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A REVIEW OF AUGMENTED REALITY APPLIED TO UNDERGROUND CONSTRUCTION

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SUMMARY: *Unintentional striking of underground utilities from construction activities often results in high economic consequences. Advanced technology and sophisticated visualization techniques such as augmented reality (AR) has the potential to play a significant role in mitigating such devastating consequences. To better understand the state-of-the-art technology of AR applications in the underground construction industry, it is important to identify challenges and barriers. This paper provides a systematic literature review of applications in the construction industry in general in which journal articles were reviewed, analysed, and summarized. Through this method, the main challenges associated with AR were revealed and feasible solutions were suggested. Issues were found with 1) data collection; 2) modelling and alignment barriers; 3) hardware limitations; 4) tracking; and 5) managing data. This research examined an efficient solution to the problems of AR by proposing a framework for future implementation with main applications in the United States, Canada, and Australia.*

KEYWORDS*: augmented reality, utilities, underground construction*

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1. INTRODUCTION

In 2016, the societal damage caused by utility strikes in the United States (U.S.) resulted in an estimated dollar amount of $1.5 billion USD, with 390,000 incidents being reported to the Damage Information Reporting Tool (DIRT) in that year (CGA 2016). For example, during a waterline insulation in Fairborn, Ohio in 2011, workers hit a gas distribution pipeline leading to an explosion that killed one person and injured five others (The Associated Press 2011). Another incident took place in St. Cloud, Minnesota when excavation workers hit a high-pressure gas service pipeline while attempting to install a utility pole support anchor. The incident resulted in the destruction of six buildings, four fatal injuries, one serious injury, and ten minor injuries including two firefighters and one police officer (Hall et al. 1998). The damage assessment was estimated at $399,000 in property losses alone (Hall et al. 1998). Underground utilities in the U.S. consist of more than 35 million miles (56 million kilometers) of buried services. Due to population growth and urban development this number is increasing every year (Nelson et al. 2012), subsequently making it challenging to maintain a database of the country's existing underground utility network (Tabarro et al. 2017).

There is always a need for the buried infrastructure to be replaced because it is perpetually aging. The U.S. water and wastewater pipeline network for example, were given failing grades in the 2017 Infrastructure Report Card from the American Society of Civil Engineers (ASCE). The ASCE estimated that a total of $2.2 trillion USD will be needed to overhaul the entire US infrastructure network between 2016-2025 and the process of replacement may cause even more damage (ASCE 2017),. This longstanding and significant problem occurs due to a lack of inaccurate utility location information, poor excavation techniques, and/or inadequate planning (Makana et al. 2016). According to Sterling (2009), this damage is caused by the lack of information pertaining to the exact location of the underground utilities. Due to the urgent need to avoid such damage, stakeholders have been searching for an adequate method of collecting utility location data, modelling these data, and visualizing the location of the specific buried utilities. It is thought that doing so will increase the ability of construction personnel to perform reconstruction and prevent utility strikes (Dong and Kamat 2013; Zhang et al. 2015; Talmaki and Kamat 2014; Li et al. 2015).

This need motivated the authors to investigate augmented reality (AR), as defined by Azuma et al. (2001) as "a visualization technique that has the power to superimpose virtual three-dimension models into physical reality with fixed geographic coordination systems" (Fenais et al. 2018a). Comparatively, AR has already proven its value in the medical, manufacturing, and gaming industries (Azuma et al. 2001; Tzimas et al. 2018). Currently, stakeholders in the underground construction industry are still being introduced to AR technology and ways it may help mitigate the issues associated with underground utility construction. Underground construction refers to any construction project that could disturb existing underground utilities. Therefore, a systematic analysis of articles published in academic journals was conducted to gain a better perspective of the current state-of-practice. This analysis uncovered the current limitations with the technology while navigating current research in the direction of the most valuable and critical areas benefiting the industry. This study revealed the challenges facing AR development by reviewing over 600 publications, while it also contributes to the corpus of literature by informing potential stakeholders of the barriers that are needed to be overcome when applying AR in an underground utility project. Finally, an efficient and cost-effective solution was suggested by developing a theoretical framework, which is instrumental in the future development of AR applications aimed at predicting the accurate location of underground utilities. The main motivation behind this research is to make the construction industry more aware of the benefits of leveraging AR to prevent utility strikes and enhance public safety.

