Automation in Construction 86 (2018) 150–162

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

A critical review of virtual and augmented reality (VR/AR) applications in construction safety

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ARTICLE INFO

Keywords:
Virtual reality
Augmented reality
Construction
Safety
Review

ABSTRACT

Construction is a high hazard industry which involves many factors that are potentially dangerous to workers. Safety has always been advocated by many construction companies, and they have been working hard to make sure their employees are protected from fatalities and injuries. With the advent of Virtual and Augmented Reality (VR/AR), there has been a witnessed trend of capitalizing on sophisticated immersive VR/AR applications to create forgiving environments for visualizing complex workplace situations, building up risk-preventive knowledge and undergoing training. To better understand the state-of-the-art of VR/AR applications in construction safety (VR/AR-CS) and from which to uncover the related issues and propose possible improvements, this paper starts with a review and synthesis of research evidence for several VR/AR prototypes, products and the related training and evaluation paradigms. Predicated upon a wide range of well-acknowledged scholarly journals, this paper comes up with a generic taxonomy consisting of VR/AR technology characteristics, application domains, safety scenarios and evaluation methods. According to this taxonomy, a number of technical features and types that could be implemented in the context of construction safety enhancement are derived and further elaborated, while significant application domains and trends regarding the VR/AR-CS research are generalized, i.e., hazards recognition and identification, safety training and education, safety instruction and inspection, and so on. Last but not least, this study sets forth a list of gaps derived from the in-depth review and comes up with the prospective research works. It is envisioned that the outcomes of this paper could assist both researchers and industrial practitioners with appreciating the research and practice frontier of VR/AR-CS and soliciting the latest VR/AR applications.

1. Introduction

Construction is a large, dynamic and complex sector that offers a large number of employment opportunities for millions of people worldwide [1]. However, fatal accidents in the construction industry tend to be higher than other sectors [2], for a long run, such a phenomenon has aroused a lot of safety concerns and discussions. Safety management, a method of manipulating on-site safety policies, procedures, and practices relating to a construction project, is one of the most frequently leveraged techniques to regulate construction activities and control risks [3]. Previous studies revealed that most accidents associated with construction undertakings were attributed to a lack of proactive and preventive measures such as workforce training, risk source identification and control, safety awareness and education, and so forth [4]. On the other hand, how effective these measures could work is subject to how much job-site knowledge could be solicited and how efficiently the knowledge could be absorbed [5,6]. To this end, information visualization techniques such as Building Information Modeling (BIM), Virtual Reality (VR) Augmented Reality (AR), as well as other game engine-based Mixed Reality (MR) techniques, have been delved into to advance the current safety management practices [7–10].

A long-established climate that safety is tied up with management has placed many construction firms and researchers' primary focus on cultural intervention, uptake of safety behaviors, organizational ideologies, espoused and enacted policies, communication and induction, and etc. [11,12]. Meanwhile, a quick look through into VR/AR-CS publications helps identify that VR/AR technologies have been probed and tentatively implemented in various safety enhancement areas, such

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https://doi.org/10.1016/j.autcon.2017.11.003
Received 29 July 2016; Received in revised form 9 October 2017; Accepted 3 November 2017

as risks identification, workforce training, skill transfer, ergonomics, and so on. Most studies have rationalized the development of a vast variety of VR/AR-CS systems for a safety enhancement purpose, and some studies have made efforts to summarize the VR/AR-CS. For example, Bhoir and Esmaeili [13] conduct an in-depth literature review to investigate the prevailing adoption rate of virtual reality environment to train workers regarding safety issues. And Guo et al. [14] examine the application of visualization technologies in construction safety and find that visualization technology can efficiently improve the safety training, facilitate job hazard area identification and accident prevention in a visual, interactive and cooperative way. However, they loosely compare how effectively these tailored technologies and systems, particularly for augmented reality and virtual reality, could be utilized to facilitate construction safety considering the disparity of evaluation method, technology characteristics, project types, scales, work complexity and other factors. Meanwhile, because the VR/AR-CS literature is found overwhelmingly diverse and vast, academia and industry may not be acutely aware of the authentic limitations and gaps in this area. Integration and classification of the reported literature within the VR/AR-CS domain may help them to gain a better understanding of the state-of-the-art and the related challenges. To cater to the industrial demands, additionally, it is also essential to have the most appropriate VR/AR devices, applications, systems, safety enhancement mechanisms and evaluation methodologies suggested. Therefore, the aims of this review are to address the aforementioned limitations and gaps through coming up with the most significant body of knowledge of VR/AR-CS and to drive the prospective research directions up to the most valuable and critical areas that the industrial and academic communities are adhering to.

