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Using Mixed Reality for electrical construction design communication

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ABSTRACT

Building Information Modeling (BIM) techniques have enabled the construction industry to realize various benefits. However, most projects still rely on 2D drawings to communicate the 3D BIM content to construction personnel. While Mixed Reality (MR) could theoretically be the primary means of communicating BIM content to onsite personnel in 3D, there is not currently a thorough understanding of how this might impact the construction performance of industry practitioners. This paper explores this topic by examining the field of electrical construction. It addresses research questions related to: MR's influence on the productivity and quality of electrical conduit construction; and the effects of an industry practitioner's background on his or her performance using MR. To address these topics, a quasi-experiment was conducted that compares the performance of eighteen electrical construction personnel who were tasked with building similar conduit assemblies using traditional paper and MR. Participants completed pre- and post-activity questionnaires to provide their perceptions of the experience. The results suggest that MR enabled: a significantly higher productivity rate; reduced the time required to understand the design; led to fewer errors during the assembly process; and increased the number of accurately constructed conduits as compared to the conduits constructed using traditional paper. Additionally, nearly all participants agreed that MR is easy to use, but most still felt that they would prefer to use paper plans for design communication. The findings of this work were noteworthy because many of the participants had substantial prior experience constructing conduit using paper plans, yet they still performed the task better and faster using MR. While the small sample size limits the extent to which these findings can be generalized, the contribution of this work is in demonstrating, as a proof-of-concept, that MR can be a viable option for communicating existing BIM content to current industry practitioners and that it can offer advantages that are not currently observed through the use of a paper-based communication methods.

1. Introduction

In the United States (US), the construction industry is considered a significant contributor to national economic growth, with a total of $800 Billion of annual spending [1]. Productivity in construction has been identified as an important research topic, constituting one of six Key Performance Indicators (KPI's) of any construction project [2]. Research suggests that the construction industry has been lagging in productivity measurement and improvements [3]. While macroeconomic viewpoints point to an increase in construction productivity over the past few decades [4], microeconomic perspectives argue the opposite, suggesting negative productivity trends over the past half-century [5–7].

Today, the construction industry is facing major challenges related to waste, which is estimated to cost more than $15 billion annually [8]. According to industry professionals, when the different stakeholders are unable to effectively communicate, as much as 30% of the total value of a given project goes to waste [8]. These productivity challenges may be further exacerbated in the future as the industry approaches a major labor shortage, which has been termed a “labor cliff” [9,10].

While there is some debate about productivity trends, there is a consensus that the industry needs to modernize its practices. Building Information Modeling (BIM) and prefabrication have been suggested to offer benefits that may support this broader effort to modernize. Prefabrication has been linked to increased productivity and enhanced quality control [11], as well as reduction in construction waste [12]. BIM leverages intelligent 3D models to support design, construction, delivery, and facility management [13]. Use of BIM has been steadily increasing in recent years, especially among contractors [14].

While BIM use has been increasing in the industry, most projects still rely on traditional 2D documentation to communicate the 3D building design concept to field personnel. Theoretically, Mixed Reality (MR) could be used to communicate 3D BIM content to onsite personnel, but there is not a thorough understanding of how this mode of

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visualization would impact practitioner performance. The authors explore this topic by examining the use of MR for tasks related to electrical construction. This paper addresses the following questions: How can MR influence the productivity and quality of electrical conduit construction? What are the effects of an industry practitioner's background on his or her performance using MR visualization technology? These questions are addressed by implementing a quasi-experimental procedure with electrical construction practitioners. The participants completed two similar electrical conduit construction tasks, once using MR and again using standard paper plans. Participants' background and perceptions were identified through pre- and post-activity questionnaires. The subsequent sections detail the research approach and findings.

2. Background

2.1. Information delivery

The process of design communication in construction typically involves a linear flow of information from the designer to the site worker. This mode of communication is explained by the theory of linear standard communication process, where a message is generated, encoded into a signal transmittable in the desired medium, and then decoded upon arrival for the receiver to get the message [15]. Additionally, noise can sometimes interfere in the coding, transmittal, or decoding of the message, leading to a mismatch between the received and sent message. Specifically, in construction, the designer creates a design, encodes it into a set of plans be sent to the site worker, who decodes the plans, understands the design, and then builds it. Traditionally, 2D paper plans have been the primary means of communication in construction [16], where their value in aiding design and design communication has been well documented [17]. Research suggests that numerous sources of noise can interfere in the communication, including: wrong or in-executable designs; missing information from the paper plans; or ambiguous design representation [18]. This suggests that while traditional paper communication offers certain benefits, it can also lead to problems in design communication.