2. BACKGROUND

2.1 Current Strike Prevention Practice

The primary method of preventing excavation damage in the United States, Canada and Australia is through the One-Call system, which requires by law those who carryout excavation operations to determine and confirm the location of existing utilities with the designated area to be excavated prior to breaking ground. The process starts with the contractor requesting a dig ticket from the One-Call center. Subsequently, the One-Call center contacts the utility service providers that fall within the center's jurisdiction, after which the utility providers mark the surface using one or a combination of the following markers; spray paint, stakes, and flags (Talmaki and Kamat 2014). When excavation begins, the markers are the first elements to be removed and the excavation operators must rely on memory to find the location of the utility or complete the One-Call system again, which will inevitably cause a delay in the project (Su et al. 2013). Fig. 1 illustrates the workflow of the One-Call system. Even with the diligent efforts of each State's One-Call system, the reality is that many undocumented underground utilities exist throughout the nation. As we continue to adopt trenchless construction methods such as horizontal directional drilling (HDD) in urban environments, there needs to be parallel technological advancements to reduce the risk of utility strikes (Fenais et al. 2018b).

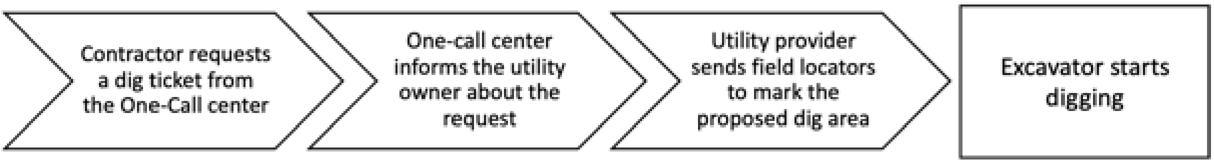

FIG. 1: Typical One-Call center workflow

Talmaki and Kamat (2014) classified two approaches for the identification of the location of buried utilities. The first approach is multisensory employing a combination of geophysical tools such as radio waves, magnetometers, and infrared thermography. The second is the information technology approach using geospatial databases, tracking technology, and computer graphics visualization. This paper focuses on the second approach and, in particular, utilizing computer visualizations to mitigate striking an existing utility because it employs software rather than hardware as in the first approach.

2.2 Augmented Reality (AR)

Augmented reality (AR) is a visualization technique that superimposes virtual three-dimension models onto physical reality, using a fixed geographic coordination system as illustrated in Fig.2 (Azuma et al. 2001). AR is more advanced than other visualization technologies in three aspects: 1) it reinforces the connection between individuals and objects; 2) it increases the awareness of the engineers performing field tasks; and 3) it reduces the cost of 3D model engineering by using real-world geographic data as background layers (Behzadan et al. 2015). Therefore, via this technique, detailed information of each utility such as land ownership, installation date, original location, and contractors can be shared among users using cloud storage or local databases. In addition, AR technology has shown great promise and applicability in the construction industry as reported by numerous researchers (Behzadan and Kamat 2007; Bae et al. 2013; Behzadan et al. 2008; Chi et al. 2013; Rankohi and Waugh 2013). One example was from Talmaki et al. (2010) who developed a visualization system to help excavators avoid collisions by enabling operators to see buried utilities ahead of time. Omar and Nehdi (2016) also wrote that AR applications are extremely promising and are suitable for all project types and sizes due to the web-based wireless technologies becoming more accessible.

FIG. 2: Using an AR system to inspect the project site before construction, extra lines were found in the system

Lightweight, mobile, and immersive AR systems are recommended for underground projects due to the dynamic environment of construction areas. They offer significant support to decision-makers by providing high accuracy and timely schedule updates. The ongoing technological development of such applications means that they are increasingly becoming more cost-effective, with an enhanced ability to provide detailed information on various project tasks.

2.3 Previous Literature Review Studies of AR in Construction

Rankohi and Waugh (2013) reviewed 133 articles published between 1999 and 2012 from eight journals. This study presented a statistical review of AR in architecture, engineering, construction and facility management. They reviewed the academic articles by classifying eight domains including improvement focus, industry sector, target audience, project phase, stage of technology maturity, application area, comparison role, and technology. In the end, the authors came up with several predictions. The most important being that future trends are moving toward the use of web-based mobile augmented systems for field monitoring (Rankohi and Waugh, 2013).

