Benefits of Using Augmented Reality in Planning, Construction and Post-Construction Phases in Specialty Contracting

by

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ABSTRACT

The construction industry has been growing over the past few years, but it is facing numerous challenges, related to craft labor availability and declining productivity. At the same time, the industry has benefited from computational advancements by leveraging the use of Building Information Modeling (BIM) to create information rich 3D models to enhance the planning, designing, and construction of projects. Augmented Reality (AR) is one technology that could further leverage BIM, especially on the construction site. This research looks at the human performance attributes enabled using AR as the main information delivery tool in the various stages of construction. The results suggest that using AR for information delivery can enhance labor productivity and enable untrained personnel to complete key construction tasks. However, its usability decreases when higher accuracy levels are required. This work contributes to the body of knowledge by empirically testing and validating the performance effects of using AR during construction tasks and highlights the limitations of current generation AR technology related to the construction industry. This work serves as foundation of future industry-based AR applications and research into potential AR implementations.

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CHAPTER 1

INTRODUCTION

Construction is one of the largest industries in the United States (U.S. Department of Commerce 2017), but is facing numerous challenges related to labor shortage (Albattah et al. 2015) and low labor productivity (Fulford and Standing 2014). Some research suggests that exploring new technologies might help alleviate some of those problems (Karimi et al. 2016). Building Information Modeling (BIM) is the development of a 3D virtual design that merges the informational and physical aspects of a project (Lee et al. 2006) and its use is increasing in the industry (McGraw-Hill Construction 2014).

Augmented Reality (AR) is a technology that enables a user to view virtual elements overlaid on top of the physical space, appearing to co-exist (Milgram and Kishino 1994). Prior research has shown that AR can extend the usability of BIM, especially on the construction site (Thomas and Sandor 2009). This research aims to explore the effect of using AR as the main information delivery tool on the human performance attributes in specialty construction tasks. The work has five distinct components, each addressing an aspect of the implementation of the AR for a specialty construction related task.

In the first components (Chapter 2), the author aimed to validate that it is possible to use AR to complete a construction task, and to explore the performance attributes that AR enables. The work was based on an experimental study using industry standard models, parts and experienced participants.

The second and third components (Chapter 3 and 4) are based on the same experiment and are both a direct result of the findings of the first component. In Chapter 3, the author aimed to understand the accuracy to which AR can place elements in space, a major performance attribute uncovered in the first component. Chapter 4 studies the effect of varying task attributes of the performance of the practitioners when using AR.

The fourth component (Chapter 5) aimed to understand the human performance attributes of using AR in post-construction tasks, primarily for deviation identification and reconciliation. The author explores the way student participants processed the deviations and false positive deviations cause by the imperfect tracking of current generation AR devices.

The final component (Chapter 6) compares to the performance of experienced industry professionals, construction-educated graduate college students, and non-construction related participants using AR to complete key construction tasks. The chapter aims to understand whether AR visualization can simplify the delivered information so that untrained personnel can properly understand to perform the required tasks.

Each component is detailed in a separate chapter thereafter. Each chapter contains its own relevant introduction, background, methodology, results and conclusions.

CHAPTER 2

USING MIXED REALITY FOR ELECTRICAL CONSTRUCTION DESIGN COMMUNICATION

2.1 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 (U.S. Department of Commerce 2017). Productivity in construction has been identified as an important research topic, constituting one of six Key Performance Indicators (KPI's) of any construction project (Cox et al. 2003). Research suggests that the construction industry has been lagging in productivity measurement and improvements (Allmon et al. 2000). While macroeconomic viewpoints point to an increase in construction productivity over the past few decades (Rojas and Aramvareekul 2003), microeconomic perspectives argue the opposite, suggesting negative productivity trends over the past half-century (Bankvall et al. 2010; Fulford and Standing 2014; Teicholz et al. 2001).

Today, the construction industry is facing major challenges related to waste, which is estimated to cost more than $15 billion annually (Gallaher et al. 2004). 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 (Gallaher et al. 2004). 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"(Albattah et al. 2015; Karimi et al. 2016).

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 (Arditi and Mochtar 2000), as well as reduction in construction waste (Tam et al. 2007). BIM leverages intelligent 3D models to support design, construction, delivery, and facility management (Hardin 2009). Use of BIM has been steadily increasing in recent years, especially among contractors (McGraw-Hill Construction 2014).

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 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.

2.2 Background

2.2.1 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 (Shannon 1948). 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 (Gould and Joyce 2009), where their value in aiding design and design communication has been well documented (Purcell and Gero 1998). 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 (Eckert and Boujut 2003). 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 (Dadi et al. 2014a). Using physical mockups does not require reinterpretation from the worker, which enables a lower cognitive workload to conceptualize a design (Dadi et al. 2014a) 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 (Dadi et al. 2014c, b; a). 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.

2.2.2 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 (Hardin 2009). BIM use can help to reduce and control project cost (Bryde et al. 2013) and minimize construction waste (Liu et al. 2015). Recently, BIM adoption has increased, especially among contractors (McGraw-Hill Construction 2014).

Prefabrication is the collection of processes, practices and management methods traditionally used in manufacturing, applied to construction (Gann 1996). BIM implementation has helped boost prefabrication by introducing better data exchange and management processes (Nawari 2012). Prefabrication has been shown to lead to higher productivity and productivity growth compared to traditional onsite construction (Eastman and Sacks 2008), and also reduce and control construction waste (Jaillon et al.

2009; Korman and Lu 2011). Prefabrication is being used for a variety of construction components, including concrete (Blismas et al. 2010), electrical, and mechanical components (Karunaratne 2011; Khanzode et al. 2008). 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.

2.2.3 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) (Milgram and Kishino 1994). 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 (Milgram and Kishino 1994). 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 (Milgram and Kishino 1994). 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 (Feiner et al. 1997a). In the design process, MR was used for information delivery by presenting relevant data points to users without interrupting normal workflows (Côté et al. 2014). In conjunction with 2D drawings displayed on touchscreen tablets, MR was used to better understand the placement of certain elements on site (Côté et al. 2014) and visualize possible implications of design changes on the actual construction site (Schubert et al. 2015).

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 (Honkamaa et al. 2007; Kopsida and Brilakis 2016a) and objects hidden behind other existing structures (Thomas and Sandor 2009). MR has also been used to augment BIM content, allowing for onsite, in-place viewing of the models (Woodward et al. 2010a), monitoring and documentation of the construction processes (Waugh et al. 2012; Zollmann et al. 2014), and detection of construction problems (Park et al. 2013a). Moreover, MR has been used to create 4D as-built models for construction monitoring, data collection and analysis (Mani et al. 2009). MR was also used to enhance onsite safety by reducing risk factors using MR based instructions (Tatić and Tešić 2017).

In addition to the design and construction uses of MR, it has also been explored for educational purposes (Liarokapis et al. 2004). MR has been shown to enhance the spatial abilities among students (Dünser et al. 2006; Kaufmann 2003). MR was also used to teach engineering students the relationship between 3D objects and their projections in engineering graphic classes (Chen et al. 2011) and allowed students to better understand the construction site by site condition simulation (Mutis and Issa 2014; Shanbari et al. 2016). 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 (Wang et al. 2004; Wang and Dunston 2007). MR was deployed to also train crane operators (Juang et al. 2011) and for providing spatially relevant data for training architects, construction crews and fireman on operation in large wooden buildings (Phan and Choo 2010).

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.

2.3 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 construction practitioners from a company located in the Southwest United States. Because of the proof of concept nature of the experiment, a convenience sampling technique was used. Participants from the company were chosen based on their time availability in the allocated day for the experiment. All participants attempted to construct two different electrical conduit assemblies using two different visualization approaches (MR and traditional paper). In addition to studying the behavior of the participants through video coding, a pretest/posttest methodology was used to identify shifts in perception among the participants. The following sections present a detailed discussion of each step of the research methodology.

2.3.1 Selection of contractor partner for participation in study

This work aimed to identify the construction performance impacts that might be observed through MR. The company with whom the researchers partnered recently conducted an independent study to determine the viability of using BIM for supporting electrical conduit construction. They concluded that BIM significantly reduces their construction time per conduit. As a result, this company uses BIM on all projects when possible to support prefabrication. Furthermore, this company has developed their own custom plug-ins for current BIM software packages to support their processes. While this company is, by several accounts, technologically progressive, they had not tested any applications of MR for construction prior to this study.

In the current workflow, the individual pieces of conduit needed for assembly are pre-bent and pre-cut offsite in the company's fabrication shop. Number tags are placed on the pieces to identify them. Pieces from a given assembly are then grouped and shipped to the site with a set of construction drawings generated from the developed BIM to guide the assembly. These drawings typically include isometric, plan, and sections views of the conduit, as well as additional detail sheets as required. Figure 1 shows an example drawing developed by the company to illustrate the type of communication approach currently used by site personnel.

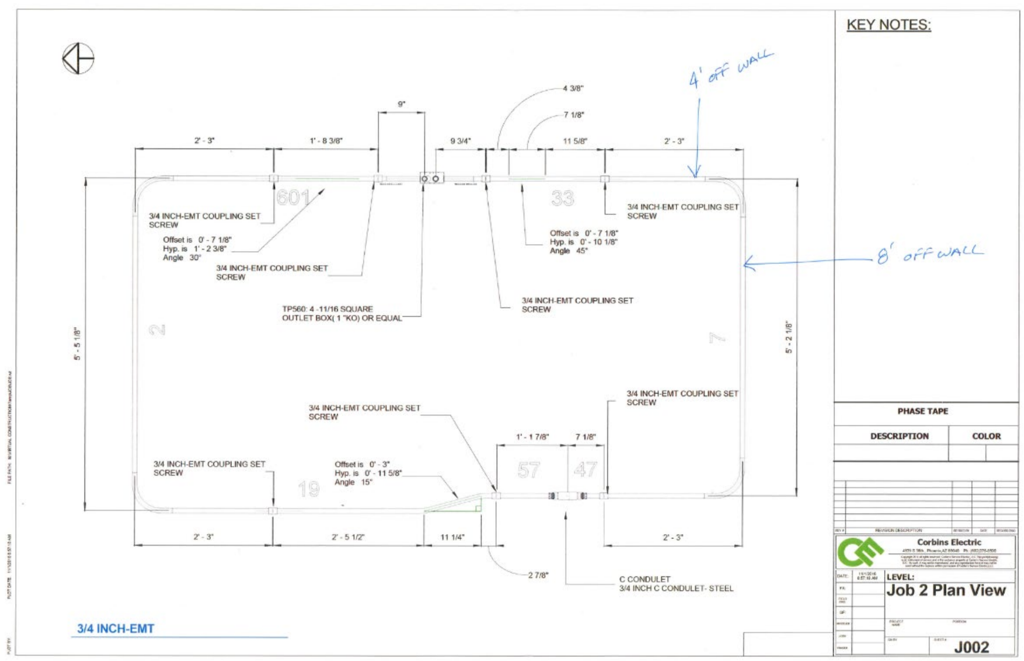

Figure 1: The Division of Groups, Subgroups and Trials by Conduit Number and Information Delivery Method

The chosen partner company developed two different conduit models to allow researchers to explore the impacts of MR and paper-based communication on construction productivity. Both conduit models included sections that would bend in the X, Y, and Z directions. Choosing a relatively complex conduit to assemble helped to illustrate potential performance differences that may not have been observable with simpler assemblies. The design choices and variations are further explained in Section 3.4. The developed conduit models are shown in Figure 2.

After the conduit models were developed, the construction company created the standard paper documents for these conduits using the same process they would normally use for communicating design information to construction personnel. All conduit pieces were pre-cut, bent and tagged as they normally would be for onsite assembly.

Figure 2: Two Developed Conduit Models

2.3.2 Development of MR visualization environment

In order to study the impacts of MR on construction tasks, the developed conduit models needed to be imported into a MR environment. A number of different devices could have theoretically enabled this work. The researchers elected to use a Microsoft HoloLens, which is a head-mounted display (HMD) device with a see-through screen capable of presenting 3D virtual objects on top of existing, physical, surfaces. The MR features provided by this device include the ability to display virtual objects by relying on infrared scanners to map and understand the area, which enables a stable, markerless, visualization of the model. The selected HMD enabled hands-free operation and did not require a physical connection to a computer when in use, which further enabled the participants to maneuver freely in space.

To develop the chosen MR environment, the industry-generated model was exported from its native BIM software (Autodesk Revit), and imported into Unity Game Engine. None of the content modeled by the construction company was altered during this process. Once the model content was successfully imported into Unity, controls were added and an application was developed to run on the HoloLens. Prior to formal testing with research participants, the scale of the model was verified in a lab environment to ensure that it was displayed at a full 1:1 scale. Figure 3 shows a view of a conduit model, as seen from the MR user's perspective.

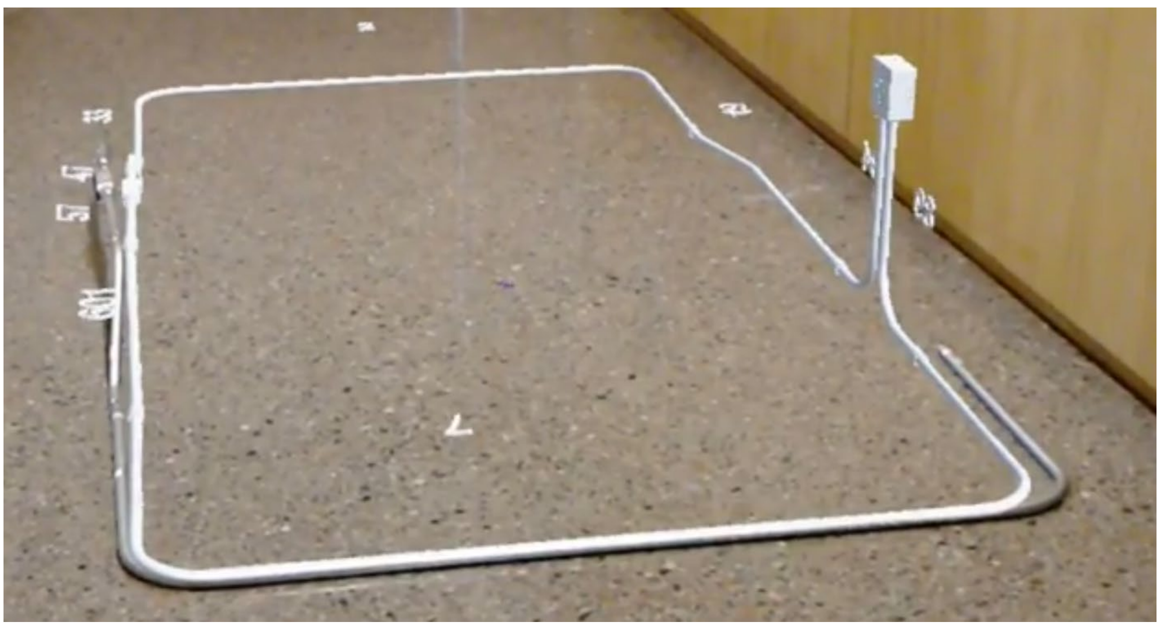

Figure 3: Conduit Model as Seen in MR

2.3.3 Pre-construction research tasks

Prior to building any electrical conduits, all participants signed an informed consent form in accordance with the Institutional Review Board's requirements. This enabled the researchers to use and analyze the data collected during the session, including multi-angle video and audio recordings of the entire session, as well as responses to preand post-activity questionnaires. Participants were subsequently provided with a brief explanation of the tasks that they would be asked to complete, followed by a pre-session questionnaire that elicited information about their general background and their perceptions about MR.

2.3.4 Conduit construction research tasks

The researchers aimed to compare the performance of each participant when using paper, and when using MR for design information delivery. The researchers used a double-counterbalanced experimental design to make this comparison. Two conduit designs were engineered for this research. Both designs used the same pre-fabricated pieces in different order and orientation to create two unique conduits. This ensured that no participant would assemble the same conduit in both attempts, while ensuring that the assembly difficulty levels were comparable. If this approach had not been used and a participant would have assembled the same conduit twice, once using paper and once using MR, their performance could have been impacted by what they learned during their first attempt. Moreover, if all participants started with one information delivery method, the results could be subject to an order-induced error. Therefore, the researchers also varied which mode of visualization was provided to a participant first.

To execute this methodology, participants were divided into two groups. Participants in one group would assemble conduit 1 using MR and conduit 2 using paper. Participants from the second group would assemble conduit 2 using MR and conduit 1 using paper. Moreover, each group was divided into two subgroups: participants in one subgroup would start with paper; while those in the other subgroup would start with MR. Table 1 below summarizes the four subgroups:

Table 1: The Division of Groups, Subgroups and Trials by Conduit Number and Information Delivery Method

Group	Information Delivery	Paper		MR	
	Conduit Number	Conduit 1	Conduit 2	Conduit 1	Conduit 2
Group 1	Subgroup 1	Trial 1			Trial 2
	Subgroup 2	Trial 2			Trial 1
Group 2	Subgroup 3		Trial 1	Trial 2	
	Subgroup 4		Trial 2	Trial 1	

When participants built an electrical conduit model using the paper-based approach, they were provided with the standard paper plans. These participants were not provided with specific instructions on how to construct the conduit based on these plans because most had prior experience with building from paper plans.

When participants built an electrical conduit using MR, they were provided with a brief (five-minute) introduction to MR. During this introduction, they were guided on how to wear the MR HMD and were shown a MR model that was not related to this task, such as a space helmet. This allowed all participants to look at a MR model and familiarize themselves with MR interaction without getting extra time to study the conduit model they were about to assemble. Since the electrical conduit assembly task required only viewing of the MR model, no training on gesture-based interaction with the device was required. After the participants felt that they were comfortable with navigating the MR environment, the MR conduit model was loaded for them to begin construction. Similar to the paper-based groups, the participants using MR were not provided with any specific instructions on how to build the conduit because of their prior construction experience.

It is worth noting that in all construction activities, participants were expected to place their constructed conduit in the correct final location, similar to what is required in typical site installations. On the paper plans, this location was noted based on dimensional offsets from nearby walls, mimicking what is usually done on site. In the MR environment, the correct location was simply defined by the placement of the virtual model on the ground. The assembly was considered complete when the participant declared that he or she was done, regardless of whether or not the assembly was correct.

2.3.5 Post-Construction Activity tasks

After completing both assembly tasks, participants were given post-questionnaires to capture their perceptions about using MR for conduit assembly and other construction tasks. The questionnaires also elicited responses related to perceptions on the viability of onsite use of this technology and for training purposes. Finally, participants were asked about their perceptions related to user experience during the activity. They were asked to identify problems experienced while using MR, to describe ease of use, and to suggest improvements for future work.

2.3.6 Analysis

Two types of data were collected during the session: perception data, in the form of pre-session and post-session questionnaires; and performance data derived from video recorded while participants performed the tasks assigned.

The questionnaire responses from the participants were imported into a spreadsheet. The multiple-choice questions from the questionnaires were assigned numerical values for subsequent analysis. The open-ended questions were simply typed and stored in a linked file.

The video files were imported into a behavioral monitoring video analysis software. Different behaviors of interest were assigned different codes and all the participants in the video files were identified. The video was coded by applying a time stamp whenever a user exhibited a behavior of interest, such as looking at the model, time when they started assembling the conduit or placing the assembled conduit in its correct final position. After the coding process was completed, the data was extracted into a spreadsheet file. This effectively transformed the video file into a series of activities and times associated with each (i.e. the time each user needs to assemble the conduit model using a given information delivery method). The data from the questionnaires and video files were then linked and imported into a statistical software program. The findings relating to performance and perception are presented in the following section.

2.4 Results and Discussion

2.4.1 Participants

Eighteen industry professionals participated in this study, including shop electricians, managers, and site electricians. Half of the participants had less than 1 year of experience assembling electrical conduit, and eight of the participants had not assembled conduit in the past year. There were seventeen male participants and one female. Table 2 summarizes the distribution of participants' years of industry experience and percentage of time spent assembling electrical conduit in their position. In general, participants had little to no experience using MR, both inside and outside of work. Of the participants that did report some MR experience, all were smartphone or tablet based.

Table 2: Cross Tabulation of Participant's Years of Experience Vs Time Spent Assembling Electrical Conduit in the past Year

Years of experience in construction	Time spent assembling electrical conduit in the past year				Total
	None	About 25%	About 50%	All the time	
Less than 1 Year	28% (n=5)	17% (n=3)	6% (n=1)	0%	50% (n=9)
1-5 years	0%	0%	11% (n=2)	0%	11% (n=2)
6-10 years	11% (n=2)	0%	0%	0%	11% (n=2)
More than 10 years	6% (n=1)	11% (n=2)	0%	11% (n=2)	28% (n=5)
Total	44% (n=8)	28% (n=5)	17% (n=3)	11% (n=2)	100%

2.4.2 Performance

All participants were able to assemble the conduit models presented using MR and paper plans. To better understand the potential performance differences when using MR, the conduit assembly process was divided in to three main activities: (1) looking at, and understanding the design, (2) the actual positioning and assembly of pieces, and (3) placement of the assembled conduit model in its final correct location onsite. Therefore, three key behaviors were identified to measure the performance of the participants, and enable direct comparison between the use of paper plans and MR for conduit assembly: (1) duration to assemble conduit, (2) duration looking at information and (3) duration to place conduit.

The duration to assemble conduit is the total time it took every participant to assemble the conduit. Using MR, the time started from the moment the model was loaded on the device. While using paper plans, the time started from the moment a user received the paper plans. In both cases, the time ended when a participant declared that he or she was done assembling the conduit, regardless of whether the finished product was correctly assembled or not.

The duration of time looking at information was defined as the total amount of time participants spent during each conduit assembly looking at the information delivered to them, but not assembling any components. Typically, when builders review the plans (or models), their goal is to understand the information presented in order to build the next component. While this time may be necessary for users to accurately conceptualize what they must build, it does not directly involve actions that lead to completion of the targeted construction task. With traditional paper, it was clear when participants were looking at the documentation and when they were building, because the two tasks are not typically performed simultaneously. With MR, users see design information while they are building. Therefore, the only time that was counted as "time spent looking" with MR was the time when participants were viewing the model, but not actively building. This enabled a more analogous comparison between time spent looking at information using paper and MR.

Finally, the duration to place the conduit was defined as the time required to place the assembled conduit in its correct final position. Using MR, the correct final location is determined by model placement on the ground. Using paper plans, the position is determined based on two offsets from the walls, similarly to what is typically done in the field.

Table 3 lists all activities and behaviors studied, the average time each activity required, the respective differences in means between using MR and paper plans, and the p-value of a paired samples t-test used to compare the two means.

Table 3: Activities Durations for Different Visualization Methods

Activity	Visualization Method (time in seconds)		Difference (Paper Plans – MR)	P-value
	Mixed Reality	Paper Plans		
Looking at Information	64	191	127	0.000478
Placement and Positioning	5	85	80	<0.000001
Assemble Conduit	277	504	227	0.000081

On average, a user spent 191 seconds looking at the paper plans, compared to 64 seconds when using MR, which indicates a significant reduction in time (p-value = 0.000478). This suggests that MR can allow users to feel ready to build in less time than when using paper plans. If there is no sacrifice in quality in the built components, this also suggests direct benefit to using MR as a method for enabling effective design comprehension among builders.

In addition to identifying the beneficial impacts of MR for design comprehension, the average time to place the conduit assembly in its final location was determined to be 85 seconds using paper plans and 5 seconds using MR. This 80 second difference is also significant (p-value = 0.0000007). When using MR, the conduit is loaded automatically in the space and placed in its correct final location. This allows users to place the actual conduit in its correct final location while they are assembling the conduit. While paper plans theoretically could be used to build conduit in place, most participants assembled the conduit first, and then measured offsets from the walls as shown on the plans to verify final conduit placement. While the finding that MR enabled faster placement of conduit is not surprising, specifically measuring this activity was useful for illustrating the extent to which it may offer value over traditional methods for this type of construction task.

Overall, the average time to assemble the conduit using MR was 277 seconds, compared to 504 seconds using paper plans. The difference of 227 seconds is significant at the 95% confidence level. It is significantly faster to use MR to assemble conduit instead of using paper plans, especially for users with less experience. The authors expected to find similar, or possibly better, performance when participants were using paper because of the familiarity with that mode of visualization. Therefore, it was noteworthy to observe significantly better performance when participants were using MR, which they had no prior experience using.

While the benefits of MR for individuals with prior experience using paper was noteworthy, the effect of their familiarity with paper was still apparent in the results. Expectedly, the fastest participants using paper plans were those with more than 10 years of experience. These individuals completed their assemblies with an average time of 294 seconds. Conversely, the fastest group using MR were those with less than 1 year of experience. These individuals completed their assemblies with an average time of 223 seconds. While both of these findings make sense intuitively, the more noteworthy finding was the fact that the less-experienced group using MR was still faster than the most experienced individuals using the current, paper-based, approach.

2.4.3 Effect of Order

The researchers also studied the effect of order on the total assembly times of the users. To further study the effect of order, 4 independent samples t-tests were used, comparing the performances of the users assembling the same conduit using the same information delivery method. The difference represents the first attempt vs. the second attempt.

Table 4: The Difference Between the Second and the First Try by Conduit Type and Information Delivery Method

	Information Delivery	Significance	Mean Difference
Conduit 1	Paper	0.273	-130.58975
	MR	0.736	-21.76255
Conduit 2	Paper	0.169	-202.88330
	MR	0.464	63.62450

The performance of the users seems to be systematically better on the second try in almost all cases, except when assembling conduit 2 using MR. However, those performances were not significantly different in any case (p-value > 0.05). This suggests that in the case of this study, the effect of order is minimal and is offset by the double counterbalancing design of the experiment.

2.4.4 Quality

In addition to analyzing participants' performance, based on time analysis, the authors also analyzed the recorded video footage to identify mistakes in construction and if they would require subsequent rework. Rework is defined as the unnecessary effort of redoing a process or an activity simply because it was done incorrectly the first time (Love, Peter E.D.; Irani, Zahir; Edwards 2003). Rework has also been shown to have severe and direct cost impact on the total cost of projects, especially for midsized projects (Hwang et al. 2009).

To measure the impact of implementation of MR for information delivery related to mistakes and rework, two metrics were used: (1) the total number of mistakes; and (2) the total count of correct final assemblies. In this context, the authors define one "mistake" as the incorrect placement or orientation of a piece of conduit, regardless of whether it was rectified by the user. The authors also define a "correct final assembly" as one that exactly matches the intended design. Throughout the experiment, participants were not told when they made mistakes.

