaces, Human In The Loop Machine Learning @ ICML 2017, https://machlearn.gitlab.io/hitl2017/schedule.

[32] J.Forren, M.Ramadan, S.Sarrazin, 2019, Action Over Form: Combining Off-Loom Weaving and Augmented Reality in a Non-specification Model of Design, James Forren's Lab, Artificial Realities: Virtual as an aesthetic medium in architecture ideation 2019, Lisbon, Portugal, pp.1-32.

[33] S.Hahm, A.Maciel, E.Sumitiomo, A.L.Rodriguez, 2019, FlowMorph-Exploring the human-material interaction in digitally augmented craftsmanship, Proceeding of CAADRIA 2019, pp.553-562.

[34] G.Goepel, 2019, Augmented Construction - Impact and opportunity of Mixed Reality integration in Architectural Design Implementation, Proceeding of ACADIA 2019, Austin, PP.2-9.

[35] T.Bock, 2007, Construction robotics, Autonomous Robots, 22, pp.201-209.

[36] C.Y.Sun, Z.H.Zheng, Y.Z.Wang, T.Y.Sun, 2018, Hybrid Fabrication: A Freeform Building Process with High Onsite Flexibility and Acceptable Accumulative Error, ACADIA 2018, pp.82-87.

[37] D.Reiners, D.Stricker, G.Klinker, S.Müller, 1999, Augmented reality for construction tasks: Doorlock assembly, Proceedings of the international workshop on Augmented reality: placing artificial objects in real scenes: placing artificial objects in real scenes, AK Peters, Ltd., pp.31-46.

[38] A.Tang, C.Owen, F.Biocca, W.Mou, Comparative effectiveness of augmented reality in object assembly, Proceedings of the SIGCHI conference on Human factors in computing systems, 2003. pp.73-80.

[39] A.Aryania, B.Daniel, T.Thomessen, G.Sziebig, 2012, New trends in industrial robot controller user interfaces, 2012 IEEE 3rd International Conference on Cognitive Infocommunications (CogInfoCom), IEEE, pp.365-369.

[40] B.Lafreniere, T.Grossman, F.Anderson, J.Matejka, H.Kerrick, D.Nagy, L.Vasey, E.Atherton, N.Beirne, M.H.Coelho, 2016, Crowdsourced fabrication, Proceedings of the 29th Annual Symposium on User Interface Software and Technology, pp.15-28.

[41] R.L.Johns, 2014, Augmented materiality: modelling with material indeterminacy. Fabricate. gta Verlag, Zurich, pp.216-223.

[42] O.Danielsson, A.Syberfeldt, R.Brewster, L.Wang, 2017, Assessing instructions in augmented reality for human-robot collaborative assembly by using demonstrators, Procedia CIRP, 63, pp.89-94.

[43] M.L.Olar, M.Risteiu, A,F.Panaite, M.Rebrisoreanu, O.Musetoiu, 2020, Controlling a robotic arm with Augmented reality, MATEC Web of Conferences 2020, EDP Sciences, 00022.

[44] F.Jasche, T.Ludwig, 2019, Appropriating 3D Printers in Augmented Reality, Proceedings of Mensch and Computer 2019.

[45] H.Peng, J.Briggs, C.Y.Wang, K.Guo, J.Kider, S.Mueller, P.Baudisch, F.Guimbretière, 2018, RoMA: Interactive fabrication with augmented reality and a robotic 3D printer, Proceedings of the 2018 CHI conference on human factors in computing systems, pp.1-12.

[46] A.Billard, S.Calinon, R.Dillmann, S.Schaal, 2008, Survey: Robot programming by demonstration, Handbook of Robotics, pp.71-94.

[47] S.Iba, C.J.Paredis, P.K.Khosla, 2005, Interactive multimodal robot programming. The international journal of robotics research, 24, pp.83-104.

[48] R.Marín, P.J.Sanz, P.Nebot, R.Wirz, 2005, A multimodal interface to control a robot arm via the web: a case study on remote programming, IEEE Transactions on Industrial Electronics, 52, pp.1506-1520.

[49] Y.Yanagihara, T.Kakizaki, K.Arakawa, Y.Isoda, 1998, A multimodal teaching advisor for sensor-enhanced robotic systems in manufacturing, Robotics and Computer-Integrated Manufacturing, 14, pp.263-273.

[50] R.K.J.Bischoff, 2006, Invited talk: concepts, tools and devices for facilitating human–robot interaction with industrial robots through augmented reality, Proceedings of the ISMAR workshop on industrial augmented reality.

[51] J.A.Dackiw, K.Kaseman, A.Foltman, A.Ollazzo, S.Garivani, 2019, Cyber-physical UAV Navigation and Operation: Drone Localization and Accuracy Validation through Onboard Odometry and External Motion Tracking Comparison, ACADIA 2019, pp.360-367

[52] H.C.Fang, S.K.Ong, A.Y.C.Nee, 2012, Interactive robot trajectory planning and simulation using Augmented Reality, Robotics and Computer-Integrated Manufacturing, 28, pp.227-237.

[53] S.Blankemeyer, R.Wiemann, L.Posniak, C.Pregizer, A.Raatz, 2018, Intuitive Robot Programming Using Augmented Reality, Procedia CIRP, 76, pp.155-160.

[54] M.Ostanin, R.Yagfarov, A.Klimchik, 2019, Interactive Robots Control Using Mixed Reality, IFAC, pp.695-700.

[55] M.Ostanin, A.A.Klimchik, 2018, Interactive Robot Programming Using Mixed Realty, IFAC, pp.50-55.

[56] Fologram, AllBrick and UTAS: Holographic Construction of the Royal Hobart Hospital, last modified February 26, 2020, https://community.fologram.com/t/constructing-curved-benches-from-cut-bricks-in-mixed-reality/434.

[57] Fologram, Speampunk Pavilion, Tallinn Architecture Biennale Pavilion, last modified October 12, 2019, https://vimeo.com/365917769.

[58] Y.Song, BloomShell: Augmented Reality for the assembly and realtime modification of complex curved structure, eCAADe 2020, pp.345-354.