Behzadan et al. (2015) gave a detailed review of augmented reality applications in civil infrastructure systems. The paper reviewed the critical problems associated with AR that prevent the civil infrastructure industry from adopting the technology and provided a technical approach to overcome the challenges facing the industry by applying AR effectively. In the research, AR challenges in the civil infrastructure industry include the alignment of virtual objects with the real environment, the blending of virtual entities with their real background faithfully, and the integration of these methods to a scalable and extensible computing AR framework that is openly accessible to the research community.

Li et al. (2018) provided a critical review of virtual and augmented reality (VR/AR) applications in the construction safety area, by reviewing journals published between 2000 and 2017. The paper includes a generic taxonomy of: 1) VR or AR technology characteristics; 2) application domain; 3) safety enhancement mechanisms; and 4) safety assessment and evaluation. Moreover, the paper listed research gaps extracted from an in-depth review, which helped with this research work. The aim of their work was to assist both researchers and the construction industry by identifying the latest VR or AR safety applications.

3. SCOPE AND METHODOLOGY

The aim of this research is to investigate the overall challenges currently preventing the construction industry from adopting AR in underground utility mapping and propose a theoretical framework to assist in capturing an accurate location of underground utilities through a systematic analysis. Synthesizing the literature enables the identification of the challenges that may arise in the future development of AR for underground construction applications, in particular.

To achieve a systematic analysis, a three-phase review was performed as illustrated in Fig. 3. In phase one, the review methodology is synthesized (Rankohi and Waugh 2013; Li et al. 2018), followed by a comprehensive search that was conducted using various library search engines for each of the selected journals: Journal of Automation in Construction (AIC), Journal of Computing in Civil Engineering (CCE), Advanced Engineering Informatics (AEI), Visualization in Engineering (VE), Institute of Electrical and Electronics Engineers (IEEE), Journal of Management in Engineering (ME), Journal of Construction Engineering and Management (CEM), Journal of Infrastructure Systems (IS), and Journal of Surveying Engineering (SE). These journals capture the main literature in construction research and are contained in the main indexes. As previously mentioned, the research uses the construction industry in general for the systematic literature review with a focus on underground construction. The reason for using the construction industry, in general, is because there are limited articles on AR specific to the underground construction sector. By using the following keywords; augmented reality, AR, mixed reality, and virtual reality in the search engine; papers containing these specific terms in the abstract or title were considered to meet the requirements of this research, while articles that came in forms such as editors' notes, volume contents, calendars, and subject indices were excluded. This phase of the search identified 619 articles; however, the results still included unwanted publications that happened to include the keywords, but do not specifically discuss the issue of augmented reality in construction. After reviewing the 619 articles in the database using a visual examination method, only 69 articles were determined to be appropriate for AR in the construction industry. This intensive method is done by comprehensively reading each article's abstract and eliminating the ones unrelated to the construction industry.