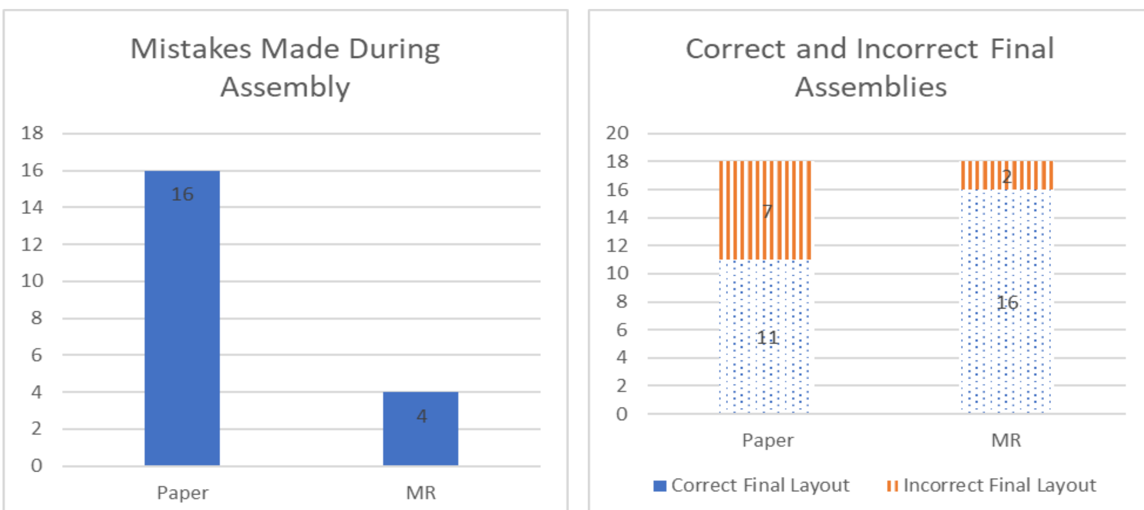

Figure 4: Summary of Quality Metrics Measured per Information Delivery Method

Figure 4 summarizes the number of mistakes and number of correct final assemblies per information delivery method. The participants made a total of 16 mistakes when using paper plans to assemble conduit, compared to only four mistakes when using MR. The increased mistakes using paper contributed to the longer assembly times detailed in Section 4.2. Some of the mistakes were not caught, and therefore not rectified by participants, leading to eleven correct final assemblies using paper compared to sixteen correct final assemblies using MR. Therefore, MR reduced the total number of mistakes by 75%, but more importantly, reduced the amount of rework required by 72%. This helps to demonstrate the benefit that MR can offer for reducing construction errors. By displaying the model at full scale, placed in its correct final location, MR allows the user to immediately compare the assembled conduit to the intended design to ensure accurate construction.

2.4.5 Perception

Introducing MR for construction information delivery represents a major shift in how design communication has occurred for years. Therefore, the authors chose to also explore the perceptions of the construction professionals who participated in this work. Pre-session and post-session questionnaires were used to understand these perceptions and identify any shifts in perception that might have occurred.

2.4.5.1 Pre-session Questionnaire

The pre-session questionnaire included questions about how the users would anticipate the experience of using MR compared to paper plans. It also included questions to elicit responses about their perception about a potential shift to paperless design communication. Several of the specific questions asked and responses provided are shown in Table 5.

Table 5: Showing Sample Pre-session Questionnaire Questions

Questions	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Mixed Reality can completely replace paper plans for communicating electrical conduit designs for construction in the field	0%	22% (n=4)	44% (n=8)	22% (n=4)	11% (n=2)
I am looking forward to eliminating the use of paper plans and relying only on digital means of design communication*	0%	11% (n=2)	39% (n=7)	39% (n=7)	6% (n=1)
Mixed Reality will be easier to use than paper for the purposes of electrical conduit construction*	0%	11% (n=2)	33% (n=6)	44% (n=8)	6% (n=1)

*One of the participants did not answer the question

The results indicated that participants generally felt that MR would be easy to use before completing the activity, with only two participants actively disagreeing with this view. In addition to reporting that they felt MR would be easy to use, a substantial portion of participants (33%) also felt that MR has the potential to completely eliminate paper plans. While this may suggest a willingness from the participants to change the way that design communication currently occurs, when asked about their preferred method of design communication, two thirds of participants stated that they would want to keep paper plans as part of the information delivery package. That being said, there were a few participants (22%) who stated that they would prefer to rely only on digital design communication.

In addition to providing feedback about levels of agreement with several statements, participants also indicated shortcomings that they believed would be a concern for using MR. These shortcomings included technical problems, inability to fully communicate the message across the work spectrum, especially in complex situations, and impracticality of applying digital technology under harsh, job site environments. These responses seem logical because the sample of participants are more accustomed to paper plans for design communication and may be hesitant to simply abandon them for a new visualization approach. Therefore, their pre-activity perceptions seemed to indicate a willingness to use MR, but a reluctance to completely shift to a model-based design communication approach in lieu of traditional paper plans.

2.4.5.2 **Post-session Questionnaire**

After completing the conduit construction tasks, participants completed post-session questionnaires about the experience. The responses from this questionnaire indicated that all participants considered MR to be an effective medium for design information delivery and communication. Two thirds of participants felt that they could effectively assemble electrical conduit using only MR, and that MR was easier to use than traditional paper plans. The remaining participants were neutral about both statements. Table 6 summarizes the findings from the post-session questionnaires.

Table 6: Sample Post-questionnaire Questions

Questions	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
With Mixed Reality, I can effectively build electrical conduit without the need for traditional paper documentation	0%	0%	33% (n=6)	28% (n=5)	39% (n=7)
It is easier to build conduit using Mixed Reality than Paper Plans	0%	0%	33% (n=6)	28% (n=5)	39% (n=7)
It would be easier for inexperienced individuals to build electrical conduit with mixed reality than with paper plans	0%	0%	11% (n=2)	39% (n=7)	50% (n=9)
I would rather use Mixed Reality than Paper plans for assembling pre-fabricated electrical conduit	0%	6% (n=1)	33% (n=6)	39% (n=7)	22% (n=4)

Furthermore, most participants seemed to believe MR was a superior information delivery method compared to paper plans. For example, only one participant disagreed with the statement that “I would rather use Mixed Reality than use Paper Plans for assembling electrical conduit”. Even though there were mixed opinions about the value of MR, it shows that industry members generally perceived this approach to be very positive.

In addition to asking participants about their perception of using MR directly, they were asked to provide input related to how MR may be used for training new practitioners. Seventeen of the participants indicated that it would be beneficial for new individuals to be trained at least in part using MR. Sixteen participants indicated that the newly trained individuals should use MR at least partially in the field. Four of the participants believed that MR should be the only information delivery technology used onsite for newly trained individuals.

2.4.5.3 **Open-Ended Questions**

In the open-ended questions, the participants described their experiences using MR. Specifically, they were asked to provide their favorite and least favorite parts of the activity. In general, participants often mentioned that they liked the fact that MR presented the model clearly and in its correct final location. Furthermore, several mentioned that MR allowed them to keep their gaze and focus on one spot, rather than going back and forth between the paper plans and the conduit on the ground. Conversely, many participants mentioned that they did not like having a device on their head throughout the construction task. Several also mentioned that the chosen HMD felt too bulky or obstructive in its current form to enable actual use on site.

The relation between the performance of the participants and their backgrounds was studied. The authors found no significant correlation between a participants' experience or amount of time spent assembling conduit and their assembly time using MR. This could potentially mean that MR is perceived similarly among individuals with different experience levels, but the lack of correlation could also be due to the relatively small set of participants being pooled from the same company. Further studies with more participants from different backgrounds is required to better study the relation between performance and background in order to draw a broader conclusion about this relationship.

2.4.6 Limitations

This work is presented as a proof of concept with an experimental design for validation of the technology use and exploration of its performance compared to the current, paper-based, workflow. The limitations of this work are related to the testing participants, environment, and MR technology in its current form.

First, the participants were all from the same company. While this company uses a paper-based design communication strategy, they actively use emerging BIM techniques. As a result, the company has a progressive stance toward technology. It is possible that this progressive philosophy extends to individual employees, which could theoretically impact their performance during the MR construction activity. Furthermore, the sample size is relatively small and results may not be generalizable beyond this particular company. While the performance benefits cannot be generalized on an industry wide level, the findings do support the claim that, when used properly, MR can enable construction performance benefits over traditional paper documentation. Future research aiming to generalize the findings of this paper would need to identify statistically representative samples.

Second, the experiment took place in a controlled environment, and not an active job site. The additional site conditions such as labor congestion, noise and safety concerns, could affect the performance of the user. Theoretically, the impact would affect both paper and MR, but it is entirely possible that the impact would be more severe when using MR. Therefore, the authors do not claim that performance difference observed in this paper would be the same as those observed through onsite applications that were not tested in this work.

The final limitations of this study relate to the technology used. Since the experiment took place in a controlled environment, the device chosen for this study was not tested for compliance with current safety requirements. For example, most hard hats are not currently designed to enable a user to wear the tested HMD in its current form without additional modifications. While these limitations would impact the ability to use this device on site in the near term, it is likely that future versions of the tested HMD or other similar HMDs will get smaller and lighter, which may diminish the long term challenges associated with wearing the device while wearing other required personal protective equipment (PPE).

Moreover, the time required to prepare the MR model was not taken into account during this analysis. As a proof of concept, the authors went through several iterations before being able to get the model on the MR device, and have not had the opportunity to perfect or automate the process of importing BIM content to a MR environment. Therefore, the development time was omitted from the analysis. However, the authors recognize that it would require additional investment over current workflows if the company chose to broadly expand their MR usage. The authors chose to focus on a paired comparison of the assembly times regardless of development time for either information delivery methods tested.

In addition to the development technological limitation, the authors faced technical difficulties during construction. The selected MR device is typically controlled using hand gestures. Since the conduit assembly task only requires viewing of the model, no training on the interaction with the device was given to the participants. Five participants accidentally closed the model during their assembly tasks by inadvertently making a hand gesture that would lead to the device "home" screen. After this event happened, participants took off the headset, gave it back to the researcher for reloading of the content, and then put it back on and continued their task. On average, each technical difficulty lasted 16.5 seconds. Although there is a practical limitation to this issue, the authors did include this time when calculating total assembly time.

In addition to technical limitations related to inadvertent hand gestures, additional technical limitations were also observed including the model brightness, the HMD weight and the screen size. Those problems were only pointed out to the researchers after the assembly was complete, and did not result in the interruption of the task. It is not clear if any of these actually impacted construction performance, but the authors recognize that these could also cause challenges for broader deployment of MR. While this research focuses on MR as a technology for information delivery, future equipment may be specially designed for construction tasks or may be compatible with standard safety gear, and the users would get extensive training before using it on site. This downstream development may further offset some of the technical limitations observed in this work.

2.5 Conclusion

In this paper, the authors propose the use of MR for design information delivery for assembling prefabricated electrical conduit. An experiment where industry participants built conduits using MR and traditional paper documentation was conducted to study the potential performance of the proposed technology. Moreover, the perception of the users toward MR before and after use was studied. The research found statistically significant performance benefits to using MR compared to using paper documents. MR models were observed to be easier to comprehend, allowed for faster assembly, and reduced the number of mistakes made during construction. It was noteworthy to see that participants with no conduit assembly experience achieved the best times using MR, and they were also faster than the most experienced participants who used traditional paper plans. After participating in the activity, all participants agreed that MR is easier to use than paper plans for electrical conduit assembly tasks, however many still prefer to have paper plans as part of the design communication. Participants noted that MR has the potential to be used for training new individuals, and helping them understand paper plans easier and faster.

This study contributes to the body of knowledge by empirically demonstrating the potential value of using MR for construction tasks as compared to traditional paper plans by using industry-developed BIM content and current industry practitioner participants. The findings do have several limitations related to the controlled nature of this research and implementation method. Therefore, future research will focus on identifying the attributes of a construction task that may maximize the benefits provided by MR to enable future researchers and practitioners to strategically plan for MR where it provides the greatest impact. Additionally, future work will also explore this visualization format to enhance training techniques as suggested by the results from this work.

2.6 Acknowledgement

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CHAPTER 3

AUGMENTED REALITY FOR CONSTRUCTION LAYOUT TASKS

3.1 Introduction:

Augmented Reality (AR) is a technology that allows virtual objects to be viewed in a user's field of view in conjunction with the physical space (Milgram and Kishino 1994). In a construction setting, this allows a user to view BIM content at full, 1:1, scale in its final construction place. Researchers have long studied the various applications of such technology in various stages of a construction project (Golparvar-Fard et al. 2009; Zollmann et al. 2014). Previous research theorized that AR use may be viable for complex, repeatable construction tasks (Dunston and Wang 2011) and AR has been shown to enable faster placement of conduit in its required final position (Chalhoub and Ayer 2018a). While there are potential benefits to using AR for these types of construction tasks, there are also practical challenges with outfitting every builder with an AR device to view design content. Therefore, this paper aims to explore AR for a point layout task that would be completed by a single person, but could theoretically offer potential for near-term benefit for project teams interested in leveraging AR. Point layout is a task where a construction worker identifies and marks a relevant point on the construction site.

To explore this topic, this research uses AR to project several BIM components at full scale on a physical space that could enable point layout tasks on a job site. In order to explore this concept in a safe, yet realistic, manner, industry practitioner participants were asked to layout the hypothetical designs using AR and paper in a controlled environment. The results enabled the authors to address the following questions: Can AR enable point layout activities for current practitioners? What are the possible implications on accuracy, time-to-complete, and effort required by practitioners? The findings contribute to the body of knowledge by empirically demonstrating the benefits that may be observed using current AR technology with current practitioners for point layout tasks. This contribution will enable researchers and practitioners to strategically plan for AR implementation based on observed results that are systematically compared to performance using the current paper-based communication approach.

3.2 Background

3.2.1 Current State of Construction

Some productivity research suggests that the construction industry is facing an impending labor cliff (Albattah et al. 2015), where not enough new individuals are entering the industry to offset those retiring. Although little research has been done on labor productivity during Mechanical, Electrical and Plumbing (MEP) point layout tasks specifically, construction has been generally criticized for having low productivity (Teicholz et al. 2001) and a negative productivity growth (Fulford and Standing 2014). The combination of a decreasing labor force and need for higher productivity highlight the opportunity for re-exploring how buildings are constructed.

Labor shortage in construction has been a cyclical reoccurrence, first mentioned in the 1980s, when a labor shortage was predicted in 1990s due to change in demographic trends (The Business Roundtable 1983). In 2007, 86% of the largest construction companies in the US expected labor shortage (Sawyer and Rubin 2007). Some regions in the US are already reporting shortage in key crafts (Albattah et al. 2016). Labor shortage often causes time and cost overruns for a variety of projects (Abdul-Rahman et al. 2006; Kaming et al. 1997; Toor and Ogunlana 2008). The recognition of these challenges has prompted researchers to suggest exploring new, innovative methods to complete the required work with less qualified labor (Karimi et al. 2016).

Mechanical, Electrical and Plumbing (MEP), also known as active building systems, present one of the most challenging coordination efforts in construction projects according to professionals (Korman et al. 2003). Due to the traditionally fragmented nature of the construction industry (Wang et al. 2016), different design teams typically work separately. Traditionally, teams would meet periodically and overlay plans to resolve conflicts between their different designs (M.Korman and Tatum 2006). The challenges associated with MEP coordination and opportunity for the use of BIM to support this illustrates the opportunity for new visualization tools to better communicate the intended design concepts to the various field professionals laying out the different active systems.

3.2.2 Building Information Modeling

Building Information Modeling (BIM) has been defined as “a digital representation of physical and functional characteristics of a facility” (National Institute of Building Sciences (NIBS) 2014). Although the first mention of BIM in research goes back to more than a quarter century ago (Van Nederveen and Tolman 1992), researchers are still trying to realize the full potential of the technology in all stages of a construction project. In the design of MEP systems, BIM use has become more common due to its many benefits in coordination and 3D clash detection (Khanzode et al. 2005; Tabesh and Staub-French 2006). Currently, more than 75% of professionals have used BIM in North America, and half use it on more than 90% of their projects (Jung and Lee 2015). Since the introduction of BIM, researchers have been advancing this field through the creation of coordination systems (Korman et al. 2006), evaluation of current practices (Dossick and Neff 2010; Lee and Kim 2014) and providing critical reviews of those practices for future improvement (Yung et al. 2014).

However, these efforts focused on using BIM to enable better design communication to support design and coordination phases. Far less research has explored the use of BIM for communicating design information for construction personnel during construction. Although significant cost and effort are invested in BIM implementation (Boktor et al. 2014), office-to-site communication still typically relies on 2D plans generated from the designed 3D model (Gould and Joyce 2009).

3.2.3 Augmented Reality

Augmented Reality (AR) is a technology that allows the merging of virtual and physical worlds, superimposing virtual objects on physical surfaces (Milgram and Kishino 1994). In the construction industry, Feiner first theorized how mobile technology and AR can be combined to present the user with hands-free, spatially relevant information (Feiner et al. 1997b). The use of AR has since been studied for several applications throughout the industry.

In the design and planning stages, AR is able to present numerous data points without interrupting current workflows (Côté et al. 2014). When used for constructability discussions during planning stages, AR enabled faster data-finding and problem-prediction without affecting accuracy (Lin et al. 2015). AR has been used to deliver chronological instruction to enable assembly non-skilled workers to build complex free-form surfaces (Fazel and Izadi 2018) and to deliver location aware safety instructions using image detection and recognition through a mobile device (Kim et al. 2017). AR is also deployed for inspection use, such as in tunneling applications (Zhou et al. 2017) and steel column deviation tracking (Shin and Dunston 2009).

On construction sites, AR has been used to visualize the 3D model in its intended final location (Woodward et al. 2010b). It has also been used to visualize BIM content related to potential improvements in hidden spaces (Thomas and Sandor 2009). In addition to visualizing content related to the building itself, AR was also used to understand process information related to constructing the building, including AR safety instructions (Guo et al. 2017) and reducing site risk factors (Tatić and Tešić 2017). While AR is a rapidly growing field, there remains little AR research that includes testing with actual industry practitioners using current standards (Wang et al. 2013). Therefore, this work targets a set of realistic point layout tasks, with industry participants, targeting currently accepted accuracy tolerances.

3.2.4 Task Classification and Attributes

Considerable effort went into the classification of different tasks in construction according to several metrics. Proctor defines any task as the succession of three steps: perceptual, cognitive, and motor (Van Zandt and Proctor 2008). Everett indicated that humans are usually more able to handle mentally intensive tasks (Everett and Slocum

1994). Most of the prior research relates to automation of construction tasks, primarily through robotics and machinery. Tucker identified 17 distinct automatable areas (Tucker 1988). Kangari defined a "robotics feasibility" score by assessing 33 processes (Kangari and Halpin 1989). Warszawski identified ten "basic activities" that can be performed by robots (Warszawski 1990).

Dunston and Wang suggested a human view point based classification system, specific to AR feasibility (Dunston and Wang 2011). A five level, hierarchical taxonomy of Architectural, Engineering and Construction (AEC) tasks was introduced: (1) Application Domain, (2) Application-specific Operation, (3) Operation-specific activity, (4) Composite Task and (5) Primitive Task. Each level breaks down to one or more of the levels below. For example: construction (Application Domain) includes fabrication (application-specific operation), which includes assembly (Operation-specific activity), which in turn includes connecting (composite task) which is a succession of reaching, grasping, and moving (Primitive Tasks) (Dunston and Wang 2011). Dunston and Wang (Dunston and Wang 2011)theorized that primitive and composite tasks are best for AR development, and recognized several limitations, namely mental workload.

Using this classification, the researchers identified "positioning" or "point layout" as a composite task that has application in a wide variety of operation specific activities. Point layout thereafter refers to the task of locating a relevant point in space and marking it for future work or installation.

Prior research suggests that AR may be able to increase the human performance in positioning tasks compared to current conventional methods (Chalhoub and Ayer

2018a), but the positioning task was secondary in the operation tested. This paper studies the potential of using AR for primarily positioning tasks and studies the effect of its implementation on the performance of current industry practitioners.

3.2.5 Point Layout & Current Practices

Point layout is a task where an individual identifies points in the space that are relevant to a given construction task. For example, in electrical construction, 'point layout' may refer to electrical device layout in a room, where a practitioner may mark the locations where electrical devices will be installed. Typically, this is followed by a construction crew installing each device where its corresponding mark was placed. The same concept is used throughout the construction industry in different applications.

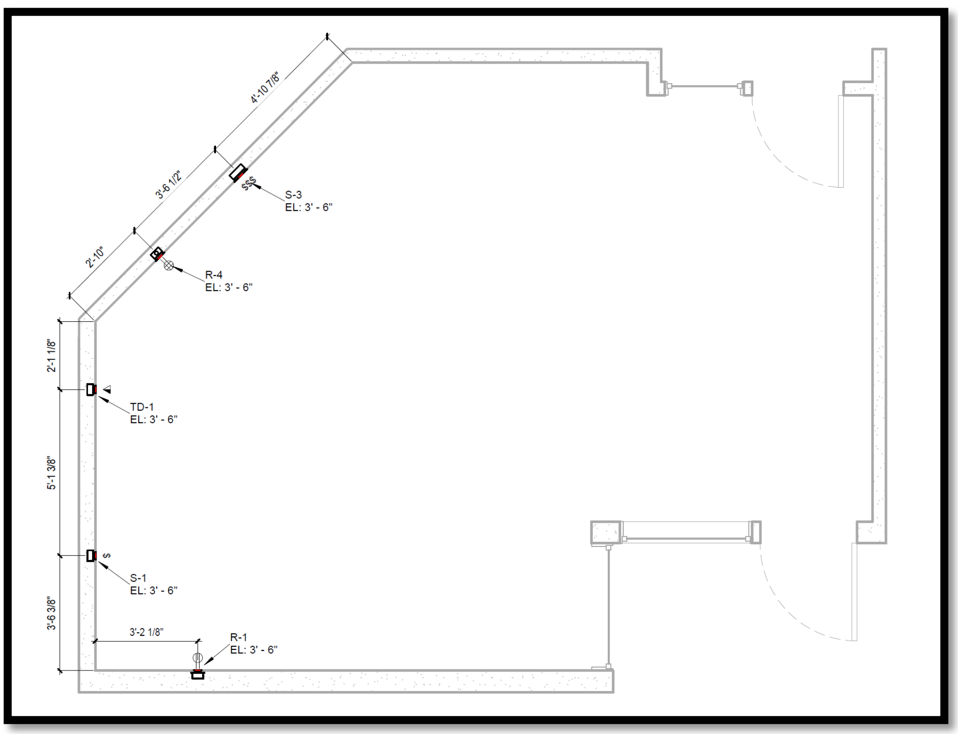

Figure 5: Typical Device Layout Shop Drawing

In this work, the researchers interviewed different personnel from an electrical partner company to understand current practices and challenges related to the point layout task. The interviewees included project managers, BIM modelers, coordinators and onsite practitioners. On BIM projects, the modelers would first model the location of the different electrical devices, and then generate shop drawings that are subsequently handed to the onsite practitioners. Figure 5 shows a typical shop drawing, which includes the names of the devices, distance from one or more walls in the room, and required elevation. All measurements are to the center of the device.

In most cases, the electrical devices are installed when only the studs are built, but not the dry wall. Therefore, the point layout task consists of placing marks on the ground where the devices would ultimately be, and a different crew would measure the vertical elevation just prior to installation. If the device is designed between two studs, depending on the project and the type of the device, the crew may either build a bracket between the studs to place the device or just affix the device to the closest stud. This research focuses on the point layout task, as the time and effort for the installation of the devices should be identical regardless of the method used to find the points.

3.3 Methodology:

This paper presents the findings from an experimental study where electrical construction industry practitioners laid out electrical devices in a construction space using AR and paper. The researchers collaborated with a large electrical subcontractor with an international and extensive national footprint. Representatives from the company stated that it currently employs BIM in almost half of its projects, and where possible, uses prefabrication in conjunction with BIM efforts. The representatives also stated that they see the company as one that is technologically progressive, working in-house on multiple research projects using Virtual Reality (VR) and other technologies. The following sections detail the methodology used to gather and analyze data to determine trends and differences between the two communication methods.

3.3.1 Experiment Design

A private conference room at the partner company's home office was selected for this experiment. The room presented a controlled and safe space to test the impacts of AR without the potential safety hazards on an active construction site. For the conference room, the company's modelers generated four different designs with different combinations of electrical devices in each design. Subsequently, each design was modified to keep the same devices, but alter their position, which essentially created eight different designs. The first iteration of each design carried a suffix "a", and the second "b". This would allow a user to layout each design variation using both paper and AR, without repeating the same exact model twice, which would allow for a paired comparison between the performances.

3.3.2 Augmented Reality

For this research, the authors opted to use the Microsoft HoloLens as the AR device. The HoloLens is a see-through head mounted display (HMD) that allows hands-free viewing of virtual content overlaid in the user's field of view. It is also a fully self-contained device, untethered from any external computers. This allows users to freely move and use their hands as they are viewing virtual content in a given area.

The designs created were supplied to the researchers in their native BIM formats, and were modified by the researchers for proper viewing through the HoloLens. First, all non-essential elements from the model were removed, including: walls, roof, flooring, doors and other objects that were unrelated to the electrical devices to be laid out. This was done to allow users to see a predominantly real view of their space with only the necessary layout items augmented on their view. The names of the different devices and crosses in the center of each device were colored in red for better viewing contrast. Figure 6.a below shows the original model and figure 6.b and modified models.

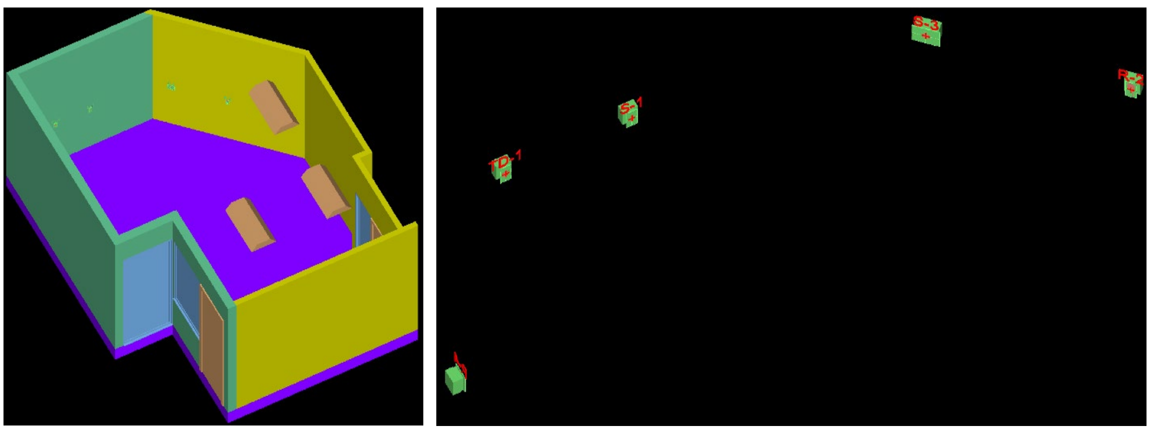

Figure 6: Complete Model (A) and Stripped out Model (B)

The remaining BIM content was exported to a universal 3D format and imported to a gaming engine compatible with the AR device. A commercially available solution was used to display the model in the right position by linking it to a marker. Each model had a distinct marker. Figure 7 shows a typical marker that was used in this experiment. Once the paper marker is scanned by the AR device, the relevant BIM content appears in its correct location in the user's field of view.