More recently, 3D physical mockups and 3D virtual mockups have been studied to determine how they may support design communication [19]. Using physical mockups does not require reinterpretation from the worker, which enables a lower cognitive workload to conceptualize a design [19] and it can reduce sources of design communication noise that lead to mistakes. Physical mockup use is associated with higher productivity rates and easier assembly compared to other means of design communication [19–21]. While physical mock-ups may offer value for design communication, they can be impractical to use to communicate the design of every building object on a project, especially when the configuration of different objects changes throughout a project.

2.2. Building Information Modeling (BIM) and prefabrication

BIM involves the development of intelligent, 3D, models that include information related to intrinsic properties of modeled objects that are stored in an attached database [13]. BIM use can help to reduce and control project cost [22] and minimize construction waste [23]. Recently, BIM adoption has increased, especially among contractors [14].

Prefabrication is the collection of processes, practices and management methods traditionally used in manufacturing, applied to construction [24]. BIM implementation has helped boost prefabrication by introducing better data exchange and management processes [25]. Prefabrication has been shown to lead to higher productivity and productivity growth compared to traditional onsite construction [26], and also reduce and control construction waste [27,28]. Prefabrication is being used for a variety of construction components, including concrete [29], electrical, and mechanical components [30,31]. While BIM use has steadily increased along with the adoption of prefabrication, the communication of BIM design information to prefabricators often relies on traditional paper documentation. Mixed Reality (MR) may offer the ability to communicate BIM content directly to field personnel.

2.3. Mixed Reality

Milgram and Kishino defined Mixed Reality as a "reality spectrum" ranging between pure "reality" (as seen by a user without computer intervention) and pure "Virtual Reality" (a computer-generated environment where the user has no interaction with the physical world) [32]. MR is any environment that incorporates aspects of both ends of this spectrum, such as overlaying virtual objects on top of a user's field of view of a real space [32]. Within the spectrum of MR, Augmented Reality (AR) is a predominantly real environment with some virtual aspects, while Augmented Virtuality (AV) is a predominantly virtual environment with some real aspects [32]. In this paper, the authors use MR to describe all environments pertaining to this study that contain both real and virtual aspects.

The use of MR for design communication has been studied through several past efforts. In the construction industry, Feiner was the first to combine 3D Head Mounted Displays (HMDs) with mobile computing technologies, creating a prototype that overlaid campus information on top of an unobstructed view of a university campus [33]. In the design process, MR was used for information delivery by presenting relevant data points to users without interrupting normal workflows [34]. In conjunction with 2D drawings displayed on touchscreen tablets, MR was used to better understand the placement of certain elements on site [34] and visualize possible implications of design changes on the actual construction site [35].

MR's potential as an onsite model visualization tool has also been well studied. It has been used to visualize a 3D building model in its physical location [36,37] and objects hidden behind other existing structures [38]. MR has also been used to augment BIM content, allowing for onsite, in-place viewing of the models [39], monitoring and documentation of the construction processes [40,41], and detection of construction problems [42]. Moreover, MR has been used to create 4D as-built models for construction monitoring, data collection and analysis [43]. MR was also used to enhance onsite safety by reducing risk factors using MR based instructions [44].

In addition to the design and construction uses of MR, it has also been explored for educational purposes [45]. MR has been shown to enhance the spatial abilities among students [46,47]. MR was also used to teach engineering students the relationship between 3D objects and their projections in engineering graphic classes [48] and allowed students to better understand the construction site by site condition simulation [49,50]. MR was also used for workforce training purposes. Wang, Dunston and Skiniewski designed two MR training systems, one for operation and one for maintenance of heavy construction equipment [51,52]. MR was deployed to also train crane operators [53] and for providing spatially relevant data for training architects, construction crews and fireman on operation in large wooden buildings [54].

While MR's capabilities in visualizing models onsite and as a training and educational tool have been well documented, the use of this mode of visualization has not been studied specifically for actual construction processes. This paper examines the feasibility of using MR to visualize a 3D model in space, and to assemble a prefabricated electrical conduit based solely on information presented by that model. The findings will help to determine the potential for using MR as the medium for information delivery on site.

3. Methodology

This work uses a quasi-experimental research approach to develop an understanding of the performance impacts observed using MR for construction tasks. Participants in the study included current electrical