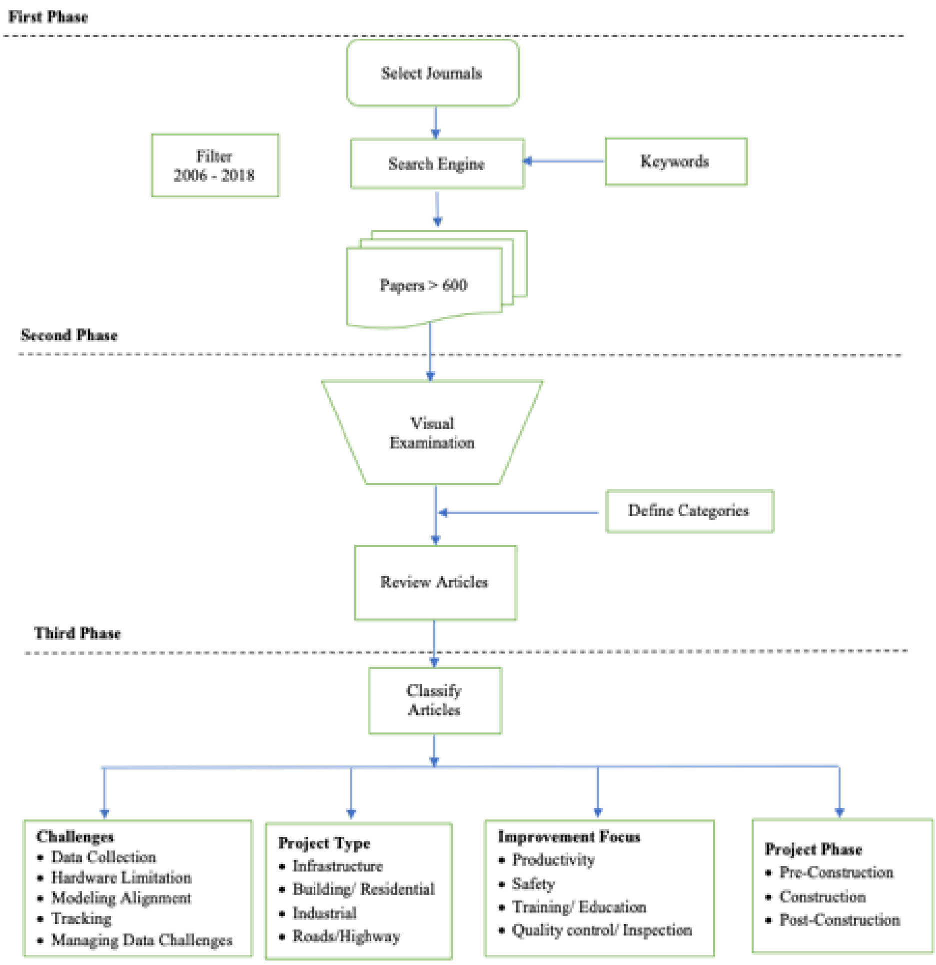

FIG. 3: The research framework methodology

3.1 The Classification of Article Characteristics

Since this review deals with a large number of articles, it is important for the methodology in the third phase to classify the selected journals that can guide the review to yield valuable findings and benefit the construction industry. The research defined three main categories, namely, challenges in applying AR system which includes project type, improvement focus, and project phase. The categories were divided into sub-categories and each article was compared to these defined sub-categories to determine the percentage of articles in the specific domain. Each category and sub-category are further explained in the next sections with Table 1 summarising the categorizations. The analysis of the categorized articles enables the extraction of general findings from the review work, which in turn could be applied to the redesign of current AR systems and generate a framework for AR best practices in the underground industry.

TABLE 1. The defined categories and sub-categories

Categories	Sub-categories
Challenges in the AR system	Data collection, hardware limitations, modelling alignments, tracking, and managing data.
Project type	Infrastructure, building or residential, industrial, and roads or highways
Improvement focus	Productivity, safety, training or education, and quality control and inspection

Project phase	Pre-construction, construction, and post-construction

4. RESULTS AND DISCUSSION

4.1 Justification of Publication Quantity

The number of archival journal articles found in each phase is presented in Table 2, while the distribution of the articles by journal and year of publication is outlined in Table 3. From 2013 to 2018, a significant increase in publications was observed. Among the reviewed journals, Automation in Construction (AIC) contained the highest number of publications, followed by the Journal of Computing in Civil Engineering (CCE). From 2006 to 2018, there were twenty-five papers for AIC, nineteen for CCE, eleven for Advanced Engineering Informatics (AEI), ten for Visualization in Engineering (VE), three for the Institute of Electrical and Electronics Engineers (IEEE), and one for the Journal of Management in Engineering (ME).

TABLE 2. List of selected journals and articles for each phase

Journal	Phase 1	Phase 2
Journal of Automation in Construction (AIC)	162	25
Journal of Computing in Civil Engineering (CCE)	124	19
Advanced Engineering Informatics (AEI)	75	11
Visualization in Engineering (VE)	22	10
Institute of Electrical and Electronics Engineers (IEEE)	11	3
Journal of Management in Engineering (ME)	49	1
Journal of Construction Engineering and Management (CEM)	111	0
Journal of Infrastructure Systems (IS)	29	0
Journal of Surveying Engineering (SE)	21	0
Journal of Geotechnical and Geoenvironmental Engineering (GG)	15	0