Figure 7: Sample Marker Used in This Experiment

3.3.3 The experiment

The experiment took place over two weeks, with four to six participants each day. Typically, each participant needed between one and two hours to finish the experiment. The following sections discuss in detail the sequence of activities undergone by each participant.

3.3.3.1 **Pre-experiment**

Before a participant would start laying out points, he or she would be given a quick overview of the activity. Each participant was informed that he or she would be completing a point layout task eight times: four times using traditional shop drawings and four times using the AR device. Before each task, the participant would be handed an envelope with stickers to mark the walls where the electrical devices were intended to be installed. Each sticker had a cross-mark to depict the center of the device orientation, and the name of the device. Figure 8 below shows a sample sticker for device R-4.

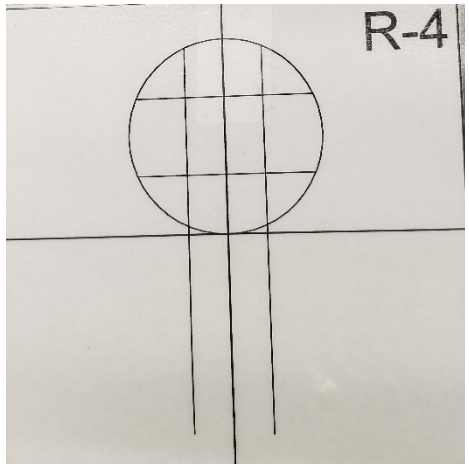

Figure 8: Sample Sticker (Device R4)

The participants were also asked to sign two copies of a consent form, one for them to keep and the other collected by the researchers. Each participant also filled out a pre-activity questionnaire. The questionnaire sampled background data including age, race, highest level of education, current job title, years of experience, and previous experience using AR or VR privately or on the job site. Another set of questions focused on the perception of the participant about the use of technology on the job and using AR for point layout. A definition of AR and point layout was provided in the questionnaire to allow for a consistent understanding when asking participants for their perceptions.

3.3.3.2 **During the experiment**

After participants completed the pre-activity questionnaire, they began the layout task. Each participant laid out all eight models (four designs, with both "a" and "b" variations). Half of the participants laid out models "a" using paper plans, and models "b" using AR, while the other half laid out models "b" using paper plans and models "a" using AR. Furthermore, the sequence of designs to be laid out was randomized, creating a unique list of participants. Figure 9 shows the process of list creation.

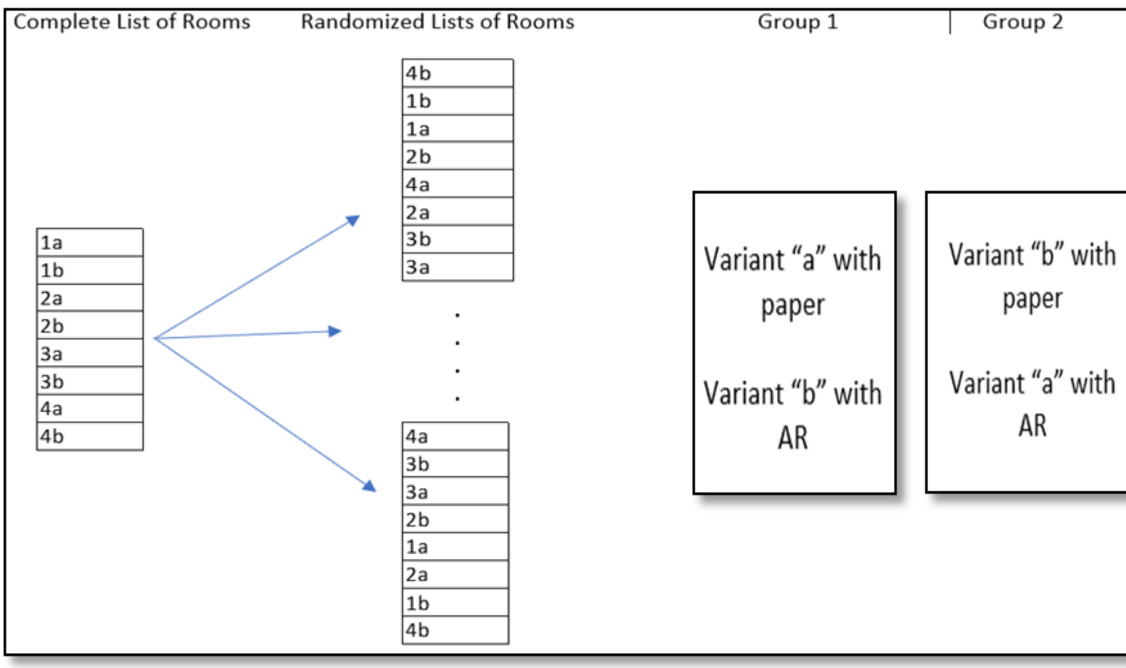

Figure 9: The Illustrated Process of List Creation

As a participant laid out the electrical devices using paper plans, they were supplied with the plans corresponding to the design they were building, and the sticker envelope. They were also told that all measurements shown are to the center of the device. The participants were offered several support devices, such as tape measures, laser tape measures, painter's tape, scotch tape, and a moveable table for support. The participants were also advised that they may use any other tools they deem necessary, and they were welcome to use some, all or none of the supplied tools.

When a participant was laying out the devices using AR, they were assisted with wearing the head-mounted AR device, and the researchers made sure that the participant was able to view the content. The participant was then handed the stickers envelope and scotch tape and they were also directed to inform the researchers if the content displayed through the headset suddenly shifted position or disappeared altogether.

Whether using AR or paper plans, to properly lay out a point, the participant would have to locate the point and the appropriate sticker so that the center of the 'X' would fall on the center of the device being laid out. Figure 10 shows one participant laying out points in the space. Participants completed the activity individually. To better study the behaviors demonstrated during the activity, the participant was videotaped from multiple angles.

Whether using AR or paper plans, to properly lay out a point, the participant would have to locate the point and the appropriate sticker so that the center of the 'X' would fall on the center of the device being laid out. Figure 10 shows one participant laying out points in the space. Participants completed the activity individually. To better study the behaviors demonstrated during the activity, the participant was videotaped from multiple angles.

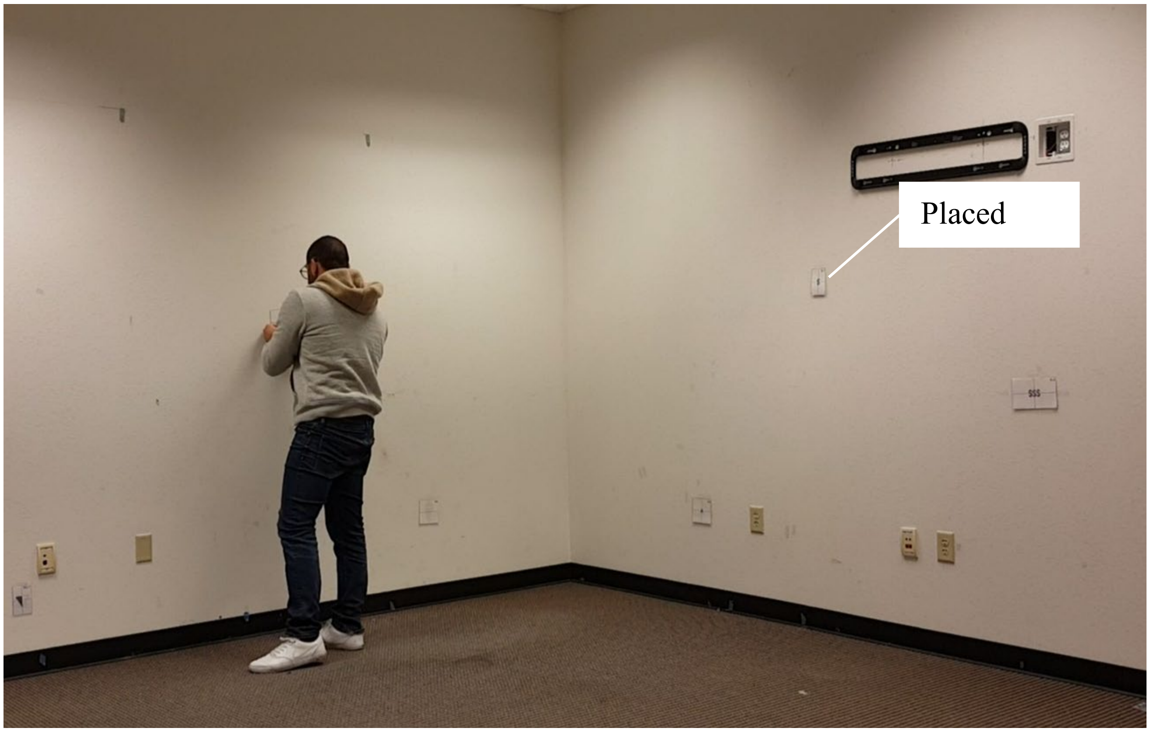

Figure 10 Showing One Participant Laying out Points During the Experiment

3.3.3.3 Post Experiment

Participants spent approximately one minute completing the NASA-TLX survey after each layout task. During that time, the researchers measured the distance from the center of each point laid out from one wall and the floor using high speed, laser tape measures, commercially advertised to have an accuracy of +/- 1/16th of an inch. Thus, each point would have a set of coordinates associated with it.

Once the participants finished completing the survey and the researchers completed the measurement, the walls were cleared of all marks and tape, and the participants received a new set of plans or a new model on the AR device with a new stack of sticky notes, corresponding to the electrical devices required for the new layout task.

When a participant was done laying out all eight models, he or she was asked to complete a post-activity questionnaire. Several Likert-scale questions sampled the perception of the users concerning comfort and ease of using AR for point layout. The questionnaire also included open ended questions to ask about the ease of using the device, comfort during use, and future use cases for the technology based on their expertise. Relevant results are presented in the results section.

3.3.4 Analysis

The researchers were interested in four metrics: accuracy, time, mental workload and perception of the participants. The following sections present the methodologies that were used to analyze each metric.

3.3.4.1 **Accuracy**

When laying out points in general, and electrical devices in specific, accuracy may be very important. According to some practitioners, project tolerances can be as low as $1/8^{th}$ of an inch deviation from intended placement. Thus, the absolute differences between the coordinates of the laid-out point and the designed coordinates of the point were calculated. The accuracy was calculated separately along the X-axis and Y-axis. Overall distance accuracy can be calculated using basic mathematics if needed.

During the experiments, the researchers noted that, in several cases, participants misread the paper plans. For example, some participants flipped the elevations of two consecutive points. This led to very large errors: for example, one device was designed to be at an elevation of 5 feet, and the one after it was designed at an elevation of 1.5 feet. Flipping the two elevations resulted two errors of 3.5 feet each, an extreme outlier when compared to other accuracies computed. Similarly, when using AR, after some participants completed a given model, they declared that the AR device had turned off or that the model had jumped significantly, but they had continued working from memory or interpretation, leading to high errors.

To account for the anomalies above, two data sets were created: the first used all the data as collected onsite (called 'Raw Data' thereafter) and the other had all extreme outliers removed from the set (called 'Outliers Removed'). The equation below was used to determine what constituted an extreme outlier, where Q1 and Q3 are the first and third quartiles in each data set, respectively, and IQR is the interquartile range (Hoaglin et al. 1986).

$$\text{Extreme Outlier} < Q1 - 3 * IQR \text{ or } Q3 + 3 * IQR < \text{Extreme Outlier}$$

The researchers did test the data sets with all outliers (mild and extreme) removed, but the results were similar to the data set where only the extreme outliers were removed, and thus were not presented in this paper.

3.3.4.2 **Time**

The researchers watched and coded the videos taken of each participant to determine the start and end time of each task. When using AR, the time started from the moment the user declared they were able to see the content through the headset. When using paper plans, the time started from the moment the participant received the paper plans. In both cases, the time ended when the participant self-declared that they were done with the given layout task. All presented times are in seconds.

When using the AR device, some of the participants had technical difficulties midway through the task: for example, the device would turn off or the content would shift location significantly. Although the times of technical difficulties do not necessarily represent time spent doing the task, it is a factor that may affect work on site. Thus, the AR times computed included all faced technical difficulties.

3.3.4.3 **NASA-TLX and Perception**

The pre-session, post-session, and NASA-TLX questionnaires were all digitized and stored in separate spreadsheets. Once all the data was linked for each participant, the data was anonymized, and hard copies were stored for reference. Direct means and frequencies are reported, as well as statistical comparisons using paired analysis.

3.4 Results:

Thirty-two practitioners participated in this study, including electricians, modelers, managers, coordinators and interns. Twenty-nine participants were male and three were female. Their ages ranged between 21 and 59 years old. Twenty-eight of the participants were full-time professionals, two were interns, and two did not specify. Only four participants had less than 1 year of experience, and seventeen participants had done some type of electrical layout task in their work in the previous year. Table 7 summarizes the distribution of participants according to years of experience and whether they regularly preformed point layout tasks as part of their work in the past year.

Table 7: Crosstabulation of Participant's Years of Experience and Doing Point Layout During the Last Year

Years of Experience	Point Layout During Last Year		Total
	Yes	No	
Less than 1 year	0%	13% (n = 4)	13% (n = 4)
1 to 5 years	25% (n = 8)	9% (n = 3)	34% (n = 11)
6 to 10 years	16% (n = 5)	9% (n = 3)	25% (n = 8)
more than 10 years	12% (n = 4)	16% (n = 5)	28% (n = 9)
Total	53% (n = 17)	47% (n = 15)	100% (n = 32)

Not all the participants finished all the tasks assigned. This was mainly due to other responsibilities in their workday that limited the amount of time they could participate in the research. In total, 232 different layout tasks were completed, 114 using paper plans and 118 using AR, for a total of 1445 points laid out.

3.4.1 Accuracy

A paired statistical test was required in order to compare the performance of each participant to himself or herself. In order to choose a statistical test, all data sets were subjected to a Shapiro-Wilk test of normality. The null hypothesis of the test is that the data is normally distributed. The alternative hypothesis is that the data is not normally distributed. Table 8 summarizes the W-values and significances for all the data sets used:

Table 8: The Shapiro W-values for the X-axis and Y-axis Accuracies, for Both Raw Data and Data with Outliers Removed

	Raw Data		All Outliers Removed		Extreme Outliers Removed	
	W-Value	P-Value	W-Value	P-Value	W-Value	P-Value
X-Paper	0.57468	<2.2e-16	0.86264	<2.2e-16	0.82159	<2.2e-16
X-AR	0.6505	<2.2e-16	0.90849	<2.2e-16	0.86181	<2.2e-16
Y-Paper	0.21754	<2.2e-16	0.87747	<2.2e-16	0.8503	<2.2e-16
Y-AR	0.7827	<2.2e-16	0.86167	<2.2e-16	0.82849	<2.2e-16

The significances of all the data sets are smaller than 0.05, suggesting that the null hypothesis is rejected, and all the data sets are considered non-normally distributed. Thus, parametric tests, such as the paired samples t-test, cannot be used to study the data sets. Non-parametric statistical tests do not assume that the sets are normally distributed and may be used in this case. One non-parametric alternative is the paired Mann-Whitney test, which was used in this case. All accuracies in this paper are presented in feet. Table 9 summarizes the results of the Mann-Whitney test comparing the accuracy of AR and paper plans along the X-axis and Y-axis, using both raw data and data with outliers removed.

Table 9: Summarizing the Findings of the Paired Mann-Whitney Tests for X-axis and Y-axis Accuracies Across Both Data Sets

Source	Testing	Number of Pairs	AR Mean (Feet)	Paper Mean (Feet)	Mean Difference	V-value	P-Value
Raw	X-Axis	667	0.1111	0.1184	-0.0073	116,900	0.2394
	Y-Axis	672	0.0974	0.0769	0.0205	175,090	<2.2e-16*
Outliers removed	X-Axis	624	0.0997	0.0837	0.016	110,760	0.002528*
	Y-Axis	598	0.0925	0.0154	0.0771	162,320	<2.2e-16*

* Indicates that a comparison is significant at the 95% confidence level.

When considering the raw data, there is no difference in the levels of accuracy between paper plans and AR along the X-axis at the 95% confidence level (p-value = 0.02384). However, paper is slightly (0.0205 feet), but significantly more accurate along the Y-axis (p-value < 2.2e-16). After removing extreme outliers from AR and paper measurements, paper becomes slightly (0.016 feet) but significantly more accurate along the X-axis (p-value = 0.002528) and the difference in accuracy increases along the Y-axis (0.0771 feet).

The results would suggest that paper is, in general, more accurate than AR for point layout along both axes, but AR is less prone to having large errors: paper plans gain a significant increase in accuracy when the extreme outliers are removed. Observations during the experiment suggest that misreading from the plans is a common error. Users would read the elevation from one device, and assign it to a different device, or they would simply read a distance incorrectly.

Another common error was miscalculating cumulative distances, since some of the measurements provided on the plans for some devices were based on other devices. Figure 11 shows an illustration of a cumulative measurement. In this example, the participant would typically start with device "R4" and use it to locate device "S3". Thus, if device "R4" is laid incorrectly for any given reason, device "S3" would also be laid out incorrectly. Moreover, along the Y-axis, measurements are typically of short distances (between 1 and 6 feet), while along the X-axis, measurements can be longer, which may explain the generally higher errors using paper along the X-axis.

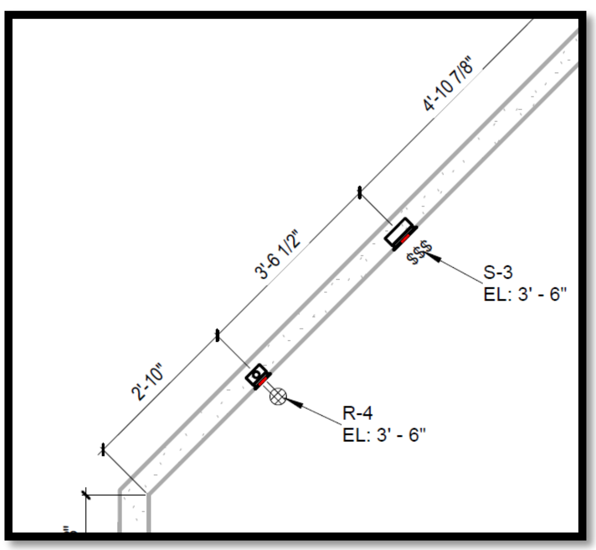

Figure 11: Example of Cumulative Measurement

3.4.2 Time

Using a paired statistical analysis, the researchers compared the time to complete the layout of the different rooms. Since different rooms have different numbers of devices, the times shown in this section reflect time in seconds per device, for consistency. Table 10 summarizes the findings of the Shapiro normality test. Since none of the data sets is normal (p-value < 0.05), the Mann-Whitney paired test was used to compare the data sets.

Table 10: Shapiro W-values for AR and Paper Task Completion Times

	W-Value	P-Value
AR Time	0.64132	<2.2e-16*
Paper Time	0.96673	7.231e-12*

Table 11 summarizes the findings from the Mann-Whitney paired test. Task completion times, per point, are significantly faster using AR compared to using paper plans (p-value < 0.005). On average, participants are 70% faster when using AR compared to when using paper. When using paper, a participant would have to read the plans, interpret the locations of the devices in the room, take the measurements, match the sticker to the point to be laid out, and then affix the sticker to where its intended location. When using AR, the participants would simply look around room, match the sticker in hand to the points shown on the walls, and then tape the point where he or she sees it.

Moreover, AR allows continuous feedback on the placement of the point. For example, if the participant laid a point in an incorrect location, it would be readily apparent and rectifying the mistake is relatively easy. When using paper, the participant would have to consult the plans to make sure of the mistake first, then repeat all measurement finding and taking tasks before rectifying the mistake. Therefore, AR enables a significantly faster point layout process.

Table 11: Paired Mann-Whitney Test for Task Completion Time Using AR

Testing	Number of Pairs	AR Mean	Paper Mean	Mean Difference	V-value	P-Value
Time Per Device	675	27.72	92.67	64.95	18850	<2.2e-16*

Of the 118 times where AR was used, 17 included technical difficulties, experienced by 15 participants. These included display flickering, excessive model shaking, and in six cases, the application closing and needing to be relaunched altogether. The participants had to take off the headset, hand it back to the researcher for resetting, and then put it back on. On average, each delay lasted 40.39 seconds, or 6.5 seconds per device laid out.

The AR device used for this research is a developer unit. A commercial unit should be more stable, and a trained user would be able to do fix most issues on their own. Nonetheless, in this research, the technical "down times" were considered part of the overall layout time and incorporated in the times presented above.

3.4.3 Experience

The researchers were also interested in studying the effect of experience on the usability of AR for the point layout task. Some research suggests that the younger generation, aptly called digital natives (Prensky 2001), are significantly better at using technology since they are engulfed in it from a very young age, and have been documented to help the "older" generation familiarize and use technology (Correa 2014).

On the other hand, some other research seems to dispute this, suggesting that if training is needed for an older generation, it is just as needed for the younger one (Kirschner and De Bruyckere 2017; Margaryan et al. 2011). Therefore, there were two potential effects of experience that were of interest: the effect of experience on AR performance; and the benefits provided by AR to individuals with more or less experience. These topics are discussed in the sections below.

3.4.3.1 **Accuracy**

To address the first topic, the years of experience were considered a categorical variable, and its effect was studied using the Kruskal-Wallis method, the non-parametric version of a one-way ANOVA, used since the data is not normally distributed. Table 12 summarizes the results of the test. Regardless of which data set is considered, experience has no effect on the accuracy of the points laid out on either axis, at the 95% confidence level. Statistically, when using AR, there is no significant effect of years of experience on the final point layout accuracy.

Table 12: Summary of the Kruskal-Wallis Test for the Effect of Years of Experience on Accuracy Using AR

Source	Testing	Kruskal-Wallis Chi Squared	Degrees of Freedom	P-value
Raw Data	X-Axis	2.7608	3	0.43
	Y-Axis	5.9511	3	0.114
Outliers removed	X-Axis	2.7266	3	0.4357
	Y-Axis	3.9864	3	0.2629

The data was split into four different sections according to the different years of experience of the participants: (1) less than 1 year, (2) 1 to 5 years, (3) 6 to 10 years and (4) more than 10 years. This would allow checking if using AR affects participants with different years of experience similarly. The performances of the subgroups were compared using both raw data and data with outliers removed. Table 13 below summarizes the results of the paired Mann-Whitney comparisons.

Table 13: Findings of the Mann-Whitney Test, Comparing the Accuracy of AR, Divided by Participant's Years of Experience

Group	Source	Testing	AR Mean	Paper Mean	Mean Difference	V-value	P-Value
Less than 1 year of Experience	Raw Data	X-axis	0.0985	0.1331	-0.0346	761	0.04212*
	Outliers removed		0.0885	0.0927	-0.0042	736	0.2623
6 to 10 years of Experience	Outliers removed		0.1054	0.0819	0.0235	7861	0.2272
More than 10 years of Experience	Raw Data	Y-axis	0.0884	0.1275	-0.0391	12961	0.004235*

Only the findings that are different than the overall population are presented in the table above. When considering the raw data, participants with less than 1 year of experience are significantly better along the X-axis by 0.0346 feet (p-value = 0.04212 < 0.05). Naturally, participants with little experience are more prone to large errors, which could explain why AR appears to be better when all the data is considered.

When considering data with outliers removed, for participants with less than 1 year of experience and between 6 and 10 years of experience, there is no significant difference in accuracy along the X-axis between using AR and paper plans (p-value = 0.2623 and p-value = 0.2272, respectively). This shows how close the accuracy is between paper plans and AR. Even though the overall population does exhibit a significant difference in accuracy, subgroups show that the difference in accuracy is not significant.

Finally, when considering the raw data, participants with more than 10 years of experience have a better accuracy along the Y-axis using AR compared to using paper plans (p-value = 0.004235). Participants with more than 10 years of experience seem to aim at what they would know as "acceptable accuracy" and finish with less overall time. To further back-up this conclusion, two of the participants mentioned they were "working as if they would on site, and not aiming for perfect accuracy".

3.4.3.2 **Time**

Regardless of the years of experience, the participants are significantly faster when using AR compared to when using paper plans. Table 14 summarizes the Mann-Whitney tests run on the participants separated by years of experience.

Table 14: Findings of the Mann-Whitney Paired Test on the Time of Task Completion, Divided by Participant's Years of Experience

Testing	Number of Pairs	AR Mean	Paper Mean	Mean Difference	V-Value	P-Value
Less than 1 year	86	25.21	102.13	76.92	0	1.13e-15
1 to 5 years	236	23.9	96	72.1	0	<2.2e-16
6 to 10 years	186	24.74	89.58	64.84	730	<2.2e-16
More than 10 years	170	36.84	87.54	50.7	3820	6.02e-13

The Kruskal-Wallis test was used to examine the differences between the performance of the different groups of participants when using AR. Table 15 summarizes the results of the test. There is a significant difference in time to complete between at least two subsets of the data (p-value < 0.05).

Table 15: Findings of the Kruskal-Wallis Test for the Effect of Years of Experience on Task Completion Time Using AR

Testing	Kruskal-Wallis Chi Squared	Degrees of Freedom	P-value
Time	19.879	3	0.0002796

Follow-up post-hoc Mann-Whitney tests were used to determine the differences between the different groups. Table X summarizes the significant results from the post-hoc tests. Participants with more than 10 years of experience are between 11 and 13 seconds slower than other participants, and the results are significant (p-values < 0.05). Table 16 shows that practitioners with more than 10 years of experience are most familiar with traditional paper documentation for layout methods and appear to have a harder time transitioning into newer methods of construction.