2. An overview of VR/AR technologies and peripherals

Virtual reality (VR) simulation is to generate immersive environments from which users can experience unique insights into the way the real world works [15,16]. The concept of VR was brought up over fifty years ago when the first immersive human-computer interaction (HCI) mock-up named “Man-Machine Graphical Communication System” was invented [17]. The formal term of VR was put up in 1989 [18]. Since then, several taxonomies have been raised by scholars to expound where a rigorous VR concept should stay from along the continuum of reality to virtuality (RV). For example, Milgram's taxonomy (Milgram and Colquhoun, 1994) shown in Fig. 1 defines four levels of RV experience based upon the degree of blending that different electronic display systems can achieve; Benford's taxonomy [19] shown in Fig. 2 classifies four spaces according to the extent to which a group of users can access virtual objects from their local space and the extent to which a space is either synthetic or is based on the physical world. VR attempts to replace a user's perception of the surrounding world with a computer-generated artificial 3D environment. And such virtual 3D environment is not necessary to be established based on a real one. In the RV continuum based on Milgram's taxonomy, VR represents effort in creating a virtual environment (VE) with visual and immersive aids to let users feeling a “real” sensation. However, it can only provide a limited level of ‘realism’ due to a lack of sensory feedback to accommodate for perceptual and cognitive viewpoints [20]. As an emerging technology, AR integrates images of virtual objects into a real world. By inserting the virtually simulated prototypes into the real world and

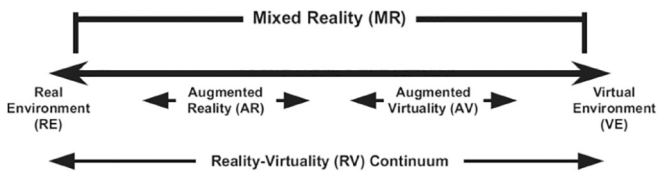

Fig. 1. Reality-virtuality (RV) Continuum [87].

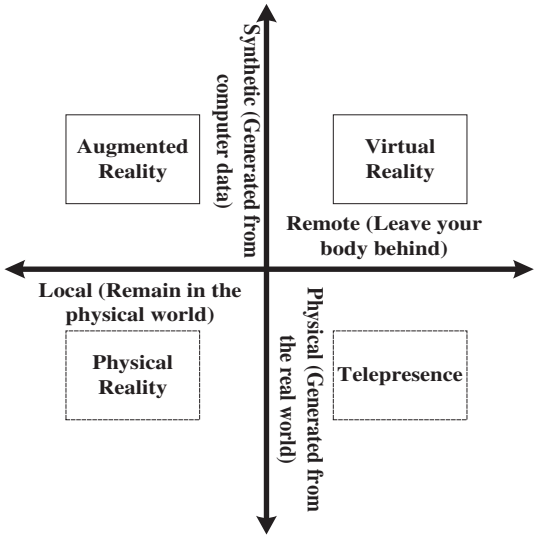

Fig. 2. Classification of Shared Spaces According to Transportation and Artificiality (adapted from [19]).

creating an augmented scene, AR technology could satisfy the goal of enhancing a person's perception of a virtual prototyping with real entities. This gives a virtual world an ameliorated connection to the real world while maintaining the flexibility of the virtual world [21]. In sum, the rigorous classification defined for VR and AR in this research is based on whether or not the visual sensations from the real world get to involve regardless of the establishment of immersion or the mechanisms of the display. While there is a blending of reality and virtuality, it can always be referred to Mixed Reality (MR) as a collective term. Such examples include a VR generated virtual environment fully superimposed on its related physical world, or the wide range of AR applications. In particular, AR, within the continuum of MR, generates an RV blended environment where the most of the visual sensation comes from the real world, and the virtual elements contributed less. The percentages of reality and virtuality can be reverted for augmented virtuality (AV) which is not discussed in this paper.

Ever since the first mature wearable VR/AR device (i.e., Google Glass, Forte VFX1) on the market, the reality of mobile VR/AR devices seems to be inevitable and have the potential to enrich the way information is accessed and presented. Technology developers (including hardware and software) from around the world have been trying to work with big brand marketers to build more tangible and auditory VR/AR solutions to deliver the best solutions matching clients' requirements and objectives (Fig. 3). Instead of just being able to interact with 3D contents in a pure computer-generated environment, users nowadays are capable of realizing a highly immersive, holistic and realistic experience underpinned by synthesized digital and physical world information presented using more sophisticated software and hardware. As shown in Fig.4, the paramount for the sensation of immersion into VR/AR are a high frame rate (at least 95 fps) and low latency. Furthermore, a pixel persistence lower than 3 ms could prevent users feel sick when moving their head around. Nowadays, the gap between the real world and its digital counterparts is becoming narrower. The tremendous potential that VR/AR could lead to a number of important changes in human life and activity has been witnessed from a wide range of application areas such as education and training [22], engineering [23], architectural and urban design [24], heritage and archaeology [25], medical science [26], entertainment [27] and so forth. In order to understand the frontier of VR/AR technologies from a broad range of application areas and uncover the possibilities of using VR/AR in construction safety, this paper provides a thorough review of mainstream literature published between 2000 and 2017. The selected articles were classified according to a four-level taxonomy: (1) technology