TABLE 3. The distribution of articles by journal and year of publication

Journal/Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
AIC	2	0	3	3	0	0	1	4	1	1	1	3	6
CEE	1	2	0	2	0	1	2	3	1	3	4	0	0
AEI	0	0	1	1	0	0	1	1	3	3	1	3	0
VE	0	0	0	0	0	0	0	5	0	3	1	1	0
IEEE	0	0	0	0	0	0	0	0	1	0	0	1	1
ME	0	0	0	0	0	0	0	0	0	1	0	0	0

4.2 Challenges with Augmented Reality (AR)

Augmented Reality utilizes five applications to integrate virtual underground utilities with the construction site. Fig. 4 illustrates the technologies integrated into a comprehensive AR system applicable to underground construction. These five applications are: 1) data collection of new or existing utilities, 2) modelling and aligning data into 3D virtual content using a global positioning system (GPS), 3) displaying the models using portable hardware, 4) tracking user locations to show nearby stored 3D model objects, and 5) storing the data so it can be accessed by future projects (Chi et al. 2013). A number of articles examined one or more of the AR challenges including data collection, hardware, modelling alignment, tracking, and managing data. Hardware limitations and modelling alignment barriers were the most frequent topics of research among the selected articles, with 19 (28%) and 15(23%), respectively. To ensure success in applying AR in an underground construction project, all potential challenges need to be overcome. The following section defines each challenge and suggests a solution based on an analysis of the reviewed literature.

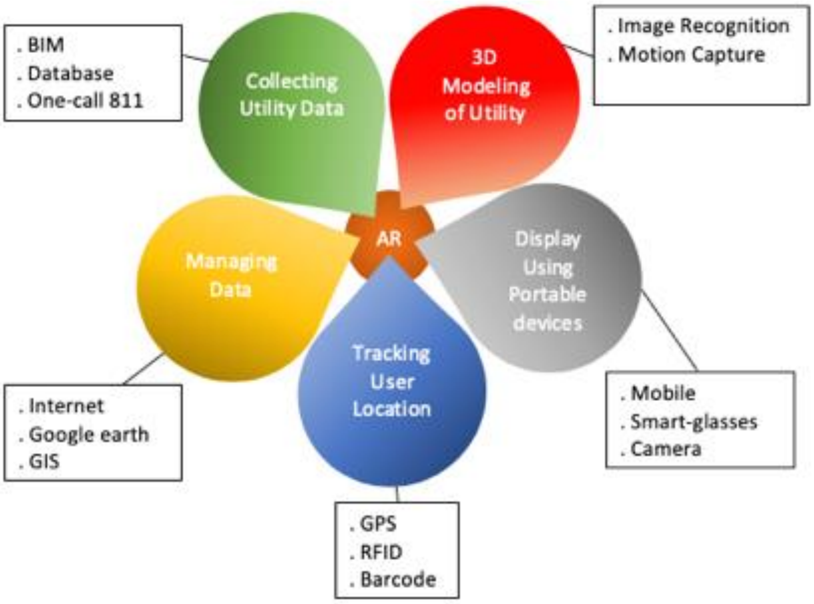

FIG. 4: Integrated technology in developing AR applications for underground construction

4.2.1 Data Collection Issues

The first step in developing an AR system is to obtain accurate underground utility data. When utilities are installed, their locations are denoted in as-built drawings; however, these can vary in terms of positional accuracy (Su et al. 2013). Having accurate as-built data on the precise location of existing underground utilities is a major issue today in underground construction. The lack of reliable data can result in damage to existing utilities with varying consequences. For example, striking an unknown or mismarked natural gas line could result in an explosion with grave consequences. Construction personnel in the United States, Canada and Australia seek to locate existing utility locations prior to excavation by calling the One-Call center, which in turn creates a dig ticket. Utility owners are required to respond to a dig ticket within a designated period (i.e. 48 business hours in the U.S.) and mark the approximate location of their respective utility. In the U.S., each State has specific accuracy tolerances according to their respective Underground Facility Regulations. Service locators usually employ as-built drawings or geophysical surveys based on sensing and locating techniques such as ground-penetrating radar (GPR), radio frequency (RF), detection techniques, terrain conductivity, and/or electromagnetic techniques (Billinghurst et al. 1998).