Table 16: The Significant Results of the Mann-Whitney Test

Testing	AR Mean	AR Mean More than 10 years	Mean Difference	W-value	P-Value
Less than 1 year	25.21	36.84	11.63	7090	0.001451
1 to 5 years	23.9		12.94	19685	0.001997
6 to 10 years	24.74		12.1	14855	5.771e - 05

3.4.4 Cognitive Workload:

The NASA-TLX questionnaire is a two-step test created to measure the cognitive workload of a task. In the first half of the test, the user rates six subcategories on a scale from 5 to 100 with 5 points increment, where 1 refers to the most desirable option and 100 referring to the least desirable. Table 17 lists the subcategories and the test description of each.

Table 17: NASA-TLX Subcategories and Associated Questions

Subcategory	Description
Mental Demand	How mentally demanding was the task?
Physical Demand	How physically demanding was the task?
Temporal Demand	How hurried or rushed was the pace of the task?
Performance	How successful were you in accomplishing what you were asked to do?
Effort	How hard did you have to work to accomplish your level of performance?
Frustration	How insecure, discouraged, irritated, stressed, and annoyed were you?

In the second half of the test, each participant should create a personalized weighing system, effectively creating a coefficient for each subcategory to to create a single cognitive workload measurement. This part of the test was omitted in this experiment, since the researchers are interested in comparing each component of the cognitive workload measurement separately.

The Shapiro-Wilk test of normality shows that none of the results follows a normal distribution. Table 18 summarizes the results of the normality test on each of the data sets of interest.

Table 18: Shapiro W-values for NASA-TLX Subcategories for Each Information Delivery Method

NASA-TLX Factor	Information Delivery Method	W-Value	P-Value
Mental Demand	Augmented Reality	0.83302	4.487e-10*
	Paper Plans	0.9462	0.0002651*
Physical Demand	Augmented Reality	0.86987	1.279e-8*
	Paper Plans	0.93395	4.386e-5*
Temporal Demand	Augmented Reality	0.73892	5.174e-13*
	Paper Plans	0.95489	0.00106*
Performance	Augmented Reality	0.75897	1.863e-12*
	Paper Plans	0.95105	0.0005672*
Effort	Augmented Reality	0.801	3.543e-11*
	Paper Plans	0.94925	0.0004259*
Frustration	Augmented Reality	0.82259	1.899e-10*
	Paper Plans	0.93846	8.337e-5*

The Mann-Whitney paired test was used to compare the results for each of the six factors when using AR and when using paper. Table 19 summarizes the results of the test.

Table 19: Mann-Whitney Test Results for NASA-TLX

NASA-TLX	AR Mean	Paper Mean	Mean Difference	Number of Pairs	V-Value	P-Value
Mental Demand	17.000	47.965	30.965	104	31.5	2.2e-16*
Physical Demand	17.870	45.740	27.870	104	96	7.50e-16*
Temporal Demand	22.000	42.405	20.405	104	447	1.6e-11*
Performance	25.305	42.360	17.055	104	675	1.165e-8*
Effort	18.520	51.665	33.145	104	127.5	3.71e-16*
Frustration	18.175	43.010	24.835	104	253	8.01e-14*

Across all six subcategories, AR performed significantly better than paper. The lower required mental demand when using AR may be explained by the fact that a user would not need to understand the plans and the measurements, but rather just see the location of the point and place it. The lower physical demand and effort levels may be lower because the user would not need to take any measurements, mark positions, or any other of the typical steps of point layout. Using AR, the only effort is the actual placement of the device. Temporal demand and frustration may be lower when using AR because, on average, a user finished significantly faster when using AR, relieving some of the pressure off the users.

Most surprisingly, self-reported performance is better when using AR. To the user, the models shown through the AR device appear to be shaking slightly, and this was expected to give a feeling of lack of confidence in the participants. This does not seem to be the case. Likely, the practitioners related the performance to speed of completion and satisfactory results rather than perfect results. Regardless of the weights assigned to each categories in creating a final cognitive workload score, AR would have generated a lower overall final score compared to paper plans.

3.4.5 Perception:

All reported questions from the pre- and post-questionnaires are based on a four level Likert scale, where "Strongly Disagree" is coded as 1, "disagree" as 2, "agree" as 3 and "Strongly Agree" as 4. Table 20 summarizes key questions from the post-questionnaire.

Table 20: Sample Questions and Results from the Post-questionnaire

	Strongly Disagree	Disagree	Agree	Strongly Agree
AR can completely replace paper plans for communicating design for the purposes of points layout	3% (n=1)	16% (n=5)	50% (n=16)	31% (n=10)
I would rather use AR than use paper plans for point layout activities	3% (n=1)	12% (n=4)	38% (n=12)	47% (n=15)
It is easy to use AR for point layout	0	0	41% (n=13)	59% (n=19)
I would be comfortable with an untrained individual laying points in the field using AR	6% (n=2)	44% (n=14)	28% (n=9)	22% (n=7)

More than 80% of the participants at least agree with the statement "AR can completely replace paper plans for communicating design for the purposes of point layout", 85% would "rather use AR than paper plans for point layout" and all participants agreed to the statement "AR is easy to use for point layout". However, half of the participants are not comfortable with "an untrained individual laying points in the field using AR".

The results generally reflect a continued positive trend in perceptions toward paperless office to site communication (Chalhoub and Ayer 2018a) although the sample is from a single company which may have skewed the results. However, it was interesting that, despite unanimously agreeing that AR is easy to use, half of the participants were not comfortable with untrained labor using AR for point layout. Interestingly, more than half of those who disagree with untrained labor using AR have at least 6 years of experience. In electrical construction, device layout is traditionally a task done by senior workers ahead of crew installation, so their prior understanding of how this task is typically completed may have influenced the answers.

Overall, it is interesting to note that using AR was not directly rejected by the participants, especially given that many of them are experienced practitioners. The authors assumed that these individuals might not want to change the way that they build projects, but this was not observed through the results. Their relative openness towards the use of AR instead of paper plans is encouraging for future development of the technology and exploring new use cases in the industry.

3.4.6 Limitations

The limitations of this work are related to the test subjects, the AR technology as used, and the overall environment. First, the participants were all from one company. The company is moderately technologically advanced, with a dedicated BIM division and a small Research and Development group. Although the company still uses paper plans for all office to field communication, its technological progressive stance may have affected its employees into adopting new technologies faster than a typical construction practitioner would.

Second, the experiment was run in a conference room, not a construction site. Working in construction site presents a set of safety and operability challenges that were not addressed in the apparatus used in this paper. In addition, congestion, noise, restricted field of view, connectivity, charging and other challenges could theoretically reduce the expected performance benefits reported in this paper. While it presents a real set of challenges, testing in a conference room allowed the researchers to gather a large dataset under the exact same set of constraints. This would have been impossible to control on an active, always changing construction site. For example, changes in the worker's workload, time of the day and location of the room would have all played unquantifiable factors, potentially skewing the findings in the process. Additionally, gathering data on an active job site for a pilot study presents potential safety and financial risk to the contractor when using unproven and untested technologies.

Furthermore, current technology is yet to be tested for prolonged, rigorous use. As reported in the results section above, almost half the participants faced technical difficulties when using the headset. Currently, tracking the environment and accurately displaying the content requires well-lit areas and is very sensitive to heavy shadows. This may present a major obstacle on any construction site. Many other participants reported the device being excessively heavy on the head, especially when worn for extended periods. While this limitation impacted this particular study, this type of technical limitation is likely to be mitigated in part or in full when the technology evolves to become more resilient and lighter-weight.

Finally, the AR application development time was not accounted for in performance comparisons. This paper focuses solely on the performance difference during the actual construction tasks. Currently, the development process is iterative and more time consuming compared to the automated production of paper plans. When such technology becomes the norm, automated processes would greatly reduce the model-to-AR deployment time.

3.5 Conclusion:

The work presented in this paper validates the usability of current generation AR technology for the finding and placement of relevant points in construction site through testing an electrical room layout with current industry practitioners. Furthermore, it presents an accuracy, performance, and effort based comparison between using AR and using traditional, 2D paper plans. When using AR, participants were able to complete tasks more than 60% faster and with significantly less cognitive workload compared to when using paper plans. Paper plans provide better accuracy, but AR is less prone to having major outliers, especially along the X-axis.

Experience had no effect on the accuracy of the points when using AR, but participants with less than 1 year of experience benefited the most from using AR compared to their performance when using paper plans, mostly because of the worse performance using paper. Timewise, participants with more than 10 years of experience were significantly slower than all other participants when using AR. Interestingly, the participants in general believed that AR should be further implemented and half of them felt comfortable sending an inexperienced individual to lay out devices using AR. The paper did not test the technology in an actual construction site, and results may differ under the increased constraints and challenges of a construction site.

This paper contributes to the body of knowledge by defining the advantages and disadvantages of using AR for point layout tasks in construction. The research tests the use of AR using industry-developed model, shop drawing, and typical construction processes. The findings enable engineers and researchers to better integrate AR in point layout tasks and develop further use cases for the technology. Future research will focus on the effect of increased task complexity and typical work challenges on the performance when using AR.

3.6 Acknowledgement

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CHAPTER 4

EFFECTS OF VARYING TASK ATTRIBUTES ON AUGMENTED REALITY AIDED POINT LAYOUT

4.1 Introduction

Adoption of Building Information Modeling (BIM) continues to grow in the civil engineering and construction industries (McGraw-Hill Construction 2014). Augmented Reality (AR) is one emerging technology that is increasingly researched for its ability to leverage the 3D models generated using BIM, supplementing its use both in design offices and on construction sites (Park et al. 2013b). For example, AR has been used to enable the assembly of prefabricated electrical conduit (Chalhoub and Ayer 2018a), enhance urban planning (Cirulis and Brigmanis 2013), and enable better indoor navigation using natural markers for maintenance purposes (Koch et al. 2014).

While previous research highlights the opportunity to use AR in industry, most current AR research is still in the proof of concept stage. Use cases for the technology are being explored by researchers, where most hardware and software has long been in the prototype stages (Feiner et al. 1997b; Wang et al. 2014). Subsequently, the effects of variations in the target tasks, such as increased task complexity, on the performance of AR have not yet been empirically identified. This makes it hard to optimize the use of AR for a construction task, and further complicates technology implementation planning.

This research studies the use of AR to enable point layout tasks for electrical construction tasks. Previous research demonstrates that AR can be used to communicate design information that had traditionally been illustrated through paper plans for electrical layout tasks (J. Chalhoub, SK. Ayer, "Augmented Reality for Construction Layout Tasks", submitted, Arizona State University, Tempe, Arizona). While this paper does not present new software or hardware related to AR in construction, it investigates how AR performance is affected by changes in design concept factors related to the construction layout task itself. This research leverages existing AR hardware and software to highlight the strengths and weaknesses of current generation AR devices, enabling researchers to investigate more suitable use cases for the technology that meet the needs of current practitioners. Furthermore, developers may use the findings to address some of the current shortcomings of AR, and engineers would be better equipped when planning whether to use AR for a given task, depending on its specific requirements. This research answers the following research question: How do task variables affect the performance of practitioners using AR from accuracy, time, and mental workload perspectives?

4.2 Background

4.2.1 Augmented Reality

Augmented Reality (AR) is a visualization technology that integrates 3D virtual content and real environment in the same field of view in real time (Azuma 1997). Milgram and Kishino proposed a "reality spectrum", ranging from a fully real environment to a fully virtual environment (Milgram and Kishino 1994). Mixed Reality (MR) is any merging of the real and virtual worlds in a single view, and AR is a subset of MR where the environment is predominantly real with some virtual content (Milgram and Kishino 1994).

In recent years, due to technological advancements, AR research in the civil engineering and construction industry grew significantly. During design and planning stages, AR was used to facilitate discussion and enhance communication concerning BIM content (Lin et al. 2015), and to provide contextually aware information on sites (Bae et al. 2013). In construction, AR has been used to enable pipe and conduit assembly (Chalhoub and Ayer 2018a; Hou et al. 2015) and to provide chronological instructions from automatically generated assembly sequences (Makris et al. 2013). AR was also used to enable non-skilled labor to build complex free-form surfaces (Fazel and Izadi 2018) and to deliver personalized safety information to workers on site (Kim et al. 2017). Post-construction, AR was used for displacement inspection in tunneling systems (Zhou et al. 2017). In education, AR was shown to contribute to student learning for structural analysis purposes by better visualizing content from different angles (Turkan et al. 2017). Generally, AR research and implementation is gaining traction throughout the different industry sectors.

However, current research efforts are still mainly focused on finding potential use cases of the technology and have not thoroughly studied the effects of variations within the task on the performance of the proposed AR solutions. This research contributes to the body of knowledge by exploring this research gap using a construction layout task in electrical subcontracting.

4.2.2 Cognitive Workload and NASA-TLX

High cognitive workload has long been associated with lower productivity, increased error rate, and slower task completion (Swain and Guttmann 1983). The NASA

Task Load Index (NASA-TLX) is a survey that quantifies the perceived cognitive workload required from a user (Hart and Staveland 1988). Although the survey is subjective in nature, NASA-TLX has been used more than a thousand times, and is widely accepted as a measurement of the cognitive workload in users (Hart 2006). In civil engineering research, the NASA-TLX survey has been used to measure the cognitive workload required for masonry construction and to evaluate different design communication methods (Mitropoulos and Memarian 2013) and quantify the differences in cognitive workload when using different information delivery methods (Dadi et al. 2014b). The survey has also been used to study cognitive workload of AR solutions in the AEC industries (Dadi et al. 2014a; Shin and Dunston 2009; Wang and Dunston 2011). Table 21 summarizes the questions asked in the NASA-TLX survey.

Table 21: NASA-TLX Subcategories and Descriptions

Subcategory	Description
Mental Demand	How mentally demanding was the task?
Physical Demand	How physically demanding was the task?
Temporal Demand	How hurried or rushed was the pace of the task?
Performance	How successful were you in accomplishing what you were asked to do?
Effort	How hard did you have to work to accomplish your level of performance?
Frustration	How insecure, discouraged, irritated, stressed, and annoyed were you?

4.2.3 Point Layout and Current Practices

Point layout is a construction activity where an individual locates a point on the construction site that is relevant to a given task. For example, in electrical construction, point layout may refer to the task of identifying where certain electrical devices will be installed in a room. A mark is typically left where the electrical device should be installed, and an installation crew would later follow to build the targeted element at the location of the mark. The same process is used for mechanical installations, plumbing and other construction activities.

Currently, point layout is solely dependent on the spatial capabilities of site workers and managers to map 2D plans onto their 3D surroundings (Kwon et al. 2014). The practitioners typically receive sets of plans, where the points are identified through a set of distance measurements to other known points in the space. On BIM projects, the plans are produced by generating 2D projections from the 3D model. Figure 12 shows a typical shop drawing for electrical devices layout.

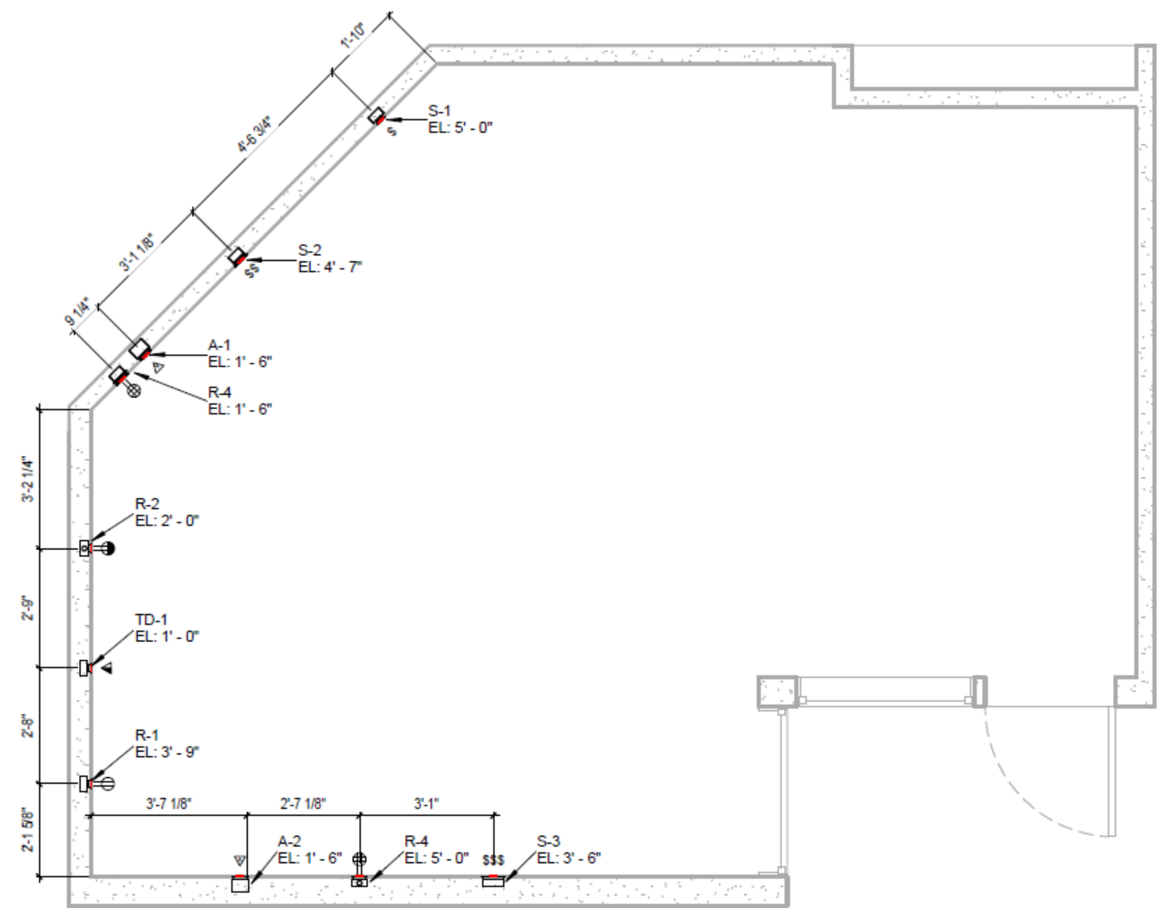

Figure 12: Standard Electrical Conduit Layout Plan

4.2.4 Task classification

For most of the twentieth century, research focusing on construction task classification studied the potential for automating those tasks. Porter divided a task into a physical component and an information component (Porter 1980). Proctor further divides a task into the chronological succession of a perception task, cognitive task and motor task (Van Zandt and Proctor 2008). Everett theorized that machines are better at physically intensive tasks that require little information exchange and understanding (Everett and Slocum 1994). Researchers also categorized tasks based on automation potential: Warszawski identified ten "basic activities" that can be performed by robots (Warszawski 1990); Tucker identified 17 distinct automatable areas (Tucker 1988); and Kangari created a "robotics feasibility" score by assessing 33 processes in a task (Kangari and Halpin 1989). Everett proposed a nine-level hierarchical system for classifying all tasks (Everett 1990). Specifically, construction field operations follow a seven-level hierarchical system, where "project" is the highest level, and "cell", referring to the fiber muscle and nerve stimulated to complete a given action, is the lowest (Everett 1991).

Recently, some classification efforts have shifted towards the potential of using AR for construction tasks. Unlike robotics and automation, AR was found to be a better fit for information intensive tasks (Shin and Dunston 2008; Wang and Dunston 2006). Dunston and Wang adapted Everett's hierarchical classification into a five level system, and concluded that the lowest two levels, "composite" and "primitive" tasks are the most appropriate for AR implementation (Dunston and Wang 2011). Shin and Dunston studied a comprehensive list of construction tasks and theoretically assigned potential AR use cases, including the use of AR for layout tasks (Shin and Dunston 2008). Because of recent advancements in simulation technologies, more robust, data driven classification systems have arisen. Some research has used smartphone sensors to identify and recognize construction tasks that often produce distinct data signatures (Akhavian and Behzadan 2016) and utilized machine learning algorithms to better recognize and classify tasks through the collected data (Akhavian and Behzadan 2018). Different software and coding solutions, such as Dynamic Time Warping techniques, are used to increase the accuracy of the recognition and classification processes (Kim et al. 2018).

Although some research suggests that complexity does not hinder performance when using AR for assembly tasks (Radkowski et al. 2015), "mental workload" was mentioned as a limitation for the potential of using AR for a given task (Dunston and Wang 2011). The research did not examine the specifics of task variations might affect the use of AR. This research fills this knowledge gap, examining the effect of some varied task attributes associated with construction layout task on the performance of practitioners using AR.

4.3 Methodology

The researchers collaborated with a large electrical subcontractor in the Southwest region of the United States. All models were created by the partner company's design team and all the participants were then current practitioners in different roles within the company. The experiment took place in an emptied conference room at the company's regional headquarters, representing a safe environment where participants can work and be effectively monitored.

4.3.1 Model Variations and Preparations

To test electrical construction layout tasks with AR, several electrical device layout designs were created based on the selected conference room location. The conference room had non-orthogonal walls, making it especially challenging for electrical device layout processes. Figure 1 shows a plan view of the room. Three walls were used for layout in this case, with the devices shown in the figure, and the other portion of the room was used by the researchers to monitor participants and run the experiment.

Although many factors may technically affect the performance of the AR device, the researchers were interested in testing the same variations that currently affect point layout task performance when using paper plans. Several project managers and BIM modelers from the partner company were interviewed, and three possible variations became apparent: (1) variation in elevation of the devices compared to all devices at the same elevation, (2) low device density compared to high device density in a room and (3) laying out different types of devices (i.e. switches and receptacles) compared to laying out only one type of device.

Four different designs were generated, and the different variables were strategically introduced to allow pairwise comparisons to isolate their effects. Table 22 summarizes the four designs and their various characteristics. All designs were originally created by the partner company using Revit, but the researchers received the models in a 3D AutoCad format.

Table 22: Summary of Room Designs and Factors in Each Design

Design	Elevation of Devices	Number of Devices	Variety of Devices
1	Same elevation	5	Different Devices
2	Different Elevations	5	Different Devices
3	Different Elevations	10	Different Devices
4	Different Elevations	5	Same Device

The models received included all 3D geometric content, but did not include any embedded information from the original BIM, such as the cost of each element. The room walls, flooring, ceiling, ceiling light fixtures, doors and windows, in addition to the electrical devices to be laid out, were all in the model. Figure 13 shows an isometric view of the received model. The model size varied between 252 Kb and 556 kb, depending on the number of electrical devices in each model.

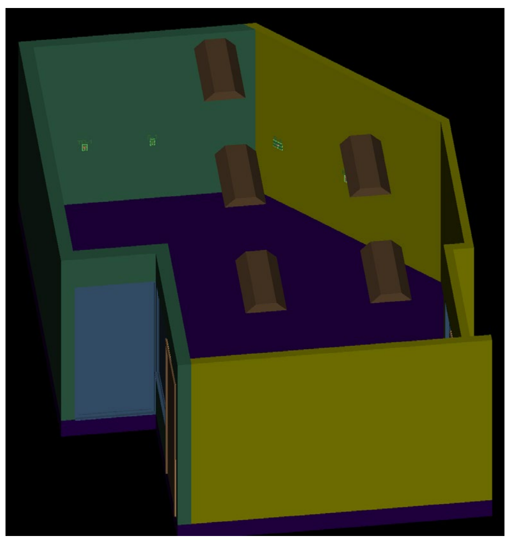

Figure 13: Design in AutoCad as Received from the Partner Company

For the point layout task, only the electrical devices were required to be viewed by the participants through AR, since all other elements physically exist in the space. For example, showing the walls would simply overlay the virtual walls directly on top of the existing walls, which may be disorienting and would further load the AR device.

Therefore, all unnecessary elements were removed. Furthermore, the shapes that represent the electrical devices are complex on the "back side", made up of 182 vertices, but are invisible by the user. The shape was simplified to only show the front plate with a cross sign on its center. The cross sign and the name of the device, which is located above the face plate, were both colored in red to create a contrast to the green front plate, enhancing visibility through the AR headset. Other than these minor changes, the original model content was unmodified from what was created by the partner company. Specifically, no content was added and the points were not moved by the researchers. Figure 14 shows the remaining portions of the model received.

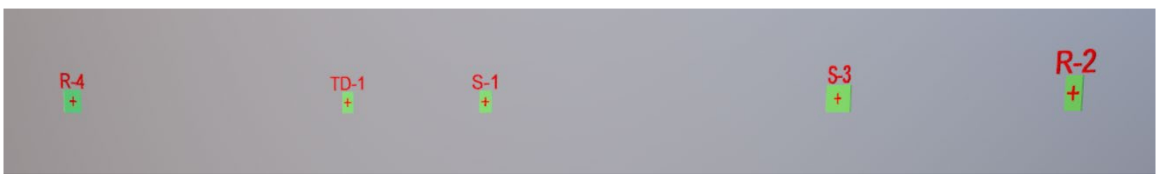

Figure 14: Design after Removing Unnecessary Elements

To be viewed through the AR device, the models must be exported from the CAD format to a universal 3D format. FBX format was used in this research because of its broad compatibility, specifically with the game engine used for deployment on the AR device. The exporting method ensured that all shape, texture and color information was retained.

When exporting from CAD to FBX, the exported model would contain all the content from the CAD model, in addition to an empty virtual point located at the origin point. Essentially, if the content of the CAD file is far from the origin point, the output FBX would be spatially as large as the distance between the model and origin point, which in turn overloads the AR device leading to numerous stability issues (Chalhoub et al. 2018). Thus, before exporting, to create the smallest possible model, the content is moved to the origin.

4.3.2 AR Preparation

The AR device chosen by the researchers was the Microsoft HoloLens, a self-contained computing unit. The unit included 12 total sensors, allowing it to scan and interpret spaces around it. It also has “2 HD 16:9 light engines, with 2.3 M total light points and more than 2,500 light points per radian” to display virtual content, positioned relevant to the scanned space (“HoloLens hardware details”).

In order to correctly display the models on the AR device, three commercial software suites were used: (1) Unity Game Engine, (2) Vuforia SDK and (3) Microsoft Visual Studio.

The Unity game engine is an all-in-one editor, that primarily enables game development on a variety of software and hardware, including the Microsoft HoloLens (“Unity - Products”). For development, Unity relies heavily on imported content using FBX and provides an Application Programming Interface (API) accessible through JavaScript and C#. Previous visualization efforts in civil engineering research have relied on Unity (Ayer et al. 2013; Keough 2009; Pauwels et al. 2011), proving its suitability for construction focused applications.

The Vuforia Software Development Kit (SDK) is a package that can be installed inside Unity. Vuforia enables advanced computer vision, which allows a broad range of target devices to recognize everyday images and objects using an ordinary built-in camera. A website interface manages a “targets” database, the given set of markers required to be recognized. Once a marker is recognized, the device would display the correct model relevant to the location of the marker in space. Finally, Microsoft Visual Studio compiles and debugs the application created, and then deploys it to the HoloLens. Once deployed, the application is fully contained inside the HoloLens, and does not require external computing power or connection to function.