Data collection is essential to define the correct level of detail by data range input (Golparvar-Fard et al. 2013). Li at al. (2015) presented a system for the mapping of underground utilities using ground penetration radar, GPS, and geographical information systems. The collected data is then visualized using AR to foster safe excavation and avoid utility strikes. Despite advancements in visualization technology, it is still difficult to efficiently process a large amount of data and visualize only the required subsets for projects (Golparvar-Fard et al. 2013). Most of the existing AR systems focus on rendering the inputted data from the database such as as-built maps. In other words, they cannot input data using AR on site. However, a feasible solution by Fenais et al. (2019) has been developed to integrated AR and GIS for mapping and capturing underground utilities using a mobile device on site.

4.2.2 Modeling and Alignment Barriers

Modelling may be performed to represent existing utility as-builts (Son et al. 2015). The primary approach to programming an AR system for underground utilities is to project three-dimensional (3D) pipeline models onto the real world and create an illusion that the 3D model and real world coexist (Dong et al. 2013). The goal of modelling alignment is to properly align real world objects, in this case utility lines, and superimpose virtual objects with respect to each other. Therefore, it is essential for objects in the real world and superimposed models to accurately align with each other in order to accurately identify the location of the utilities (Behzadan and Kamat 2007).

There are two common types of errors when registering virtual objects with a background. The first type are static errors including: 1) inaccuracies in sensor measurements; 2) mechanical misalignments between sensors; and 3) an incorrect registration algorithm (Dong et al. 2013). The second type are dynamic errors including the duration of delays in the occurrence of a real event and its arrival on the host, and synchronization delays (Dong et al. 2013).

4.2.3 Hardware Limitations

For augmented reality, the term "hardware" refers to the use of a portable display devices to view the merged virtual and real worlds. Azuma et al. (2001) classified displays from head-worn devices (HWD), handheld units, and projection displays. Hardware plays an especially crucial role in the advancement of AR systems and can improve tracking, storing data, and aligning the virtual and real worlds. According to the literature review (Fig. 5), the hardware limitation is the most challenging problem that developers need to overcome to reach the desired goals. Nineteen articles reviewed mentioned such limitations. The literature illustrates the Vincenty method, which is widely used in geodesy to compute the location of a point that is a given distance and azimuth (direction) from another point (Vincenty 1975). It is accurate to within 0.5 mm (0.020 in) on the Earth's ellipsoid. This method is commonly used among developers for AR assembly; however, problems have still been found when displaying the virtual models (Behzadan and Kamat 2007; Fuge et al. 2012), .

Handheld displays – also known as mobile-based augmented reality (MAR) systems for field construction monitoring (Wang et al. 2013) – are one alternative. MAR consist of portable devices such as smart phones and tablets, and modern-day MAR are becoming cheaper, more powerful, and smaller, which will decrease the hardware limitations and ensure the feasibility of applying AR (Chi et al. 2013).

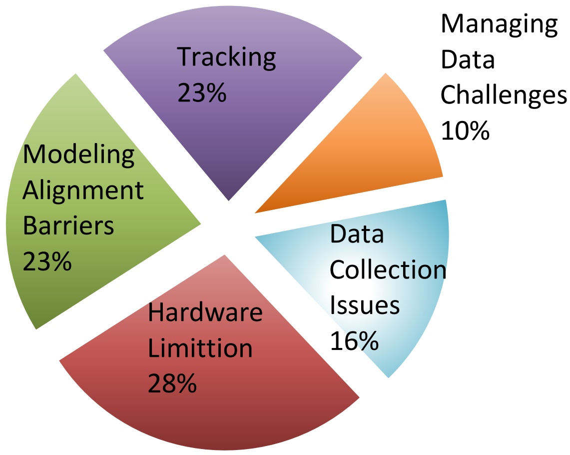

FIG. 5: The number of articles that examine one or more of the AR challenges (N = 69)

4.2.4 Tracking Limitation

Positioning technology to track both outdoor and indoor project site activities is important to support information delivery (Behzadan et al. 2008). The research presented in this paper focuses on outdoor tracking, because underground construction projects are performed in an outdoor environment. The use of GPS is an effective tracking tool for underground utility projects; however, in order to obtain an accurate reading of the user's location, it has to be visible to a certain number of GPS satellites (Song et al. 2006). Additionally, tracking of both user and utility location is needed to provide continuous relative correction when the user is moving. A well-designed GPS receiver can typically reach a positioning accuracy of 3m to 6m (Renfro et al. 2018). Nearby high-rise buildings can affect the reading of GPS signals as illustrated in Fig. 6, showing satellite signal blockage. Bea et al. (2013) suggested a feasible solution that involves modelling alignment barriers by developing a tracking system for AR that does not require any location tracking models, GPS, and/or markers. Instead the user's location and orientation are derived by comparing images from pre-collected site photos. The authors claim that the system of image-comparing processing is thirty-five times faster than other state-of-the-art structure-from-motion algorithms. Therefore, the use of additional tools will likely boost accuracy that includes image tracking, wireless sensors, Bluetooth, or radio frequency identification (RFID). These can also be used as tracking technologies for augmented reality (Jian et al. 2018). The need for better positional accuracy is desirable to track the location of utilities. This need for higher accuracy motivated Chen et al. (2016) to propose a novel way of providing reliable positioning using a differential GPS (DGPS) technique by adding a ground station that increases accuracy to 5 cm attached to an AR device. The literature review showed that tracking is the second most important challenge to overcome in the course of AR development, especially for underground utility applications.

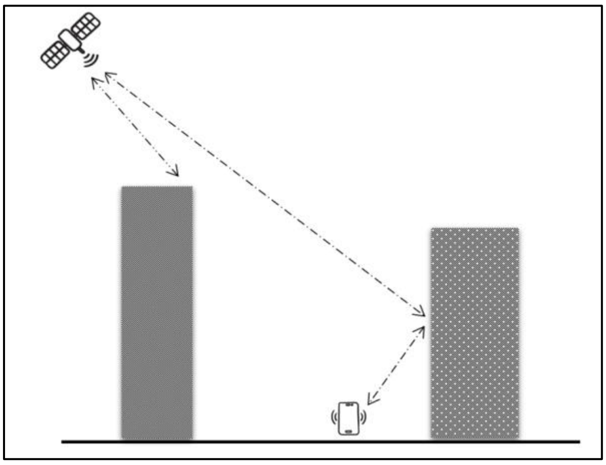

FIG. 6: Satellite signal blockages can affect GPS accuracy

4.2.5 Managing Data Challenges

The underground construction industry generates massive amounts of data throughout the life cycle of a project which is also difficult to efficiently process (Soibelman and Kim 2002),. Some of the types of data obtained from construction sites may include 3D point clouds, 2D images, video frames, and other sensor data (Bilal et al. 2016). After solving the problem of data storage, the next most significant challenge is managing the data. This can be resolved by GIS, which allows utility owners to store a complete utility inventory in a single repository that is easy to update and extract (Behzadan and Kamat 2007).

4.3 Project Type

In the construction industry, there are a number of project types that can benefit from AR technologies. To classify these project types, the following industry sectors were chosen based on Rankohi and Waugh (2013): 1) infrastructure, e.g., inspection of segment displacement during tunnelling (Zhou et al. 2017); 2) commercial or residential buildings, e.g., steel column inspection (Shin and Dunston 2009); 3) industrial, e.g., integration with building information modeling (BIM) in the liquefied natural gas industry to monitor onsite construction activities (Wang et al. 2014); and 4) roads or highways, e.g., evaluating pavement cracking through the use of image recognition (Tedeschi and Benedetto 2017).

Fig. 7, showing the percentage of articles that examined these different project types, indicates that 36% of the articles focus on the use of AR technology in the building or residential sector.

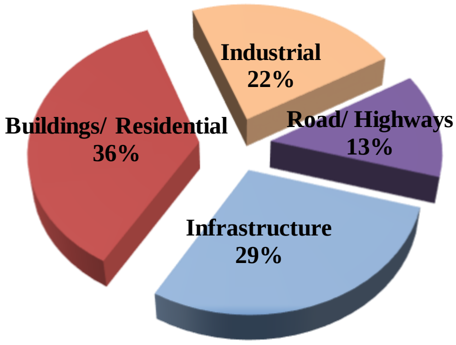

FIG. 7: The percentage of articles published for various types of industry (N = 69)

The highest number of articles published in a single year on building or residential projects took place in the year 2013. This outcome is reasonable and not surprising considering the fact that AR technology is enhanced by BIM (Park et al. 2013). Additionally, the complexity of building projects requires integration of technologies, compared to roads and highways. Table 4 presents a list of selected articles for each sub-category of project type.