4.3.3 The Experiment

The experiment took place over the span of six business days, spread evenly over two weeks. Four to six participants completed the experiment each day. Before starting, the participants were told they would be participating in an electric device room layout exercise using AR technology, but were not given any further information.

Prior to starting the experiment, each participant received two copies of a consent form and a pre-session questionnaire. One signed copy of the consent form was collected, and the other was left with the participant. The pre-session questionnaire asked general questions about each participant, including age, years of experience, average time spent doing point layout, highest education level, prior experience using AR and VR technologies and the participant's perception towards AR use on a construction site. Definitions of point layout and AR were presented at the beginning of the questionnaire for the participants' reference.

In practice, device locations are often indicated with the use of a marker pen or spray paint. Since the experiment was completed in a finished conference room, sticky notes were used as a non-permanent mark of the location of a given point. Figure 15 shows a sample sticky note. To correctly lay out a point, the participant would have to line up the cross on the sticky note to the cross on shown on the device in the model. This allowed the researchers to quickly reset the room to an empty canvas between the different exercises and participants.

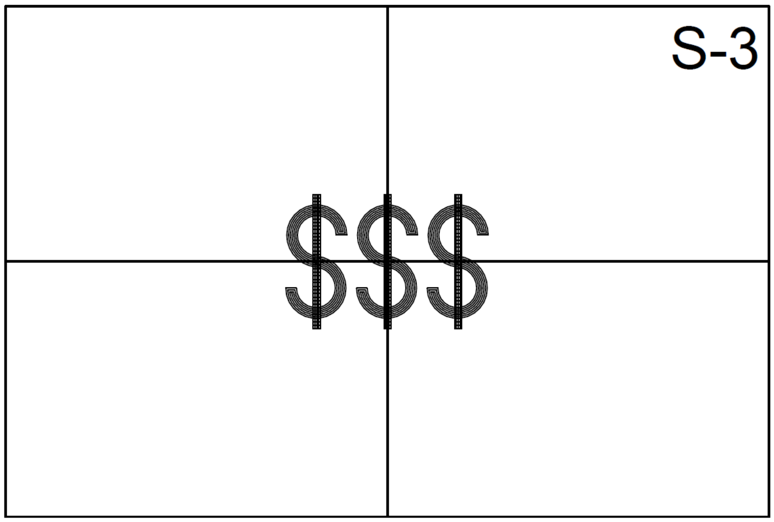

Figure 15: Sample Sticky Note (Device S3)

Each participant laid out the room using all four designs, but the order of the designs was randomized to mitigate the learning effect. For each run, the content was loaded onto the AR device by the researcher, and the participant was assisted in wearing the device. Once the participant acknowledged that they were able to see the content, they were handed a set of sticky notes corresponding to the devices in the model that they are laying out. The entire session was video recorded from multiple angles to study the behaviors demonstrated during the activity.

Once the layout task was complete, the participant was assisted in removing the headset, and they were handed a NASA-TLX questionnaire to fill. Meanwhile, the researchers measured distances from the center of sticky notes to the walls and floor using a laser measuring tape, quoted by the manufacturer to be accurate to the nearest millimeter. The measurements create a coordinate system for each laid out point, comparable with the coordinate system of the points in the model, enabling a one-to-one accuracy comparison. When the measurements were taken and the NASA-TLX was completed, all sticky notes were removed from the walls, the next design model was loaded, and the process was repeated until all designs were laid out. When the last design was laid out, in addition to the NASA-TLX, the participant received a post-session questionnaire including questions about their comfort level and thoughts for other high-potential applications for the technology in electrical construction based on their experience.

4.3.4 Analysis Approach

The researchers considered three metrics to assess the performance of the AR solution proposed: accuracy, time, and mental workload.

4.3.4.1 **Accuracy**

The main purpose of the layout task is to lay out the points accurately where they were designed. Specifically, in electrical construction, depending on the type of the project and contract, accuracy tolerances can be as low as $1/8^{th}$ of an inch (0.003 meter) from intended placement. Each designed and laid out point were assigned a set of coordinates, that represent the distance from a wall on the X-axis and the distance from the floor on the Y-axis. Separate differences between the designed and actual point placements along each axis were calculated. The overall distance (hypotenuse) from the targeted point can be computed using the X and Y values.

4.3.4.2 **Time**

The researchers used the videos recorded of the activity to accurately determine the start and end time of each task. The start time was determined as the moment the participant declared he or she can see the content through the AR device, and the end time was determined when he or she declared they were done with the layout task. All times presented in this paper are in seconds.

During some tasks, the participants had technical difficulties viewing the content. Specifically, the content would either shake significantly because of poor spatial tracking, or the application would close and the content would no longer be viewable. In these instances, the participant had to take off the headset, and the researcher had to reset it. The task times presented in this paper include both times with and without technical difficulties. It is reasonable to expect those times to be reduced as practitioners become more accustomed to using and fixing the device when needed and as the technology matures, but both datasets are included to increase the fidelity in reporting the findings.

4.3.4.3 **NASA-TLX**

The collected NASA-TLX questionnaires were digitized and stored in spreadsheet files. Each entry had the responses of the user, the model design it corresponds to, and the order in which that design was laid out for each user. The responses were analyzed using paired statistical analysis to adjust for personal bias from the responders. Additionally, the responses were also analyzed linearly to investigate whether using the AR tool would change the perceived cognitive workload.

4.4 Results & Discussion

This paper aims to quantify the effect of the varying task attributes on the performance of the participants when using AR for electrical device layout tasks. In the experiment, each participant laid out four different layouts with different factors included in each design. The experiment allows the pairwise comparison of designs to isolate the effect of each task attribute. Table 23 below summarizes the factors included in each design.

Table 23. Summary of Effect Studied and Relevant Designs

Effect Isolated	Design 1	Design 2	Design 3	Design 4
Elevation Difference		X	X	X
Number of devices			X	
Diversity of Devices	X	X	X	

Comparing design 2 and 3 isolates the effect of having increased number of devices. Finally, comparing designs 2 and 4 isolates the effect having different devices during the layout tasks.

4.4.1 Accuracy

The accuracy was studied along the X-axis and Y-axis separately. Table 24 summarizes the overall accuracy along the X-axis and Y-axis in both data sets. All measurements shown are in meters.

Table 24. Overall Accuracy in Each Design for the X-axis and Y-axis

	Design 1	Design 2	Design 3	Design 4
X-Axis	0.0302	0.0369	0.0357	0.0311
Y-Axis	0.0253	0.0268	0.0344	0.0271

In order to utilize suitable comparative statistical tests, the Shapiro-Wilk test of normality test was used on all datasets tested. The Shapiro-Wilk test of normality is one statistical test that determines whether the population of a dataset follows a normal distribution: the null hypothesis assumes the population is normal, and if the returned *p-value* is less than 0.05, the null hypothesis is rejected and the population is considered not normally distributed. Table 25 below summarizes the *p-value* for the Shapiro-Wilk test of normality run on each of the cases above. Most of the data was not normally distributed, except for the Y-axis accuracy for designs 2 and 3.

Table 25: Summary of the Shapiro-Wilk Test on the Datasets

	Design 1	Design 2	Design 3	Design 4
X-Axis	4.744e-6	2.105e-9	8.937e-5	6.736e-5
Y-Axis	2.948e-5	0.1404*	0.8986*	1.152e-8

* indicates non-significant values; data is normally distributed

4.4.1.1 Task Variations effects

Along the X-axis, none of the task variations had any effects on accuracy. Along the Y-axis, the increased number of devices affected the accuracy. As discussed above, designs 2 and 3 are compared to isolate the effect of increased number of devices and their accuracies along the Y-axis are normally distributed (Shapiro-Wilk test *p-value* = 0.1404 and 0.8986, respectively). A paired t-test can be used, and Table 26 presents the results of the paired t-test. The paired t-test compares the performance of the same set of users under two different circumstances, and if the returned *p-value* is less than 0.05, the performances are considered statistically different. When there are only 5 devices in a room, device placement is 0.00762 meter (22%) more accurate along the Y-axis compared to when a room has 10 devices, and the difference is significant at the 95% confidence level (*p-value* = 0.01121).

Table 26: Summary of the Paired T-test on Y-axis Accuracy

Testing	Y-axis accuracy (Meter)		Difference (Meter)	t-value	p-value
	Design 2	Design 3			
Number of Devices	0.0268	0.0344	0.00762	2.7225	0.01121

4.4.1.2 **Distance from paper marker**

The application developed for this experiment utilized a marker-based approach to accurately place the digital content on site, using the process described in detail in (Chalhoub et al. 2018). When using marker-based AR, the device stabilizes the content based on the location of the marker. However, as the user gets farther from the marker, the fidelity of the placement of the digital content may also change. The relation between the distance of the point from the marker and the overall point accuracy is studied.

A linear regression approach was used to explain the relation between the distance from the marker and the accuracy of the point placed. First, the distance to the marker was used to explain the variation in accuracy; however, when the model was further analyzed, a power transformation was deemed required on the regressor. The model presented in this paper uses the distance to the marker squared as the predictor to explain variation in accuracy. Figure 5 shows a graph of the scatter plot of each point placed, where the Y-axis represents the overall accuracy of the point placed and the X-axis represents the distance from the marker squared, and the regression line passing through them. All distances are in meters.

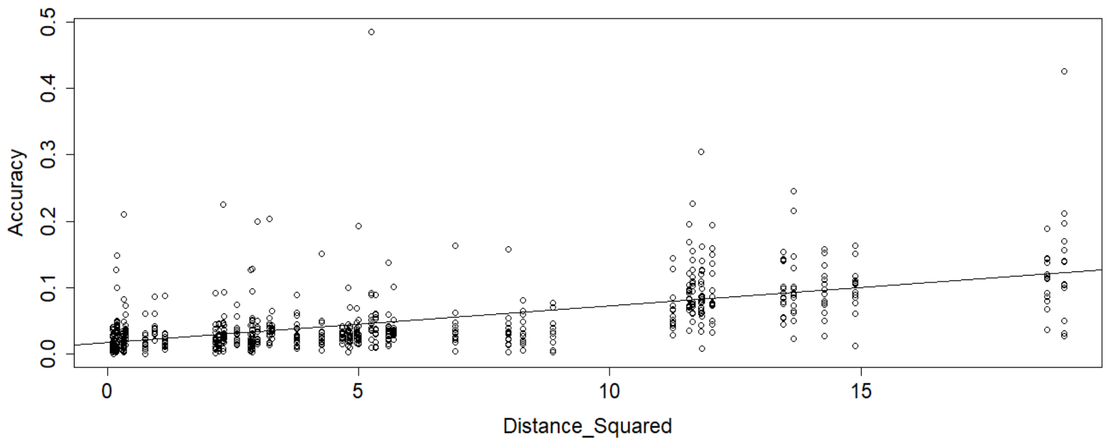

Figure 16: Plot of Accuracy of Points Vs the Squared Distance from the Marker to the Device

During the experiments, some participants mentioned that the model had significantly shifted from its original location, and he or she either used the new points locations or tried to place the points by memory and correlation to other point. These cases have created several outliers that are clear in Figure 16. However, due to the high number of observations, the data was not adjusted in any way and the outliers did not affect the accuracy findings significantly. Table 27 summarizes the regression and Table 28 presents the corresponding ANOVA table.

Table 27: Summary of the Linear Regression

	Coefficient	Standard Error	t-value	p-value
Intercept	0. 018162	0.0021517	8.441	<2.2e-16
Distance to Marker ^2	0.005508	0.0002823	19.508	<2.2e-16

Table 28: ANOVA Associated with the Linear Regression

	Degrees of Freedom	Sum of Squares	Mean Sum of Squares	F-value	p-value
Distance to Marker ^2	1	6.2085	6.2085	380.56	<2.2e-16
Residuals	732	11.9419	0.0163		

A positive coefficient of the square of the distance to the marker indicates that the distance between the placed point and its intended location increases as the distance from the marker increases, and the relation is significant (*p-value* <2.2e-16). The Pearson correlation factor between the predictor and variable is 0.5849, and R-square is 0.3421. The regression is significant: The *F-value* is 380.56 with a corresponding *p-value* < 0.05.

While the regression would not be necessarily appropriate to predict the exact placement errors of points in future layout jobs when using AR, given the high sample size (734 points), decreased accuracy levels at distant locations from the marker should be expected to follow a parabolic curve in future implementations of this type and generation of technology.

4.4.1.3 **Effects of repetition**

The accuracy of point placement on either axis did not change as the participant went through the four exercises. Table 29 shows the mean accuracy along each axis for the different runs (in meters), and the significance of the paired Mann-Whitney comparison of each run and the one that precedes it. On average, accuracy ranged between 0.024 and 0.0358 meter, and all *p-values* are higher than 0.05, indicating no significance at the 95% confidence level.

Table 29: Cumulative Paired Mann-Whitney Test on the Consecutive Layout Runs Concerning Accuracy on X-axis and Y-axis

Run	X-Axis			Y-Axis		
	Accuracy	Cumulative V-value	Cumulative significance	Accuracy	Cumulative V-value	Cumulative significance
1	0.0344	N/A	N/A	0.0268	N/A	N/A
2	0.0304	318	0.1757	0.0310	190	0.2639
3	0.0334	281	0.3285	0.0311	172	0.2206
4	0.0358	161	0.9789	0.0244	144	0.6338

4.4.2 Time:

The effect of varying task attributes on time to complete the layout of the devices was computed. Because some designs have different numbers of devices, the overall time was divided by the number of devices in each run, and the times presented thereafter are times per device in seconds. Table 30 summarizes the Shapiro-Wilk test of normality findings. Since the data is not normally distributed, the paired Mann-Whitney test was used. The paired Mann-Whitney test is similar to the paired t-test: it compares the performance of the same group under two different circumstances, and if the returned *p-value* is less than 0.05, there is a statistically significant difference. However, unlike the paired t-test, the Mann-Whitney does not require normality of the datasets, and so it was used when the samples where not normally distributed.

Table 30: Summary of Shapiro-Wilk Test on Time Datasets

Case	Design	W-value	P-value
With Technical Difficulties	Design 1	0.66201	2.463e-7
	Design 2	0.70821	2.765e-6
	Design 3	0.55525	2.165e-8
	Design 4	0.59086	7.981e-8
Without Technical Difficulties	Design 1	0.65501	1.971e-7
	Design 2	0.68395	1.248e-6
	Design 3	0.54612	1.706e-8
	Design 4	0.54228	2.217e-8

When the devices were designed at different elevations and when the devices designed were themselves different, there was a significant difference in the time required to layout each time. The findings are described below. Notably, the layout time per device did not significantly vary when more devices were in the room (*p-value* = 0.1414).

4.4.2.1 **Effect of Elevation Difference**

Time to complete designs '1' and '2' were compared to quantify the effect of difference in devices' elevation on the layout times using AR. Table 31 summarizes the findings of the test for both times with and without technical difficulties.

Table 31: Summary of Mann-Whitney Paired Test on Effect of Elevation Difference

Cases	Mean of Design 1 (seconds)	Mean of Design 2 (seconds)	Difference	V-value	P-value
With Technical Difficulties	23.54	32.17	8.63	52	0.0003598
Without Technical Difficulties	23.37	31.49	8.12	53	0.0003907

In both cases, the participants were on average 8 seconds faster per device laid out when all devices were at the same elevation, compared to when they were at different elevations, and the difference is significant at the 95% confidence level (*p-values* < 0.05). In effect, splitting a design into separate layouts where all devices are at the same height may reduce the time to finish the overall task faster.

4.4.2.2 **Effect in variability of devices**

Time to complete designs '2' and '4' were compared to quantify the effect of variability of types of devices used on the layout times using AR. Table 32 summarizes the findings.

In both cases, the participants were around 7 seconds faster per device when all the devices in the layout are the same, compared to when different devices are in each room. The difference is significant at the 95% confidence level (*p-values* < 0.05). Similar to the case of elevation difference, splitting a design into separate layouts where all devices are the same type may enable faster overall task completion.

Table 32: Summary of Mann-Whitney Paired Test on Effect of Device Diversity

Database	Mean of Design 4 (seconds)	Mean of Design 2 (seconds)	Difference	V-value	p-value
With technical difficulty	24.88	32.17	7.29	103	0.02346
Without technical difficulty	23.61	31.49	7.88	96	0.0153

4.4.2.3 **Effect of Repetition**

As previously mentioned, each participant laid out four separate room designs. It is possible that the participants got more comfortable with the AR device and layout task after the first use and may perform better in the second or third runs. Table 33 summarizes the performances of the participants and the comparisons between the first and second, second and third, and third and fourth runs using the paired Mann-Whitney test for the datasets with and without technical difficulties.

Table 33: Cumulative Paired Mann-Whitney Test on the Consecutive Layout Runs Concerning Time per Device

Cases	Run	Mean Layout Time per Device (seconds)	Cumulative V-value	Cumulative Comparison significance
Case 1: With Technical Difficulties	1	33.57	NA	NA
	2	26.48	415	0.000644
	3	25.12	309	0.1191
	4	24.33	146	0.6668
Case 2: Without Technical Difficulties	1	32.55	NA	NA
	2	25.96	418	0.0004954
	3	23.95	331	0.04265
	4	24.29	121	0.2699

Table 13 summarizes the findings of the cumulative Mann-Whitney test on both datasets. Generally, the participants tend to perform better in each subsequent layout task compared to the one that proceeds it. When considering the dataset with technical difficulties, the performance gains are significant at the 95% confidence level only between the first and second runs (*p-value* = 0.000644). When considering the dataset without technical difficulties, the performance gains are significant in both the second (*p-value* = 0.0004954) and third (*p-value* = 0.04265) runs. Generally, the results indicate that the performances of the participants tend to be enhanced as the participants get more familiar with using the technology.

4.4.3 Cognitive workload:

When considering cognitive workload, each of the six NASA-TLX questions were compared separately. The only difference was between design '2' and '3'. Specifically, participants required an average of 5.43 extra "effort" points to layout 10 devices compared to when laying out 5 devices, and the difference is significant (*p-value* = 0.02663). Table 34 summarizes the findings of the paired Mann-Whitney test. This finding is largely intuitive, as more effort would likely be required to layout more devices.

Table 34: Summary of Mann-Whitney Paired Test on Effort Factor in the NASA-TLX Questionnaire

Mean of Design 3	Mean of Design 2	Difference	V-value	p-value
23.52	18.09	5.43	34.5	0.02663

Interestingly, none of the cognitive workload factors changed significantly as the participants repeated the tasks. Overall, perceived cognitive workload is independent from repetition and varying task attributes presented in this experiment.

4.4.4 Limitations

This research explores the effects of varying task attributes on performance when using AR. The limitations of this work are related to the technology, the task attributes studied, and the environment where the work took place.

First, this experiment is based on commercially available hardware and software solutions. The aim of the researchers was not to create a new AR device or a new software suite to display virtual content, but rather to measure the capabilities and limitations of what current technology can afford to any interested party. It is expected that new generations of hardware and software will be developed, and the accuracy may be enhanced. However, the human behaviors involved, especially relating to how participants dealt with more complex situations, is less likely to change.

Second, not all perceivable task variations were studied. The researchers based the designs on discussions with stakeholders from the partner company, in order to quantify the effects of relevant factors. The factors represent the opinions and experience of individuals from a single company in one engineering discipline, and other individuals may consider other task variations, and may require separate studies to understand their effects. Furthermore, when AR becomes more commonly used in the industry, task variations uniquely related to AR may emerge and require separate exploration.

Finally, a conference room was used for the experiment. While the researchers aimed to mimic as closely as possible the layout tasks required on a typical construction site, they did not want to conduct the experiment on an active site because of potential safety concerns. Active construction site conditions, such as varied lighting, noise, congestion, heat or cold, and other conditions may not only affect the AR device, but also the associated human behavior as well. Many of these factors already present challenges to professionals when using traditional paper plans, but their effect on AR remains unknown.

4.5 Conclusion

The work presented in this paper explores the effects of changing various task attributes on the performance of current generation AR hardware and software. The researchers chose an electrical device layout task to complete using AR, and strategically introduced three task attributes variations in four designs: (1) number of devices laid out, (2) difference in elevations of laid out devices, and (3) diversity of the type of devices laid out. Practitioners from the partner company participated in this experiment and completed all four designs in randomized orders. The practitioners also completed NASA-TLX after completing each design to measure their perceived cognitive workload.

First, the accuracy of placement of the points was measured. There is a mild positive correlation between the accuracy of placement of the points and the distance from the paper marker, placed at the center of the marker (r=0.5849). Points were also laid out more accurately when there were fewer devices in a room compared to when there are many devices. Rooms with more devices also required a significantly higher effort as reported by the NASA-TLX.

The layout completion time per device was computed for each case. In general, the layout process was faster when designs were less complex. Participants required nine seconds less per device when all devices were at the same elevation, and 8 seconds less when devices were all similar and not of different types. Moreover, participants performed significantly faster in the second run compared to the first and also faster in the third compared to the second.

The contribution of this paper is in identifying and validating the attributes of a construction layout task that make it advantageous or disadvantageous for using current AR devices with industry practitioners. These findings will allow practitioners to strategically leverage AR, or avoid its use, to support the needs of a given layout task. This enables managers to optimize the technology planning and implementation in construction tasks. As new AR technologies become more prevalent and powerful, the findings from this work may further guide the industry in planning for new use cases and implementation processes.

4.6 Acknowledgments

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CHAPTER 5

DEVIATION IDENTIFICATION AND MODEL RECONCILIATION USING AUGMENTED REALITY

5.1 Introduction

Project models and documents are key deliverables to Facility Managers (FMs) at the end of a construction project and are particularly important for the long-term success of any project. Research suggests that 70% of current buildings will be operational in 2050 (Kelly 2010), but most owners are dissatisfied with traditional closeout documents and as-built plans (Clayton et al. 1999). This poses potential long-term challenges to building operators and FMs. Currently, about 4.8 billion dollars are spent yearly to ensure that available information matches what was actually built (Gallaher et al. 2004). These trends highlight the need to find better ways of turning over information to owners to ensure that the information accurately represents what was constructed.

During the design and construction phases, Building Information Modeling (BIM) is being increasingly used by architects and constructors (McGraw-Hill Construction 2014). While its use is less common during the operation and facility management phases of a building project, some researchers suggest that effective BIM use during operation could provide benefits related to process, workflow, and safety of operations and maintenance (Love et al. 2013). Others developed a tool to enable facility managers to better understand the value of BIM to their work, and proposed using it as a learning mechanism to continuously question the value BIM is providing (Love et al. 2014). Currently, several commercial software suites target the use of BIM for FMs (Kang and

Hong 2015). Additionally, Construction Operations Building Information Exchange (COBIE) has been created as a data format to allow the exchange of construction information to support the operation phase (East 2007). COBIE is being adopted by FMs for enabling increased operational efficiency (Sullivan et al. 2010), especially when implemented early on in the design and construction phases (Lavy and Jawadekar 2014). While not all of the information available in a typical BIM is essential to facility managers, accurate geometrical representation is of particular importance (Mayo and Issa 2014). Currently, most field verification processes collect a point cloud of the building using photogrammetry (Klein et al. 2012) or laser scanning (Boukamp and Akinci 2007), and compare this content to the model, but these methods can be time consuming and labor intensive (Cho et al. 2002).

Augmented Reality (AR) is a technology that allows the viewing of both real and virtual content in the same field of view (Azuma 1997). AR use has been theorized and applied in the construction industry, including during construction (Chalhoub and Ayer 2018a), pre-construction (Carozza et al. 2014) and project monitoring (Zollmann et al. 2014). A recent review of AR applications revealed interest from the different project stakeholders for non-immersive visualization technologies to enhance progress monitoring and defect detection processes (Rankohi and Waugh 2013). AR can enable users to visually compare the model to the built environment and determine potential deviations, which may be able to save time for scanning and data processing compared to current photogrammetry and laser scanning practices. Furthermore, prior research has shown that novices and experts tend to perform and behave similarly when completing certain construction tasks using AR (Chalhoub et al. 2019), creating an opportunity to leverage individuals with varied levels of experience in supporting model-verification checks.

This research investigates the performance advantages and disadvantages of using AR to verify deviations between the model and the built environment among Mechanical, Electrical and Plumbing (MEP) systems installed in a ceiling plenum when used by graduate students with varying levels of industry experience. Specifically, the paper answers the following questions: To what extent does AR enable deviation detection in a complex environment? What are the types of deviations that can be detected by users of AR? And what is the frequency of false positive observations when using AR for this type of deviation detection? The findings will enable practitioners to integrate AR technology into field verification processes in ways that directly leverage performance evidence. Furthermore, the findings highlight opportunities for future researchers to target specific performance improvements to AR devices to support field verification (and related) use-cases.

5.2 Background

5.2.1 Building Information Modeling

Building Information Modeling (BIM) is the digital representation of the physical and functional properties of a building (National Institute of Building Sciences (NIBS) 2014). BIM is being increasingly used during the different construction phases, enabling contractors to reduce errors and omissions, collaborate with design firms, reduce rework, and reduce overall cost and duration of a project (McGraw-Hill Construction 2014).

When a BIM is turned over at the end of the construction phase, it can enable owners to effectively access design and construction information, and also to document changes to the building throughout its life cycle (Vanlande et al. 2008).

For building operation, BIM can help to locate and manage building components (Mallepudi et al. 2011) and can facilitate space management (Bansal 2011). Using Radio Frequency Identification (RFID) in conjunction with BIM enhances accessibility to accumulated lifecycle information (Motamedi and Hammad 2009). Recognizing its many benefits, owners and facility managers are increasingly asking for accurate models of the project after the construction phase (Computer Integrated Construction Research Program 2011). While these potential benefits to using BIM for FM are becoming increasingly well documented, they are generally dependent on having accurate BIM information turned over to owner teams by construction teams at the conclusion of projects. This process of turning over accurate information can pose practical challenges.

Contractors have been increasingly leveraging BIM during construction for applications such as creating accurate geometric representations of building parts in an information rich environment, managing cost control processes, and monitoring environmental data (House et al. 2007). Currently, most applications are focused on deriving value from BIM during the construction phase of the project. Developing accurate as-built BIM content requires contractors to thoroughly check what was built compared to what was supposed to be built, which traditionally is very resource intensive. The next section details the different deviation detection and model rectification mechanisms used.

5.2.2 Field Verification and Deviation

The aim of field verification is to reconcile the model and the built environment. Ideally, these environments should match exactly, but deviations made during construction may introduce discrepancies between the BIM and physical spaces. Typically, one of various reality-capture technologies is used to record the state of the built environment in order to identify the location of deviations between the BIM and physical building elements. This process involves the generation of a point cloud of the built environment, often using laser scanners (Klein et al. 2012), photogrammetry (Lato et al. 2013), or videogrammetry (Brilakis et al. 2011) technologies. Once point clouds or models are created that represent the actual built conditions of a project, they are compared with the original BIM for construction. This comparison can be supported through the use of technology (Bosché et al. 2015), but the determination of how to reconcile differences between BIM and actual conditions is typically done by a human decision-maker. Depending on the type of deviation and phase of construction, either the model is adjusted, or the built element is reworked. In response to the need for effective field verification technologies to support decision-makers, researchers have explored various strategies to improve the technologies and processes related to this task, which are detailed in the subsequent paragraphs.

Photogrammetry is a technology that compares two overlapping still images to create a stereo-model by calculating light rays (Lato et al. 2013) enabling a portable sensing of the current surroundings (Zhu and Brilakis 2009). Essentially, the photos are used to create low-density 3D point clouds of areas of interest. Researchers have used site pictures to recreate 3D models and compare them to the planned models for construction progress monitoring (Memon et al. 2005). Others have used images taken from Unmanned Arial Vehicles (UAV) to recreate low cost 3D as-built models of electrical stations (Rodriguez-Gonzalvez et al. 2014). Furthermore, researchers have used single frame photos of 3D objects to identify building defects (Lee et al. 2012). Videogrammetry is a similar technology that uses a video feed instead of overlapping pictures to recreate 3D models (Brilakis et al. 2011). However, research suggests that photography on site may not always lead to sufficiently accurate 3D point cloud models (Jadidi et al. 2015) and current generation photogrammetry technology may be inadequate for infrastructure modeling (Bhatla et al. 2012).

Depth sensing cameras have also been used to evaluate deviation between planned and constructed elements. Researchers have used a two-step depth sensing algorithm to recreate a 3D model from the associated imagery, compare that content with BIM, and do a discrepancy check to identify deviations (Wasenmuller et al. 2016). This technique has also been used with a moving camera setup with both 2D and depth sensing cameras (Kahn et al. 2010). In an industrial setting, depth sensing cameras are used to detect and quantify differences between assembled products and a reference 3D model for one model in a fixed area (Kahn et al. 2013).

Another technology used to acquire point clouds is laser scanning, otherwise known as Light Detection And Ranging (LiDAR). Laser scanners are capable of registering millions of points in a short period of time (Klein et al. 2012) that can be imported into Computer Aided Drawing (CAD) environments (Jaselskis et al. 2005).

Numerous software suites have been developed to automatically detect relevant geometries, such as cylinders and beams from point clouds (Ahmed et al. 2014; Wang et al. 2015), but more work is required to optimize the software for the different uses (Pətrəucean et al. 2015). Laser scanners are usually very accurate (Tang and Akinci 2009), subject to environmental parameters and the properties of the materials of the objects being scanned (Becerik-Gerber et al. 2011). The main limitations of current laser scanning technologies are cost and training time (Remondino et al. 2005). Furthermore, laser scanned point clouds can require more time to analyze compared to photogrammetry (Golparvar-Fard et al. 2011). Hybrid photogrammetry and laser scanning based systems have been suggested, but could still require significant time and effort for accurate data capturing (Son et al. 2015).

In general, reality-capture technologies rely on digitizing the built environment and comparing the digital representation with the designed BIM. Because of the capital and time resources required for capturing field conditions, one of the significant challenges related to field verification practices is determining which areas are required to be scanned and compared (Bosché et al. 2014). Since the scanning and data processing can be time consuming, reducing the areas required for scanning could reduce overall time and cost, especially when one task is being delayed while analyzing the reality-capture models. Augmented Reality provides a theoretical benefit by enabling individuals to view as-planned BIM content over their view of as-built physical spaces. In premise, this technology could enable individuals to either verify the accuracy of field conditions without a separate reality-capture model, or it could at least help to define potential discrepancies that warrant subsequent reality capture approaches for accurate viewing and comparison. This opportunity for more streamlined field verification through augmented reality motivates this work.

5.2.3 Augmented Reality

Augmented Reality (AR) is a technology that allows the viewing of both virtual and real content as if they coexisted in the same field of view (Milgram and Kishino 1994). Recent research has explored the use of AR for construction planning (Yabuki et al. 2011; Zhang et al. 2018) and operation and maintainability by providing relevant information intuitively throughout a project lifecycle (Lee and Akin 2011). The use of AR for quality control and assurance, and specifically deviation detection has also been researched, as detailed in the following paragraphs.

In non-construction industries, AR has been utilized to identify discrepancies between as-planned and as-built pipe placement in ship construction (Olbrich et al. 2011) and to compare 3D mockups to CAD 3D models in the automotive industry (Webel et al. 2007). Several researchers attempted to use AR for defect identification in the built environment. Kwon et. al developed a handheld mobile device-based application that overlays the BIM on top of a Reinforced Concrete formwork to check for missing steel reinforcement (Kwon et al. 2014). Dunston used a camera based AR solution to replace a Total-Station to check the deviation and angle of steel columns (Shin and Dunston 2009). Zhou used AR onsite to rapidly check segment displacement during tunneling construction and noted that it is generally faster to use AR than traditional inspection methods (Zhou et al. 2017). In these studies, AR was used to detect specific deviations in specialty construction elements, not deviations of overall constructed systems compared to designed models. Others have attempted to use images to recreate a 3D model and compare the as-built to the CAD model in an AR environment (Georgel et al. 2007; Langer and Benhimane 2010). Research has also highlighted the need for technical advancement in both tracking and viewing technologies to better enable onsite AR-based inspection (Shin and Dunston 2010). In response to this, new registration mechanisms that do not require markers or GPS systems were developed (Kopsida and Brilakis 2016b).

Prior research suggests that AR can be used to identify some deviations between planned and built elements in experimental, controlled settings, or to identify specific deviations in specialized elements. In this paper, the authors use AR to enable users to identify numerous types of deviations in a common field verification use-case related to the comparison of built MEP systems in a ceiling plenum space and the intended BIM. The experiment utilizes current generation AR devices to display the BIM content in the field. The new knowledge provided by this paper relates to identifying the types of deviations that users can identify with current generation AR for performing field verification use-cases in an actual built environment.

5.3 Methodology

This research aims to understand the types of deviations that can be detected by an AR user when comparing built MEP systems to the intended BIM for field verification. To explore this topic, a fully constructed MEP system was modeled, and several deviations were intentionally introduced to the model to simulate the types of differences that may exist between model and field in practice. The researchers strategically chose a built environment with exposed MEP systems to allow users to see it with the unaided eye, similar to how construction professionals might check MEP systems in a plenum space prior to covering them with finish materials. Using AR, the modified model was then overlaid on the constructed system, and participants were instructed to find the deviations. The types of errors, observations, and false positives captured by the practitioners were recorded and analyzed. The following sections detail each step of the experiment methodology.

5.3.1 Partner company & Model Development

The researchers partnered with a large electrical subcontractor in the southwest region of the United States for developing the materials required for this experiment. The partner company regularly provides as-built BIM content as part of their close-out deliverables. To support this process, the company often uses laser scanning to collect accurate point clouds of as-built conditions to compare to planned BIM content. This partner company provided BIM development and field capture services for this research, which yielded an accurate point cloud, which was used to generate an accurate as-built model for the targeted space for field verification, as shown in Figure 1.

Figure 17: Photograph of the built environment (left), laser scan (center), and resultant model (right)

The targeted area for field verification (Figure 17) was located in a finished building on the authors' institution's campus. The hallway was strategically chosen because it does not have a ceiling that blocks the view of the various building systems installed. This effectively simulates the type of view that construction professionals would have when field verifying the locations of systems prior to covering them with typical finish materials. The selected hallway included electrical conduits, telecommunications cable trays, lighting, heating, ventilation and air conditioning (HVAC) ducts, water pipes, and fire sprinkler lines. This scenario could directly benefit from effective field verification.

The authors worked with the partner company to generate an accurate, as-built, BIM according to their typical field verification processes. First a technician from the partner company used a laser scanner to generate an accurate point cloud of the space, with an accuracy of less than 1/8th of an inch. The point cloud was then imported into a modeling software and used to recreate a model that exactly replicates the built environment. After the accurate as-built model was created, several types of deviations were strategically incorporated into the model for subsequent tasks aimed at determining the extent to which users of AR could identify those types of deviations.

The authors introduced deviations into the model to simulate the types of deviations that may occur in practice. Three types of deviations were introduced: (1) small deviations, (2) large deviations and (3) missing elements. In this paper, small deviations were defined as those smaller than two inches, and large deviations were defined as those larger than two inches. Missing elements were defined as elements that were present in the BIM, but not present in the built environment. There were four total deviations in the modified model: two large deviations, one small deviation, and one missing element. Figure 18 shows the four deviations compared to the constructed environment. Table 35 summarizes the deviations added to the model.

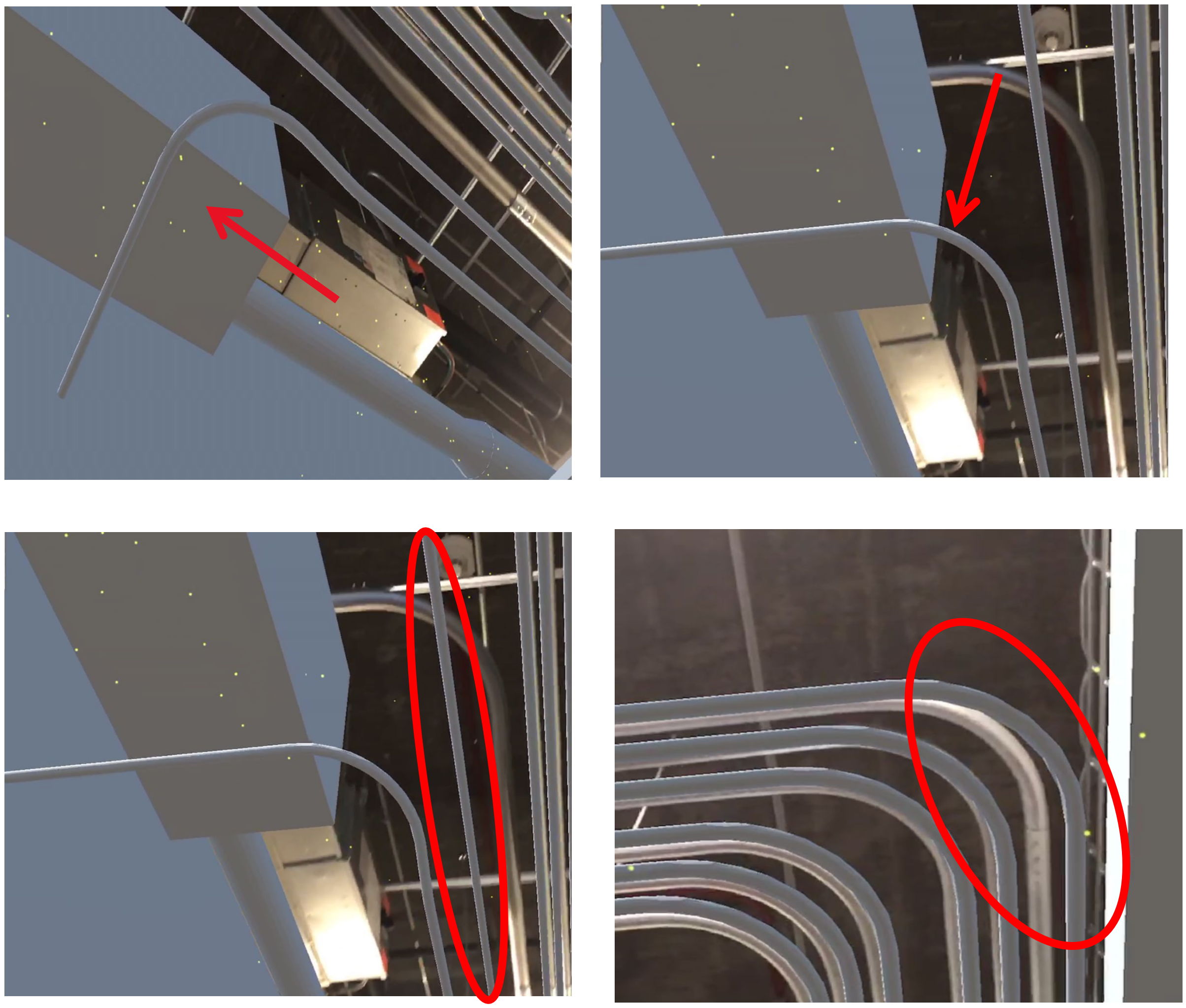

Figure 18: Large Deviation 1 (Upper Left Corner), Large Deviation 2 (Upper Right Corner), Missing Element (Lower Left Corner) and Small Deviation (Lower Right Corner)

Table 35: The model deviations and descriptions

Deviation Name	Description
Large Deviation 1	Variable Air Volume (VAV) Box shifted by eighteen inches, overlapping with built Box
Large Deviation 2	Electrical conduit shifted by a foot to the South, not overlapping with built conduit
Missing Element	Electrical conduit added the model, not built
Small Deviation	Electrical conduit has been shifted to the East by two inches

After defining the deviations in the model, the components in the BIM were color coded, based on the different types of systems, as shown in figure 19. The HVAC system was colored green, the electrical conduits were colored blue, the cable tray was colored pink, and lights were colored in light green. The coloring allowed the users to easily distinguish between the built systems. It also enabled the research participants to easily stipulate which system they were considering when performing the field verification tasks by simply referring to their color. This was done to reduce the chances of misinterpretation of participants' statements by researchers during data collection and analysis. Other than the deliberate changes made to the model to enable the research, no additional modifications were made to the model in order to replicate the type of modeled content that would typically be delivered in practical settings.

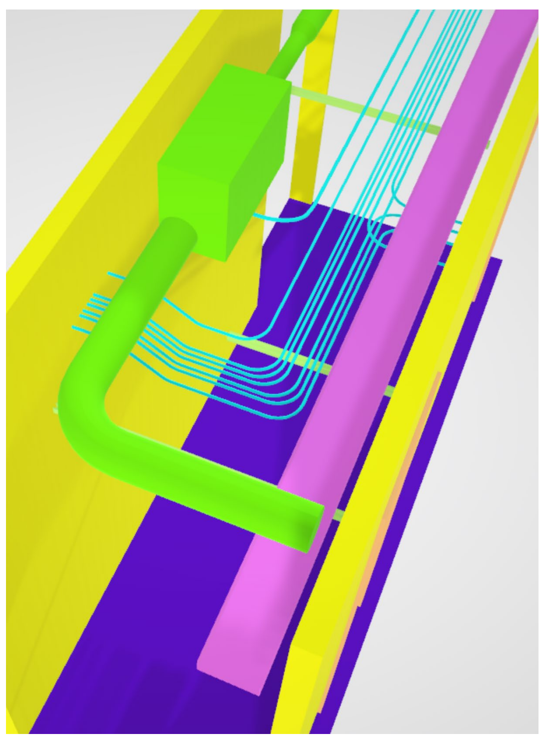

Figure 19: colored model used for the AR environment

5.3.2 AR deployment

The Microsoft HoloLens was chosen as the AR device for this experiment. The HoloLens overlays virtual content directly on top of the user's unobstructed view instead of relying on a video-pass-through display. This enables a safer and more comfortable alternative to video-pass-through based AR systems because of the lack of video latency. Furthermore, the HoloLens is a self-contained, untethered Head Mounted Display (HMD), which allows the users to freely walk around the space to check for model discrepancies.

All AR development was done in Unity Game Engine. First, the Revit models were extracted to FBX files, a universal 3D file type. The FBX models were then imported into the Unity Game Engine and linked to a printed fiducial marker to enable accurate placement of the model in space. When a user says the word "model", the entire model would disappear, and when the user says it again, the model would reappear. This modification leveraged the AR device's built-in voice command capability and enabled users to have completely unobstructed views of the space if they chose during their field verification task.

5.3.3 Identifying Participants for Experiment

The researchers were primarily interested in determining the types of deviations that an AR user could identify between field and BIM. To provide a large sample of participants, students from a graduate level construction class were recruited for this experiment. Graduate students typically have a strong foundational understanding of their discipline from the completion of their undergraduate degree. The students represent a group with varying backgrounds and levels of experience, but are not necessarily trained to complete field verification tasks. Using student participants provides an opportunity for tasking comparatively large numbers of participants with field verifying the same space, which would not realistically be possible to replicate on an active job site. Furthermore, the participants did not have prior experience with the space or prior experience with the specialty contractors involved with its construction. Prior knowledge of the space and working experience with specific subcontractors could create bias for or against specific disciplines, increasing or decreasing the likelihood of detecting errors. While this type of bias would likely be present in practical implementations of AR, introducing the bias in a study on AR could obfuscate results and suggest findings based on information outside of what was presented through AR. The students received a small class credit for participating in the experiment, regardless of their performance.

5.3.4 Experimental Protocol

Before starting the experiment, the participants were informed that the session would be video and audio recorded, and they signed an informed consent form to allow the researchers to use the data collected for analysis. Each participant then received a pre-session questionnaire. The questionnaire included general background questions, such as age, experience in construction, experience completing QA/QC tasks, and experience with AR technology.

After completing the pre-session questionnaire, the participants were briefed on the think-aloud protocol that they would be asked to follow during the experiment. A think-aloud protocol asks participants to verbally describe their thoughts during a given task (Joe et al. 2015). For this work, this involved participants stating the deviations that they identified as they navigated the targeted space. They were also informed that the researcher might ask follow-up questions when necessary. During the activity, the researcher only intervened for follow-up information when participants voiced unclear statements. For example, if a participant stated "the tube is shifted to the front" the researcher would ask "what color is the tube? Would you point to the direction it is shifted to?" to clarify the statements made. When a deviation was detected, the researcher asked the participant to estimate the deviation distance and direction. This data collection process enabled the researchers to understand what the participants were thinking during the activity, without influencing them to state a specific type of comment (Joe et al. 2015).

After participants understood the task required of them in this experiment, they were introduced to the specific AR device involved in this work. Since most of the participants did not have previous experience with AR, they were provided with a brief technical introduction to the headset used. The researcher assisted each participant in wearing the headset and made sure that the participant could view the model. After the participant verbally verified that he or she could see the modeled content and understood the task assigned, the experiment began.

Participants were not told how many deviations they should find in the space to simulate the uncertainty about deviations that could be present during actual field verification processes in practice. Instead, they were told to explore the modeled portion of the hallway and identify all discrepancies that they believed existed between the model and physical space. After participants reached a point where they believed they had found all discrepancies, they simply told the researcher that they were finished with their review of the space. At that point, the experiment stopped, even if the participants had included incorrect statements or missed deviations that they should have theoretically caught through their verification process.

Upon completion of the AR review activity, participants were asked to complete a NASA-TLX (Task Load Index) form and a post-session questionnaire. The NASA-TLX is a questionnaire that enables researchers to measure perceived cognitive workload (Hart and Staveland 1988), and the questionnaire included questions related to the experiment, including several Likert-scale based questions about the ease of finding deviations and the participant's confidence in his or her results, and open-ended questions about the ease of using the device itself, comfort during the experiment, and future potential uses of this technology in his or her experience and opinion.

5.3.5 Analysis

The raw data collected included the participants' completed questionnaires, the videos recorded for each experiment and notes taken by the researcher during the experiment. The questionnaires and the NASA-TLX responses were anonymized and digitized. The questions based on a Likert-scale were digitized in a spreadsheet format, while open-ended questions were saved in plain text documents. Descriptive and paired statistics were calculated, where appropriate, to extract relevant findings.

The researchers referenced the video recordings and the notes to assess the performance of the participants during the experiment. In the same spreadsheet, the researchers recorded which deviations were detected, the stated classifications of the deviations (missing items, large deviation, small deviations) and any false positive observations. This data was analyzed using appropriate statistical tests, and the results are elaborated in the results section.

5.4 Results & Discussion

Twenty-seven graduate construction management students from Arizona State University participated in this experiment. The age of the participants ranged between 22 and 57 years old, and all had at least a bachelor degree in a construction-related field. Table 36 summarizes the years of experience and prior experience completing quality control and assurance tasks among participants. In general, most participants had between 1 and 5 years of experience and 60% of them had some completed some QA/QC related tasks.

Table 36: Cross-tabulation of participants' years of construction experience and quality control experience

Years of construction Experience	Has QA/QC Experience	Has No QA/QC Experience	Total
No Experience	15% (n=4)	0%	15% (n=4)
Less than 1 year	0%	4% (n=1)	4% (n=1)
Between 1 and 5 years	41% (n=11)	22% (n=6)	63% (n=17)
Between 5 and 10 years	0%	7% (n=2)	7% (n=2)
More than 10 years	4% (n=1)	7% (n=2)	11% (n=3)
Total	60% (n=16)	40% (n=11)	100% (n=27)

5.4.1 Deviation detection

The participants needed between two and three minutes to finish the task. In this paper, *deviation identification* refers to when a participant verbally states that a building element has deviated from the original model. *Deviation classification* refers to when a participant indicates how or why the building element is different from the original model. For example, if the participant states that there is a difference between the model and built environment related to the Variable Air Volume (VAV) box, it is considered a correct deviation identification because this was one of the deviations intentionally introduced into the model. If the participant states that the VAV box is not constructed, this is still considered to be a correct identification, but it is considered to be an incorrect classification of the deviation because the box is indeed constructed, but its placement is shifted from the BIM.

Table 37 summarizes the correct deviation detection and deviation identification rates of the different building components by the participants. 96% of all participants were able to detect the shift in the VAV box and correctly identified it as shifted, typically estimating the shift between 18 inches and three feet. 96% of participants detected the large conduit deviation, 88% of which correctly identified this deviation to be between eight inches and one foot, while the remaining 12% considered the conduit to be missing or not installed. 74% of participants detected the missing conduit, 80% of which correctly identified it as missing while the remaining 20% considered it to be installed elsewhere, but shifted by two to four feet. Finally, only 41% of participants detected the small conduit deviation, all of whom correctly identified it as a small, one to two-inch deviation.

Table 37: Detection and Identification rates of deviations

Deviation	% Correct Identification	% Correct Classification (of % Correct Identification)
Small Deviation	41%	100% (41% Overall)
Large Deviation 1	96%	100% (96% Overall)
Large Deviation 2	96%	88% (84% Overall)
Missing Element	74%	80% (59% Overall)

In general, AR seems to enable high levels of identification of large deviations and missing items, but it is less likely to enable the identification of small deviations. Although all aspects of the AR experience have advanced over the past several years, AR still suffers from significant tracking and parallax effects. AR tracking refers to the placement of the model relative to the real world. Parallax is defined as the effect whereby the position of a virtual objects changes when viewed from different angles. Current generation AR can place virtual models almost perfectly when stationary, but as the user moves around the space, the experience suffers from reduced tracking performance and subsequently the parallax effect. Some participants understood the visual cues of the parallax effect as overall shifting of the model (incorrect tracking), leading them to miss the small deviation. A smaller percentage of participants correctly understood the difference between slight shifting when moving and “real” deviations and could identify the small deviation.

One counter-intuitive observation regarding the results obtained was the fact that fewer participants detected the missing conduit compared to those who identified large deviations. Prior research theorized that AR can enable practitioners to immediately find missing building elements in a space when comparing the virtual model in an AR environment (Kwon et al. 2014). However, 26% of participants failed to notice that an extra electrical conduit should have been constructed. One possible explanation is that some participants may not have realized that the parallax effect exists, leading them to think that the virtual conduit was simply perfectly overlaid on a real conduit, and did not think to further check if there was actually an installed model. This further illustrates the importance of testing this technology in a complex building environment, where the user might not be able to focus on compare single elements. One possible remedy could be to lower the brightness of the virtual model view, which may enable the user to identify mismatches more easily.

Finally, it is important to understand the difference in the rates of correct identifications between the building components. Although all participants who correctly identified the VAV box as a deviation correctly classified the deviation as a large deviation, 12% of the participants who identified the electrical conduit as deviating considered it missing, when in reality it was a large deviation. The reason for the discrepancy in the correct classification rates may be due to the nature of the element itself. There are comparatively fewer VAV boxes within the space than there are conduits, which may make it easier to quickly define the type of deviation related to the VAV box. In this specific experiment, two of the three participants that incorrectly classified the largely deviated conduit as missing attempted to count the number of present conduits out loud, miscounted, and then classified the conduit as missing. This suggests that, in high density areas where numerous building elements are repetitively used, the usability of AR may be hindered, and the use of a hybrid checking method, where the results presented through AR inspection are subsequently rechecked may be required.

5.4.2 False positives

In this paper, false positives refer to instances where a participant identified an area as being different from the AR model, even though the model was not modified from the original laser scan of the built space. For example, the cable tray modeled is in its correct place, according to the laser scan. If a user identifies it as deviating from the model, this would count as a false positive. Table 38 summarizes the number of false positives identified by the different participants.

Table 38: Frequency of False Positive Identifications

Number of False Positive(s) identified	Percentage of participants
0	60% (n=16)
1	33% (n=9)
2	7% (n=2)

Sixteen participants did not identify any false positives, nine found one false positive, and two found two false positives, and no participant found any more than two false positives. In total, thirteen false positives were identified. Nine false positive observations alleged that all electrical conduits have shifted by an inch or less to the right, three considered the HVAC duct to be slightly shifted to a side, and one alleged the lights were slightly shifted forward. All false positive observations were described as smaller than two inches, or small deviations. These may also be attributed to the aforementioned parallax effect. In these cases, the participants did not acknowledge the existence of the parallax effect, and identified every small shift as a deviation. While this does illustrate a limitation observed through the technology, the recognition of this effect by participants may be something that could be mitigated through more exposure or training for practical applications.

It is important to remember that AR is used to help human decision makers not only to determine whether a deviation exists, but also to determine what to do next. In many cases, when small deviations are identified, rectifying the model to perfectly match the built space or reworking the physical space to perfectly match the model are unnecessary, and tracking and rectifying such small deviations may not be critical for FM purposes. In these cases, the decision maker will likely decide to ignore the small deviation, regardless of whether or not it is a false positive observation or a real deviation. In the cases where high levels of accuracy are required, the decision maker can spend the time and resources necessary to check the specific areas with more accurate capturing technologies, such as laser scanning.

5.4.3 Perceptions and Cognitive Workload

Table 39 summarizes the results of the post session questionnaire. While all participants agree or strongly agree that it is easy to identify large deviations between the model and the built environment using AR, 7% of participants disagree that missing elements are easy to identify using AR, and 33% of participants disagree that small deviations are easy to identify using AR, signifying that the participants were aware of the limitations of the device upon first use. Furthermore, the results reflect the confidence of the participants in their findings. These further support the observational results presented in the prior sections, where all participants detected at least one large deviation, whereas smaller numbers of participants detected the missing elements and smaller deviations.

Table 39: Results of post-session questionnaire

Question	Strongly Disagree	Disagree	Agree	Strongly Agree	Total
Small Deviations (less than 3 inches) are easy to identify using Augmented Reality	7% (n=2)	26% (n=7)	33% (n=9)	33% (n=9)	27
Large Deviations (larger than 3 inches) are easy to identify using Augmented Reality	0% (n=0)	0% (n=0)	22% (n=6)	78% (n=21)	27
Missing elements are easy to identify using Augmented Reality	0% (n=0)	7% (n=2)	33% (n=9)	59% (n=16)	27

To measure the cognitive workload required to complete the deviation detection using AR, the researchers employed a NASA-TLX questionnaire. The NASA-TLX ranks the mental demand, physical demand, temporal demand, performance, effort and frustration associated with a task on a -10 to 10 scale. For this task, all categories average between -5 and -8, indicating that the participants found the task to be relatively easy to complete and reported that it does not require high cognitive workload. This further confirms that the participants were fully capable of completing this task with relative ease.

5.4.4 Potential Implications

Based on the strengths and weaknesses of AR when applied for field verification, the findings of this work suggest two ways for using AR in the QA/QC process: (1) for quick checks throughout the construction process and (2) as a compliment to using laser scanners.

5.4.4.1 **AR for Quick Field Checks**

In the first scenario, AR can be used as a tool to check that all construction is complete before moving on to another construction task. AR enables individuals to effectively identify missing items and items with large deviations, which makes it well suited for conducting quick checks throughout construction, especially to check that all systems are installed or that building elements are within previously negotiated spatial constraints. This further leverages the comparatively faster process of checking the built environment to the virtual model through AR, rather than relying on typically slower Scan-to-BIM technologies. For example, a foreman using AR can check that all electrical conduits are correctly placed below grade level before pouring concrete for the slab on grade. When deviations are observed, the foreman will be able to make a judgement as to whether the model needs to be changed using appropriate methods, or the area needs rework to more closely match the model.

5.4.4.2 **AR to Guide Laser Scanning**

The second scenario suggested by the results of this paper is using AR as a tool to determine where it may be worthwhile to use laser scanning for deviation detection in the built facility. Instead of laser scanning the entire building to detect deviations, which can be data- and time-intensive (Remondino et al. 2005), the construction team may be able to use AR to quickly identify locations in the building where some deviations may be present by comparing the model to the built environment using AR. As observed in the results of this paper, accurate descriptions of why or how the space deviates from BIM can be prone to errors. Fortunately, in this suggested approach to using AR, accurate descriptions of deviations are inconsequential. Instead, what matters is the fact that users can quickly identify whether something appears to be different in the built space. In this type of instance, subsequent laser scanning can help to resolve the reasons for the discrepancies. This type of use may offer value by reducing the number of spaces that teams elect to laser scan, which may reduce scanning and processing times required for the project. It is worth noting that, depending on the size of the project and the amount of checking that is to be conducted at a given time, this approach could potentially require users to wear the AR device for extended periods of time. It is possible that this could lead to fatigue, but it is also possible that users would simply remove the head mounted display when discussing areas after assessing them for deviations, which may mitigate this discomfort. Furthermore, if this mode of field verification is adopted by future practitioners, it is very likely that future generations of commercially available AR devices will continue to get lighter, which may further reduce discomforts from their extended use.

5.4.5 Limitations

In this paper, the researchers set out to understand the performance and behaviors associated with the use of AR for deviation detection. However, the findings presented in this paper have several limitations, related to the study sample and current technology maturity.

First of all, the participants in this study are graduate construction management students representing a wide range of relevant experience. In this study, no correlation between experience and performance was found, corroborating the findings of other research suggesting that performance using AR is not dependent on industry experience (Chalhoub et al. 2019). However, it is plausible that experienced professionals dedicated to QA/QC tasks may perform better when completing the same task. While this does offer a limitation to the extent to which the observed results may match those with practitioner participants, it is likely that the results observed in this work are actually conservative because of the comparatively lower experience possessed by the students.

Current generation AR also suffers from tracking and parallax problems, which have at times significantly increased setup time. For example, depending on the lighting conditions, the paper marker needed to be moved for the model to be accurately overlaid on top of the built environment. The authors aimed to determine what types of deviations could be detected through AR rather than the exact productivity of identifying these deviations, so this setup time was not considered in this analysis. However, the authors recognize that setup time could impact overall value provided by the technology if it were to be used on an active construction site with stringent time constraints. Fortunately, some commercially available software suites have been developed that claim to streamline the process of getting models onto AR headsets using plugins to popular BIM software applications (i.e. HoloLive, Fusor), but these were not tested through this work, so the authors do not make any performance claims about them. For companies that are already beginning to use AR for inspections, the process of transferring model content from BIM environments to AR is likely a workflow that they are already performing, which may further reduce the added time required for setting up the devices for inspection.

5.5 Conclusion

This research studied the performance and behaviors of graduate student participants when using AR for deviation detection during QA/QC tasks. An open-ceiling hallway with complex MEP systems was modeled, and four deviations were introduced: two deviations larger than two inches, one deviation smaller than two inches, and one missing building element. Using an AR headset, each participant compared the modified model to the real environment and attempted to identify the deviations.

In general, when using AR, participants were able to identify all three types of deviations, however, they were significantly more likely to identify larger deviations than smaller ones. In most cases, the participants were also able correctly identify the cause of the deviation, although some identified the missing component as a large deviation. The participants also identified several false positive observations, in which the participant incorrectly assumed there was a deviation, but in fact, there was not.

To capitalize on the strengths of the AR technology, the findings of this work led the researchers to propose two high potential use cases: (1) using AR as quick construction monitoring and progression tool, to check that all building components are installed before continuing to other activities (i.e. checking that all electrical sleeves are installed before pouring concrete), and (2) using AR as a tool to guide what areas should be laser scanned, thus reducing the total scanning and data processing times required for the project. The findings of this paper contribute to the body of knowledge by providing evidence of how current generation AR may enable (or fail to enable) effective detection of deviations between BIM and as-built conditions. Furthermore, the suggested AR inspection use-cases identified will allow future researchers and practitioners to define inspection strategies based on empirical evidence in order to conduct field verification tasks more effectively.

5.6 Acknowledgments

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CHAPTER 6

AUGMENTED REALITY FOR WORKFORCE DEVELOPMENT IN SPECIALTY CONSTRUCTION

6.1 Introduction

Construction is one of the largest industries in the United States, contributing to 4.4% of the Gross Domestic Product (GDP) of the nation (U.S. Department of Commerce 2017). The construction industry grew from an estimated $640 Billion income in 2014 to $781 Billion in 2017 (U.S. Department of Commerce 2017). It currently employs more than 9 million workers (Dong et al. 2014) and is expected to require an additional 790,000 workers by 2024 (Office of Occupational Statistics and Employment Projections 2015). However, this industry has been prone to a cyclical workforce shortage problem. First spotted in the 1980’s (Castañeda et al. 2005), the severity of the labor shortage has increased over the past few years (Karimi et al. 2016), further underlining the importance of increasing labor attraction to the industry.

The construction industry has been historically criticized for low labor productivity (Fulford and Standing 2014). Specifically, the value added per worker-hour has been steadily declining over the past few decades, especially when compared to other, non-farming industries such as manufacturing (Teicholz 2013). The combination of these two trends poses a major challenge to the construction industry and highlights the need for the industry to improve its productivity, while also mitigating challenges related to labor shortages.

The use of emerging technologies may address part of this industry-wide problem. For example, new technologies may be able to replace human labor by using more efficient machinery and automation (Bock 2015). Alternately, new technologies may also be able to increase the ability of workers, thereby leading to higher efficiency and reduced rework (Prasath Kumar et al. 2016) and can facilitate labor training processes (Lin et al. 2018). In this paper, the authors explore the use of Augmented Reality (AR) to determine whether it can automate the process of presenting contextually relevant design information to un- and under-trained participants completing construction-related tasks. AR superimposes virtual information on top of a user's view of a physical space (Milgram and Kishino 1994). This superimposition of virtual content onto the real environment may provide a more intuitive mode of design communication than traditional 2D drawings or "blueprints", which have been the standard mode of construction communication for years. AR has shown potential to increase the productivity when used as the main design communication tool for select construction tasks (Chalhoub and Ayer 2018a; b). It is possible that this mode of interaction may support design comprehension among non-skilled participants to allow them to accurately complete some construction tasks. Therefore, the intellectual contribution of this paper is in empirically demonstrating the feasibility of current generation AR technology to support design comprehension among laypersons to complete construction tasks. This understanding provides a potentially better process to target groups of individuals who had traditionally been overlooked for construction positions because of lack of discipline-specific knowledge, which may enable access to a new source of workers to address both labor shortage and productivity deficiencies suggested to be present in the construction industry.

In order to explore this broad topic, this paper addresses two specific research questions: 1) Can individuals without any prior construction experience perform basic construction tasks correctly using AR? and 2) How does the performance of the un- and under-trained individuals compare to the performance of current industry professionals? This paper addresses these questions using an experimental approach, by comparing the performance of three groups with varying levels of construction education and training completing select construction tasks using a 3D model viewed through an AR headset. The findings will enable construction managers to increase overall crew productivity and face current shortage of workforce availability by using technology to allow able-bodied, untrained individuals to perform several key construction tasks using AR for information delivery, thus freeing trained, experienced practitioners to perform more technically challenging tasks.

6.2 Background and Literature Review

6.2.1 Training and labor shortage

Lack of skills and training among construction workers can lead to schedule and budget overruns (Karimi et al. 2017). Historically, trained workers have a higher productivity rate compared to untrained workers, but still have an adverse effect on profitability of a given project (Addison and Hirsch 1989; Lu et al. 2010). The skills learned through training are advantageous to the workers' performance, but the increased salaries demanded by these highly skilled individuals can negatively affect their employer.

However, lack of proper training is considered to be one of the two main causes for long term construction labor shortages (Albattah et al. 2015; Castañeda et al. 2005; Healy et al. 2011). Research also shows a high level of apprenticeship dropout rates when training is provided (Mitchell and Quirk 2005; Watson 2012). Electricians and other trade labor groups are already experiencing severe, training-related, labor shortages (Albattah et al. 2015). These trends indicate a major labor shortage in many different sectors of the construction industry and highlight the opportunity for enabling un- and under-trained labor to perform key tasks to ensure that trained professionals can focus on more technically challenging tasks.

6.2.2 Building Information Modeling

Building information modeling (BIM) is the development of a 3D virtual design containing both physical and informational aspects of a project (Lee et al. 2006). The construction industry has been increasingly adopting BIM, especially among contractors (McGraw-Hill Construction 2014). Research has also demonstrated the potential for BIM to support design visualization and interaction for Architects (Yan et al. 2011). Furthermore, with increasingly powerful mobile and tablet-based computers, BIM can be used on site for model visualization and job progress documentation (Davies and Harty 2013). On the other hand, advanced technologies, such as Augmented Reality, enable photorealistic onsite visualization of the model (Wang and Love 2012). The continued expansion of the use of BIM in the industry provides a wealth of 3D content that may be further leveraged using emerging visualization technologies. In this paper, the authors discuss leveraging the 3D content generated for an industry standard BIM to view in an Augmented Reality environment.

6.2.3 Augmented Reality

Milgram and Kishino defined Augmented Reality (AR) as a subset of Mixed Reality (MR), where some virtual content is overlaid on a predominantly real view (Milgram and Kishino 1994). Various efforts have been made to facilitate the migration of BIM content to an AR environment (Williams et al. 2015), enabling numerous applications in the industry. AR may be used to visualize BIM objects hidden behind walls (Thomas and Sandor 2009) or planned improvements in space (Thomas et al. 2000). AR was also used for site monitoring and documentation (Zollmann et al. 2014), reducing site risk factors (Tatić and Tešić 2017) and providing contextually aware safety instructions (Guo et al. 2017). These works illustrate the potential for AR to offer value to design and construction applications when used by practitioners and users with domain-specific expertise.

AR use for training and education has been explored in construction and other industries. For example, it was shown that using AR for extended training procedures reduces stress compared to traditional training methods (Tumler et al. 2008). Furthermore, AR has been used by the military to train mechanics on performing repairs by supplying relevant contextual information (Henderson and Feiner 2009) and it may be useful for maintenance and assembly related tasks (Webel et al. 2013). In construction education, AR helps the students better achieve their learning objectives compared to traditional teaching methods (Lin et al. 2013) and has a significant positive impact on a student's learning, both in the short term and long term (Shirazi and Behzadan 2015). For example, AR helped enhance the understanding of three dimensional objects among students (Dünser et al. 2006; Kaufmann 2003) and was used to teach the students about the relationship between 3D objects and their 2D projections in engineering graphics classes (Chen et al. 2011). AR also enables construction students to better understand the construction site through site condition simulation in a classroom environment (Mutis and Issa 2014; Shanbari et al. 2016). As AR technology continues to mature, researchers continue to study potential industrial applications. This paper studies the use of AR as a workforce development tool, enabling untrained individuals to complete key construction tasks.

6.2.4 Previous Research

The researchers have previously attempted to use AR to enable a conduit assembly task (Chalhoub and Ayer 2017) and an electrical point layout task. During the conduit assembly task, the researchers received two similar electrical conduit models from a partner company and loaded the model on an AR head-mounted display (HMD). Practitioners from the partner company attempted to assemble the prefabricated conduits. In one treatment group, the practitioners used standard paper plan documentation. In the other treatment group, they used AR. The results revealed that using AR reduced assembly time by 45% and assembly mistakes by 75% (Chalhoub and Ayer 2018a).

During the point layout task, the researchers collaborated with another electrical subcontractor to create eight room designs where electrical devices needed to be installed. Practitioner participants were tasked with placing an adhesive note on the walls where the electrical devices were to be installed according to the plans. All models were loaded onto the AR HMD and standard paper documentation was created. Practitioners from the company were randomly assigned four layouts to be completed with paper plans, and four to be completed with AR. The results suggest that layout is up to three times faster when using AR compared to when using paper, although accuracy is marginally lower.

The combination of prior results provides a theoretical basis to suggest that AR may offer potential productivity improvements and design comprehension benefits. When considered in conjunction with the literature that indicates that the construction industry might be facing a labor shortage, this further suggests a theoretical benefit to using AR for training purposes. In order to provide empirical evidence of these theoretical possibilities, this work explores how different individuals with no experience and varying degrees of familiarity with construction perform construction tasks using AR. The results help to provide an empirical basis to justify the use of AR as a workforce development tool to enable un- and under-trained individuals to be able to fill desperately needed construction roles with minimal instruction.

6.3 Methods

6.3.1 Test Subjects

In order to assess the effectiveness of using AR for supporting basic construction activities, an experiment was run with participants from three groups: 1) experienced industry professionals, whose performance was previously tested; 2) current students studying construction management; and 3) participants with no construction education or experience.

The industry professionals involved in this work consisted of current electricians with varying levels of experience. This group had experience completing construction-related tasks using traditional design communication tools including 2D construction plans and Building Information Models (BIM), and was chosen to act as a benchmark against which the performance of other groups will be compared.

The construction management students were recruited from the Del E. Webb School of Construction at Arizona State University. These students did not generally have substantial construction industry experience, but they have completed several years of construction coursework as well as two mandatory field internships. This group was considered to test whether some education or construction knowledge was required to reap the benefits of using AR as the main design communication method for some construction tasks.

The third group included participants recruited from Arizona State University who self-declared that they had no construction experience or related education. This group was selected to test whether able bodied individuals without any construction experience could complete the construction tasks when using AR, regardless of their background or skills. While some of the participants from the third group were pursuing college degrees, their education should not affect their performance when completing construction tasks. According to (Dunston and Wang 2011), construction tasks may be divided into a five level hierarchical system, starting with primitive tasks, such as grasping and reaching, then composite tasks, such as moving a conduit or driving in a nail, followed by more complex tasks. For this experiment, the tasks required are within the first two levels, both of which are not taught specifically to college students. Prior to starting the activity, the researchers asked the participants whether they were capable of performing the basic tasks required to complete the activities required, such as using a screwdriver, moving large pieces of conduit, and using adhesive tape.

6.3.2 Activities

Two basic construction activities were identified for this research: 1) conduit assembly and 2) point layout. Assembly is the act of joining pieces together to create an intended design and is primarily used in conjunction with prefabrication. Prefabrication is a construction technique where different pieces are prepared offsite and assembled on site. For electrical conduit prefabrication, all the pieces are pre-cut and bent in a shop, and the finished pieces are shipped to the jobsite where they are subsequently assembled according to the intended design for field installation. Prefabrication has been on the rise in construction, especially in electrical and mechanical construction (Karunaratne 2011; Khanzode et al. 2007). Point layout is the act of identifying relevant points in space on a construction site. Point layout is an essential task for surveying, electrical, mechanical and other specialty construction. Both tasks are applied in a variety of construction related contexts, making them essential knowledge for potential construction professionals.

6.3.3 Setup of Augmented Reality Environment

The Microsoft HoloLens was used for AR visualization in this experiment. The HoloLens is an AR-capable HMD with inward facing projectors and a transparent visor that enables users to see the real environment around them with virtual content overlaid without requiring them to view this content through a traditional computer screen. The virtual content overlaid in the view behaves similarly to real objects. For example, if a virtual object is placed on the ground, it stays there when the user moves around the room. The HoloLens is also self-contained, so that the users can move freely around the space without requiring a wired connection to computers or other hardware. For each activity, a separate AR environment was generated. Both environments are based on an industry standard BIM at a Level Of Development (LOD) 350, where the model represents an accurate placement of the content, such as the electrical components to be built, walls, studs and other presented building elements. The models were initially created in Autodesk Revit, and exported to an FBX file, which is a generic 3D file format. Then, the models were exported to the AR headset using the Unity Game Engine.

For the conduit assembly activity, the conduit design was modeled in a BIM software by a partner company following their typical workflow procedures. The model shows the conduit with numbers next to each piece. The numbers serve as identifiers for each piece and the actual conduit pieces are tagged with the same numbers. The model was then exported to the AR environment without any alteration. The AR environment depicts the conduit at full scale, placed on the ground in its intended location in the room. Figure 20 shows the model as seen using AR with a few pieces being built.

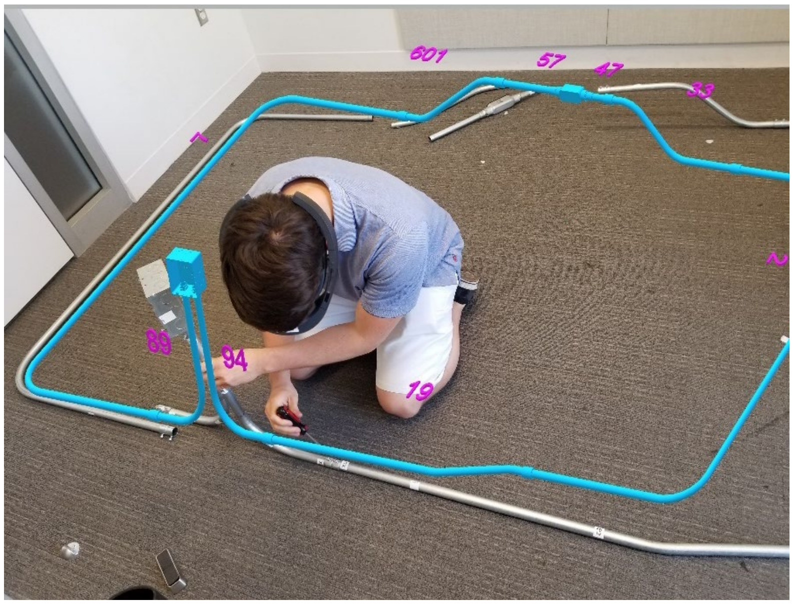

Figure 20: Participant Assembling the Electrical Conduit with the Virtual Model Added to the View (in Blue)

For the point layout activity, a corner of a room with the points indicating the location of electrical outlets was modeled. The researchers removed all of the non-required elements from the model including walls, ceilings, floors, doors and other elements. The only elements left in the model were the electrical devices required for the activity (i.e. face plate of each device with a red cross across the middle). Additionally, the name of the device was shown on top of each plate. The model was exported from the native BIM software and into the AR environment. This enabled AR users to see full-scale models showing outlets on the walls in the room, based on the BIM. Figure 21 shows the view of the room with the virtual outlets from the perspective of a participant.

Figure 21: Participant Laying out Electrical Devices with the Virtual Points Shown on the Walls Around Him

6.3.4 Experimental Procedure

The experiment took place over several days. Upon arriving at the activity location, participants were provided with the AR HMD and were given a brief introduction to the tasks that they were asked to complete. Prior to the experiment, all participants were asked to complete a pre-session questionnaire. The questionnaire captured relevant background data, construction experience, age, current position, and an indication whether they had previously used AR.

After completing the pre-activity questionnaires and forms, the participants were briefed on the tasks they were required to complete. The tasks were explained orally to each participant using the same, previously developed script, and the researchers answered all the questions from the participants until they stated that they understood how to complete the task. The construction student participants and non-construction participants completed the conduit assembly task first and then proceeded to complete the point layout task. The construction industry professionals' data was collected through two separate data collection activities with two separate companies. As a result, each practitioner participant completed only one of the two tasks, but still completed similar pre- and post- activity questionnaires to provide their perception feedback.

For all participants completing the conduit assembly task, researchers video recorded the entire assembly process. Participants were assisted in wearing the headset, loading the model, and the researchers checked that each participant could clearly see the model on the ground. For each participant, the time required to assemble the conduit, starting from the moment the participant wore the headset to the moment the participant self-declared he or she were done with the assembly task, and whether the conduit was correctly assembled were recorded.

For all participants completing the point layout task, researchers also video recorded participants to support time-based analyses after data collection. Similar to the conduit assembly timing, the point layout timing spanned from the moment the participant put on the headset to the moment he or she finished the task. Additionally, high accuracy laser tape measures, reported to be accurate to one mm, were used to calculate actual distances for each laid out point as shown in figure 22. Research assistants measured the distances between the centers of the adhesive notes and known points in the room (i.e. distances to adjacent walls or to the floor) between each layout design. This provided accurate coordinates to support subsequent analyses related to accuracy of the laid-out points.

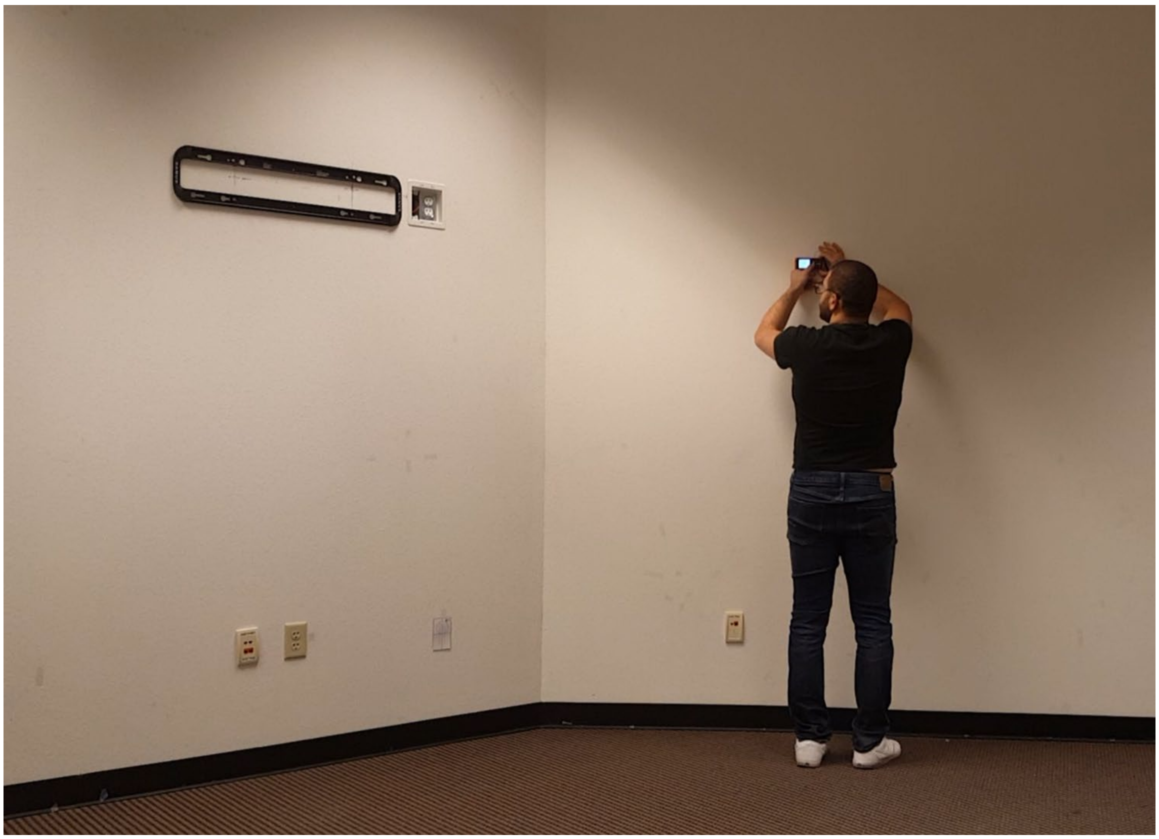

Figure 22: Researchers Measuring Point Offsets of Points Laid Out

When all point layout and conduit construction activities were completed, participants were presented with a post-session questionnaire. This questionnaire contained multiple choice questions pertaining to the use of AR and their perception of the activities. Furthermore, open-ended questions to solicit their perceptions regarding their favorite and least favorite aspects of the exercise were administered. The specific question text used to elicit this feedback is presented in the results section along with the related findings.

6.4 Results

6.4.1 General

Ninety-one individuals participated in the experiment. Table 40 illustrates the specific numbers of participants who completed each task. Participants' ages ranged between industry practitioner participants (21-59 years old), construction management students (22-30 years old), and non-construction related participants (20-28 years old).

Table 40: Numbers of Participants Completing Each Task

	Conduit Assembly	Point Layout
Industry Professionals	18	28
Construction Students	18	21
Non-Construction group	21	21
Total	57	70

The industry participants included journeymen electricians, foremen, modelers, coordinators and construction managers. Table 41 summarizes whether the participants had laid out points or assembled conduits during the last year and their total years of construction experience. The results related to performance of these participants are organized in the following sections according to the different construction tasks studied.

Table 41: Experience of Industry Participants

Years of Experience	Laid out Points / Assembled Conduit last year		Total
	Yes	No	
Less than 1 year	9% (n=4)	11% (n=5)	20% (n=9)
1 to 5 years	22% (n=10)	7% (n=3)	29% (n=13)
6 to 10 years	11% (n=5)	11% (n=5)	22% (n=10)
more than 10 years	17% (n=8)	13% (n=6)	30% (n=14)
Total	59% (n=27)	41% (n=19)	100% (n=46)

6.4.2 Conduit assembly

All participants, from all three groups, were able to complete the assembly of the conduit, but not all of the assemblies were "correct". An assembled conduit was considered "incorrect" when the orientation or placement of at least one piece was wrong. For example, if a piece of conduit was supposed to be installed perpendicular to the ground, but was installed flat on the ground, the conduit would require rework, and was considered incorrect. Table 42 summarizes the overall performance of the three groups in the conduit assembly and presents the results of the Shapiro-Wilk test of normality related to the assembly times. On average, the assembly time varied between 275 seconds and 300 seconds, and the percentage correctness varied between 61% and 89%. The Shapiro-Wilk test of normality had a significance of less than 0.05 for all three groups. Thus, the null hypothesis is rejected, and the groups are not normally distributed.

Table 42: Average Performance of Each Group in the Conduit Assembly Task and Corresponding Results of the Shapiro-Wilk Test of Normality

Group	Assembly Time (seconds)	Shapiro-Wilk Test (p-value)	Percentage Correct
Industry Professionals	284.94	0.005*	89%
Construction Students	299.59	0.006*	61%
Non-Construction group	275.86	0.000*	71%

*Indicates groups are not normally distributed at 0.05 significance level

Conduit correctness is a categorical variable, and statistical significance was tested using a cross-tabulation chi-square approach, presented in table 43. According to the Chi-Square test (p-value > 0.05), there levels of correctness of the assembly between the different groups is not statistically significant. This indicates that all groups are equally likely to assemble the prefabricated conduit correctly when using AR.

Table 43: Summary of the Cross-tabulation and Pearson Chi-square Test Results

<table>
<tr><th rowspan="2">Groups</th><th rowspan="2">Count, % Within Deviation</th><th colspan="2">Correct Conduit Build</th><th rowspan="2">Total</th><th rowspan="2">Pearson Chi-Square P-Value</th></tr>
<tr><th>Incorrect</th><th>Correct</th></tr>
<tr><td rowspan="2">Industry Professionals</td><td>Count</td><td>2</td><td>16</td><td>18</td><td rowspan="6">0.16</td></tr>
<tr><td>% Within Group</td><td>11.1%</td><td>88.9%</td><td>100.0%</td></tr>
<tr><td rowspan="2">Construction Students</td><td>Count</td><td>7</td><td>11</td><td>18</td></tr>
<tr><td>% Within Deviation</td><td>38.9%</td><td>61.1%</td><td>100.0%</td></tr>
<tr><td rowspan="2">Non-Construction Group</td><td>Count</td><td>6</td><td>15</td><td>21</td></tr>
<tr><td>% Within Deviation</td><td>28.6%</td><td>71.4%</td><td>100.0%</td></tr>
</table>

Since the times to complete the conduit assembly task were not normally distributed, the non-parametric Kruskal-Wallis test was used. Table 44 presents the results of the Kruskal-Wallis test. There was no evidence to suggest that the performance of the groups was significantly different (p-value = 0.435>0.05). In terms of correctness and speed of conduit assembly task when using AR, there is no statistically significant differences between the three groups.

Table 44: Results of the Kruskal-Wallis Test for the Conduit Assembly Time

Testing	Total N	Test Statistic	Degrees of Freedom	P-value
Conduit Assembly Time	57	1.666	2	0.435

6.4.3 Layout

All participants successfully laid out the electrical devices in the room, placing the adhesive note corresponding to the intended electrical device in the correct general area on the walls. The time required to layout the space and the accuracy of each laid-out point were compared. The accuracy was further divided into vertical accuracy and horizontal accuracy. Table 46 presents the results of the performances of participants from the three groups and the corresponding normality tests. For all but two of the test groups, the p-value for the Shapiro-Wilk test of normality is less than 0.05, indicating that the groups are not normally distributed.

Table 45: Average Performance of Each Group in the Point Layout Task and Corresponding Results of the Shapiro-Wilk Test of Normality

Groups	Layout Time (seconds)	Shapiro-Wilk Test (p-value)	Average Absolute Vertical Accuracy (meter)	Shapiro-Wilk Test (p-value)	Average Absolute Horizontal Accuracy (meter)	Shapiro-Wilk Test (p-value)
Industry Professionals	164.38	0.006	0.027	0.000*	0.038	0.000*
Construction Students	114.42	0.005	0.030	0.000*	0.023	0.000*
Non-Construction group	102.76	0.45	0.071	0.614	0.046	0.000*

*Indicates the groups are not normal at the 0.05 significance level

Since most of the data is not normally distributed, the Kruskal-Wallis test was used to determine whether there exists a significant difference in the performances of the different groups during the layout tasks. Table 46 summarizes the results of the Kruskal-Wallis tests on layout time. The results suggest that there is a significant difference in performance between the groups (p-value <0.05). A post-hoc adjusted Mann-Whitney test was used to determine the groups between which there exists a significant difference. The results of the adjusted Mann-Whitney post-hoc test are presented in Table 47. There only exists a difference between professional and non-construction participants at the 95% confidence level. Surprisingly, non-construction participants were faster, on average, than construction professionals by 61 seconds.

Table 46: Summary of the Kruskal-Wallis for the Time to Complete the Layout Task Between the Three Groups

Testing	Total N	Test Statistic	Degrees of Freedom	P-value
Layout Time	70	6.957	2	0.031

Table 47: Post-Hoc Analysis for the Time Required to Complete the Point Layout Task Using Corrected Mann-Whitney Tests

Group 1	Group 2	Mean Difference	Standard Test Statistic	Adjusted P-value
Professionals	Construction Students	49.95776	2.018	0.131
	Non-Construction Group	61.61824*	2.399	0.049*
Construction Students	Non-Construction Group	11.66048	0.356	1.000

*Indicates there exists a statistically significant difference between the compared groups at 0.05 significance level

Table 48 summarizes the results of the Kruskal-Wallis test comparing the accuracies of the laid-out points by the different groups, both vertically and horizontally.

The results suggest that at least one group had significantly different accuracies horizontally and vertically (p-value < 0.05). A post-hoc adjusted Mann-Whitney test was used to determine the groups between which there exists a significant difference. The results of the adjusted Mann-Whitney post-hoc test are presented in Table 50.

Table 48: Summary of Two Kruskal-Wallis Tests for the Accuracy of the Laid-out Points along the Vertical and Horizontal Axis

Testing	Total N	Test Statistic	Degrees of Freedom	P-value
Vertical Accuracy	341	115.319	2	0.000*
Horizontal Accuracy	341	34.632	2	0.000*

*Indicates there exists a statistically significant difference between the compared groups at 0.05 significance level

In general, non-construction participants were found to have significantly less accuracy in point layout placement. When compared to industry professionals, non-construction participants were, on average, 0.035 meters less accurate horizontally, and 0.065 meters less accurate vertically (p-value <0.05), as shown in table 49. Furthermore, when compared to construction students, non-construction professionals were 0.042 meters less accurate horizontally, and 0.058 meters less accurate vertically (p-value <0.05). However, there is no difference in the layout accuracy of the devices between industry professionals and construction students.

Table 49: Adjusted Mann-Whitney Post-hoc Analysis for the Accuracy of the Laid-out Points along the Vertical and Horizontal Axis

Dependent Variable	Group 1	Group 2	Mean Difference (Meter)	P-value
Horizontal	Industry Professionals	Construction Students	0.007	0.072
		Non-Construction Group	-0.035	0.000*
	Construction Students	Non-Construction Group	-0.042	0.000*
Vertical	Industry Professionals	Construction Students	-0.007	.798
		Non-Construction Group	-0.065	.000*
	Construction	Non-Construction Group	-0.058	.000*

*Indicates there exists a statistically significant difference between the compared groups at 0.05 significance level

6.4.4 Perceptions

At the end of the experiment, the participants filled out a post-session questionnaire. 96% of all participants indicated that it was easy to use AR to complete construction tasks, and 75% of the industry practitioners agreed that it is easier to complete the assigned construction task using AR than it is using traditional paper plans. These findings are aligned with prior studies conducted concerning the use of AR to complete construction tasks (Chalhoub and Ayer 2018a).

In the open-ended questions, users indicated that they liked seeing the model in space, making it easier to understand and visualize the design in space. However, many participants complained that the headset can become top heavy, especially for prolonged use, which can lead to neck fatigue if used all day. Some participants also noted that the model was too bright or too dim, and others found the field of view to be too small. While all these concerns are valid, the hardware of the device is likely to continue to improve as the technology matures, leading to lighter, smaller, and more adjustable headsets. Furthermore, if the device was to be deployed at scale, training the users would enable them to easily control the settings of the device to personalized comfort levels.

6.5 Discussion

In this experiment, laypersons with no construction training were asked to complete construction-related tasks using BIM content presented in AR. The performance of these laypersons was compared to the performance of participants with discipline specific work experience and education. While the non-construction participants would normally be expected to fail because of their lack of training, they were able to complete all assigned tasks using AR. For the two tested applications, the time required by non-construction participants to finish the tasks was not statistically different than the time required by trained professionals or construction students. Specifically, for the conduit assembly task, the average time required by the different groups to finish the task was within 5% of one another, as shown in figure 23. Furthermore, during the point layout task, non-construction participants finished the task significantly faster than professionals. This suggests that AR can be used by personnel with little or no construction background to quickly perform some key construction tasks at similar performance levels as trained construction workers, freeing those with more experience to complete more technically challenging tasks.

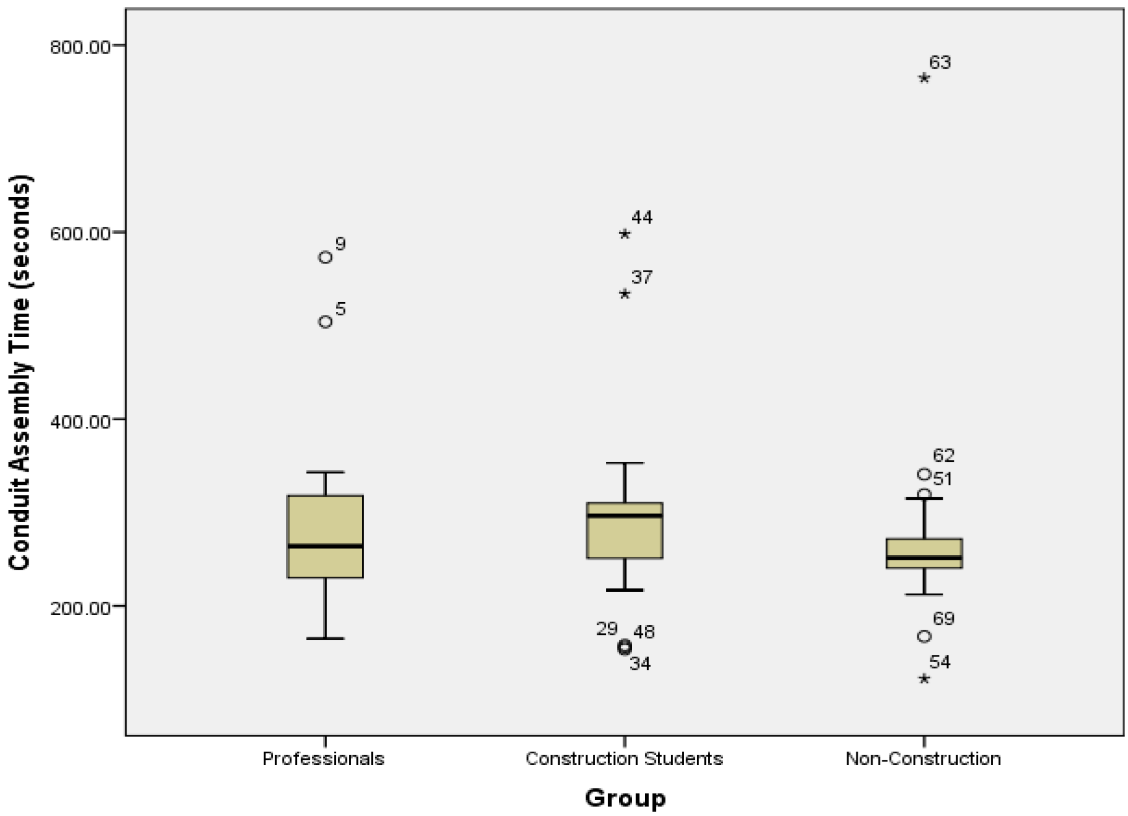

Figure 23: Box Plot of times Taken to Complete Construction by the Three Groups

The only statistically significant difference in performance related to the accuracy of point layout where the average accuracy of the non-construction group was significantly lower than that of the construction professionals and construction students. One possible reason for the reduced accuracy could be the lack of understanding among participants with no construction experience related to the importance of accuracy during the layout process. This rationale is further supported when comparing results with construction students. These participants performed layout more accurately, but also did not have substantial construction layout experience. However, as construction students, they may understand the impact of layout on subsequent construction processes. This may indicate that, for the task of carefully aligning the adhesive note to the augmented

BIM content, accuracy may be more relevant to construction minded students and practitioners because they understand the context in which that task is performed. They may also understand the consequences of inaccurate layout compared to those with no construction background. It is worth noting that, among all participants, the placement of the points was still within 0.071m vertically and 0.046m horizontally. For applications that require relatively low accuracy, such as the electrical layout of a residential project where devices are likely to be installed horizontally to the nearest stud and vertically based on a physical template, the "errors" in AR may be acceptable given the productivity gains observed and the specific workflows involved in current practice.

This research presents a new tool for managers to use to maximize the performance of their personnel by enabling less-experienced professionals to complete construction tasks that had traditionally required more-experienced professionals to handle. If this strategy was leveraged, it would enable more-experienced individuals to manage even more complex challenges that require their domain-specific expertise, and allow less-experienced individuals to handle less complex tasks with AR.

6.6 Limitations

The limitations of this work are related to the test groups, location of testing, and the time required to export BIM for AR use. this research only measured the ability of the participants to learn and perform complex tasks, and not learn new basic skills. All participants in the study had prior knowledge of moving pieces of conduit and using a screwdriver and tape. It should be noted that additional construction training would still be needed for workers to learn the use of new tools and basic skills. Furthermore, the authors recognize that having a different group of individuals, or having the same groups perform slightly different set of tasks could have slightly affected the results. However, the contribution of this work is not in the exact time differences reported, but rather in empirically demonstrating that a group, that might be expected to fail to complete a task using paper, was successful in using AR to complete a task with a similar performance to that of trained professionals using the same technology.

Second, for safety reasons, the research presented was completed in controlled environments. Active construction sites may pose additional challenges for current AR technology. It is possible that additional noise, safety concerns, or other ergonomic constraints related to prolonged AR use could hinder the long-term viability of using AR on actual sites. Fortunately, as the value of AR continues to be documented by researchers, and the practical viability of the technology is studied through pilot case studies with industry, this will continue to encourage developers to enhance the technical attributes of the technology to mitigate observed practical challenges. While this future development is likely to mitigate many of the potential limitations associated with implementing AR on active sites, the authors recognize that the exact magnitude of performance gains offered by AR in this work may be impacted by the environment in which it is used.

Finally, one limitation associated with AR for widespread adoption relates to the process of exporting BIM content to AR. Currently, this process of preparing content for AR is typically performed manually. While the process has been documented in several publications (Alsafouri and Ayer 2017; Chalhoub et al. 2018), if it were to be substantially scaled up, it could require a substantial time investment. Similar to the limitation related to AR environment, this limitation related to exporting BIM content to AR will likely improve in time as more programs and add-ons become available to streamline this process.

6.7 Conclusion

This research tested the use of Augmented Reality (AR) to enable un- and under-trained individuals to complete construction-related tasks. In order to study this, three groups of participants were identified: 1) construction industry practitioners; 2) construction management students; and 3) laypersons without any construction-specific training. All three groups performed two construction tasks using AR, including: 1) prefabricated conduit assembly and 2) electrical point layout. During the conduit assembly task, all participants performed similarly; however, during the point layout task, non-construction participants finished significantly faster, albeit with lower accuracy compared to construction practitioners.

While there were some slight differences in performance among the three groups, the similarity between them was noteworthy. Typically, new employees require between three and five years of training (“Electrician School in Arizona” 2018) to be effective construction personnel. The findings of this work indicate that for certain types of tasks, AR may be an effective tool to enable un- and under-trained individuals to contribute to construction tasks with far less training than has been traditionally required.

These findings provide empirical evidence of the types of performance similarities and differences that may be enabled or hindered among un- and under-trained individuals through the use of AR. These findings may be leveraged by managers to address critical workforce development needs. Potentially, this will enable practitioners to strategically expose new hires to certain types of construction tasks where they may be able to provide immediate value to projects with the use of AR. In the near term, this may help companies to more effectively handle labor shortage concerns. However, practitioners planning to integrate this technology on project and job sites need to independently check the cost of integration. Depending on the number of headsets deployed and the current state of technological advancements within the company, this type of application may require high initial investment. While this high upfront cost could dissuade certain companies from implementing AR, it also underscores the importance of documenting empirical AR testing results in order to support managers in calculating returns on their investment. This research provides initial results to help guide this type of decision-making.

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CHAPTER 7

RESEARCH CONTRIBUTION

Each chapter in this research presents a different aspect of utilization of Augmented Reality in specialty construction. In chapter 2, the author proved that AR can deliver design information to site worker, and enable faster assembly of prefabricated electrical conduit, while lowering mistakes and increasing placement productivity. Chapter 3 found that practitioners using AR can place points in space significantly faster than when using paper plans, but that accuracy is lower, and may be not meeting acceptable tolerances for many applications. Chapter 4 also found that the performance of participants using AR is dependent on several task variables and general complexity of the task. In chapter 5, the author proved the usability of AR as a mechanism of deviation detection, but it still suffers from the same accuracy constraints as active construction tasks. Finally, chapter 6 showed that AR can simplify construction design to enable untrained personnel to complete several key specialty construction tasks at a performance level similar to that of experienced professionals.

The first contribution of this work is in proving that AR can deliver design information to enable pre-construction, construction, and post-construction tasks using industry standard designs and practitioners. The various studies also showed that AR is a capable information delivery mechanism when points need to be identified in space, enabling users to find those points faster compared to using traditional paper plans and measuring tools. This presents and opportunity to increase productivity of craft labor, enabling them to complete more work, thus alleviating the effects of labor shortage.

A recurring limitation of current generation AR technology is related to accuracy: while AR can show elements in their designed location in space, the virtual model shown is only accurate to within an inch. Many construction operations are held to higher levels of accuracy, especially in specialized projects, making the utilization of AR impractical. However, some construction tasks, like vertical electrical devices layout or deviation detection in low risk areas do not have stringent tolerances. These tasks may benefit from the performance gains afforded by AR implementation, further increasing the productivity of available labor.

This work also highlighted the opportunity of using AR for workforce development, by showing that untrained professionals could complete key construction tasks using AR, freeing up more experienced professionals to tackle more technically challenging construction tasks. This could alleviate some of the effects of craft labor shortage.

Another recurring finding throughout this work is related to the positive perceptions towards the technology from the industry practitioners. Even before trying the Augmented Reality experiments, the participants all held a positive perception towards the introduction of technology into their work, and no significant changes in perception after the experiments were observed. While some caution that practitioners and the industry in general is technology adverse, the general perception of the participants towards the technology was positive. The participants further suggested using it with new or untrained workers, or as a training tool for new recruits. Many also suggested using a hybrid method, where both AR and traditional documentation methods are used to ease the transition while the technology matures. This is particularly important, since the practitioners' "buy-in" is essential for the successful implementation of any technology.

Finally, this work provides a set of examples of hybrid approaches that leverage the benefits of AR visualization while minimizing its limitations. While it is impossible to test the applicability of AR on every single construction task, the tested applications and proposed solutions provide a framework that could be generalized to enable informed decision making when planning to implement AR for a new construction task.

The findings highlighted the current performance gains and limitations related to the human performance when using AR for specialty construction tasks through a behavior observation based approach. While observing behaviors may provide insights into the cognitive activity, this work makes no claims as to how AR affects cognitive understanding or processing compared to traditional information delivery methods. Future work can address the identified limitations, especially related to the hardware. Furthermore, the explored human performance attributes could be aggregated and supplemented to create a learning decision-support tool to further support decision making processes related to using AR for new tasks or under new conditions.

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APPENDIX A

SAMPLE QUESTIONNAIRES

MR-Case Study Questionnaire

General Information

1. Study ID: ______________________________________
2. Age: _____________ ☐ Do Not wish to Answer
3. Race/Ethnicity

☐ White	☐ Hispanic/Latino	☐ Black/African American
☐ Asian	☐ Other: ______________________	☐ Do Not wish to Answer

4. Highest level of education achieved

☐ No schooling		☐ Some High School/No diploma
☐ High School diploma	☐ Some College/No Degree	☐ Trade/Technical training
☐ Bachelor's degree	☐ Graduate work/degree	☐ Do Not wish to Answer

5. Current Job Title:

☐ Student/Intern ☐ Other: _________________

6. How many years of experience do you have in the electrical construction industry:

☐ Less than 1 years ☐ 1-5 years ☐ 6-10 years ☐ More than 10 years

7. We define "point layout" as locating the points were electrical boxes and braces will be installed and identifying them on the walls. Have you done any layout exercise before? If yes, about how much of your time is currently spent in layout exercises?

☐ Yes ☐ No

☐	☐	☐	☐	☐
None	About 25%	About 50%	About 75%	All

8. Do you currently use any types of mobile computing devices in your job? If yes, list the name(s) of these devices:

☐ Yes ☐ No

Mobile computing device 1 ____

Mobile computing device 2 ____

PRE-QUESTIONNAIRE

For this experiment, we define the following:

Mixed reality (MR), is a technology that allows viewing of virtual object in real space. For example, the yellow first down line in football is using MR technology, since the line does not really exist but it shows as if it is on the field.

1. Mixed Reality can completely replace paper plans for communicating designs **for the purposes of point layout**:

☐	☐	☐	☐	☐
Strongly Disagree	Disagree	Agree	Strongly Agree	N/A

2. Mixed Reality can completely replace paper plans for communicating point layout designs **for construction in the field**:

☐	☐	☐	☐	☐
Strongly Disagree	Disagree	Agree	Strongly Agree	N/A

3. I am looking forward to eliminating the use of paper plans and relying only on digital means of design communication:

☐	☐	☐	☐	☐
Strongly Disagree	Disagree	Agree	Strongly Agree	N/A

4. Mixed Reality will be easier to use than paper for the purposes of the point layout exercise:

☐	☐	☐	☐	☐
Strongly Disagree	Disagree	Agree	Strongly Agree	N/A

POST QUESTIONNAIRE

1. Mixed Reality can completely replace paper plans for communicating designs **for the purposes of points layout**:

☐ Strongly Disagree ☐ Disagree ☐ Agree ☐ Strongly Agree

2. Mixed Reality can completely replace paper plans for communicating point layout designs **for construction in the field**:

☐ Strongly Disagree ☐ Disagree ☐ Agree ☐ Strongly Agree

3. I am looking forward to eliminating the use of paper plans and relying only on digital means of design communication:

☐ Strongly Disagree ☐ Disagree ☐ Agree ☐ Strongly Agree

4. Mixed Reality will be easier to use than paper for the purposes of electrical conduit construction:

☐ Strongly Disagree ☐ Disagree ☐ Agree ☐ Strongly Agree

5. Rate your agreement with the following sentence: It is easy to use Mixed Reality for points Layout

☐ Strongly Disagree ☐ Disagree ☐ Agree ☐ Strongly Agree

6. Wearable Mixed Reality devices, such as the HoloLens, provide an effective visualization interface for points layout:

☐ Strongly Disagree ☐ Disagree ☐ Agree ☐ Strongly Agree

7. With Mixed Reality, I can effectively layout points without the need for traditional paper documentation:

☐ Strongly Disagree ☐ Disagree ☐ Agree ☐ Strongly Agree

APPENDIX B

NASA-TLX QUESTIONNAIRE

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Study ID	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

APPENDIX C

SUPPLEMENTAL DATA

Chapter 2

Metric	Count	Mixed Reality		Paper Plans	
		Average	Standard Deviation	Average	Standard Deviation
Overall Time	18	277.85	101.85	504.15	190.89
Time to place first piece	18	20.07	10.07	47.99	41.67
Time spent looking at model	18	43.84	38.8	143.34	103.57
Time to place the conduit	18	5.18	4.32	85.73	45.56
Number of mistakes	18	4	NA	16	NA
Number of correct final layouts	18	16	NA	11	NA

Chapters 3 and 4

Times (in second)

	Augmented Reality		Paper Plans	
	Average	Standard Deviation	Average	Standard Deviation
Room 1	124	95.5	466.3	251.5
Room 2	171.8	120.6	464.5	223.8
Room 3	270.6	204.3	958.3	441.4
Room 4	144.1	137.8	486.6	289.1

Accuracy in Feet

	Paper			
	X-axis		Y-axis	
	Average	Standard Deviation	Average	Standard Deviation
Room 1	0.08	0.105	0.041	0.092
Room 2	0.104	0.161	0.126	0.4816
Room 3	0.149	0.206	0.068	0.271
Room 4	0.113	0.1834	0.0832	0.2944

	AR			
	X-axis		Y-axis	
	Average	Standard Deviation	Average	Standard Deviation
Room 1	0.0985	0.117	0.0833	0.0791
Room 2	0.121	0.135	0.088	0.09
Room 3	0.117	0.135	0.1134	0.1201
Room 4	0.1022	0.0925	0.0889	0.1164

	students	Non-construction group
Conduit Time average (seconds)	299.59	275.87
Conduit time Standard Deviation (seconds)	111.05	118.7
Points Time average (seconds)	114.42	102.76
Points time Standard Deviation (seconds)	48.96	32.28
Conduit correct	61.1%	71.4%
X-axis accuracy (feet)	0.096	0.237
X-Axis Standard Deviation (feet)	0.181	0.362
Y-axis accuracy (feet)	0.109	0.303
Y-axis Standard Deviation (feet)	0.193	0.388

Deviation	Correctly identified	Correctly Classified	Total number of observations
Big Deviation 1	26	26	27
Big Deviation 2	26	23	27
Missing Element	20	16	27
Small Deviation	11	11	27