TABLE 4. Reference articles for various construction industries

Industry Type	References
Infrastructure	(Azar 2016; Talmaki and Kamat 2014; Hammad et al. 2009; Li and Lu 2018)
Building residential or commercial	(Liu and Seipel 2015; Dong et al. 2013; Irizarry et al. 2013; Omar and Nehdi 2016)
Industrial	(Blanco-Novoa et al. 2018; Wang et al. 2016; Son et al 2015)
Roads or highways	(Bea et al 2015; Balali and Golparvar-Fard 2016)

4.4 Project Phases

There are several ways in which AR can be integrated throughout the life cycle of a construction project. According to De Wit (1988) and Dawood et al. (2009), life cycle can be divided into three main phases: pre-construction; construction; and post-construction. Shin and Dunston (2008) identified nine areas suitable for AR application in the architecture, engineering, and construction industries based on usability and benefits. This research synthesizes the studies performed by Shin and Dunston (2008) and Piroozfar et al. (2018) to summarize construction life cycle activities as presented in Fig. 8.

FIG. 8: The applications of AR in project life cycle activities

4.4.1 Pre-Construction

Key benefits of utilizing AR applications in the pre-construction phase were found to improve the design stage between all parties involved. AR can help architects to gain a more realistic understanding of surrounding environments (Portman et al. 2015). Moreover, AR formats have potential in planning for logistics system to track materials and equipment. During the construction planning process, the scenario of equipment operations can be simulated in the office using AR (Kim et al. 2012). In addition, studies have shown that owners typically favor the use of AR to evaluate the complete design of projects (Meža et al. 2015). In the underground utility construction, AR could be used as an inspection tool for identifying buried marked, existing utilities to help contractors identify these prior to commencing excavation activities.

4.4.2 Construction

Complex tasks in construction processes require highly trained workers (Yi and Chan 2014). According to Piroozfar et al. (2018), AR solutions can provide a functional use to the various construction industry phases. In addition, keeping track of the tasks accomplished can necessitate an excessive amount of time to gather information from each worker. Subsequently, this makes AR an effective tool for training, supervising, and collaborating during construction (Park et al. 2013; Bosché et al. 2016). Although diverse in possible applications to construction related tasks, AR may be more suitable for certain tasks than others.

4.4.3 Post-Construction

In the maintenance or operation phase, integrating AR with BIM can be done by means of facilities management (FM) systems to increase asset value; e.g., hidden utilities in a building can be shown with a great deal of precision (Liu and Seipel 2018). Additionally, it enhances efficiency for complex tasks such as those performed in the oil industry (Hou et al. 2014). Fig. 9 illustrates the percentage of articles, based on project phase, indicating that 49% of the articles focus on the construction phase, which is understandable, given the fact that AR can increase a worker's productivity and safety.

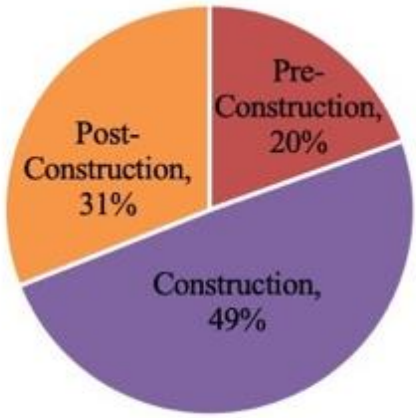

FIG. 9: The percentage of articles based on project phase (N = 69)

4.5 Improvement Focus

Current studies and development in AR can be used in a wide range of areas in the construction industry to improve the overall project. Also, it aids the spatial cognition of construction personnel by supporting user tasks in newly experienced or complex environments (Wang and Dunston 2006). The improvement area can be classified into four areas: 1) productivity; 2) safety; 3) training or education; and 4) quality control. Articles would be classified based on where the proposed improvement in the article would occur.

Fig. 10 illustrates the number of articles within each improvement focus. Thirty-one articles (45%) have a focus on productivity, while fifteen articles (22%) have a principal focus on quality control and inspection. Additionally, fourteen articles (20%) and nine articles (13%) have a principal focus on safety, and training or education, respectively. The majority of the articles reviewed in the literature focused on improving productivity by utilizing AR applications in the constructing industry.

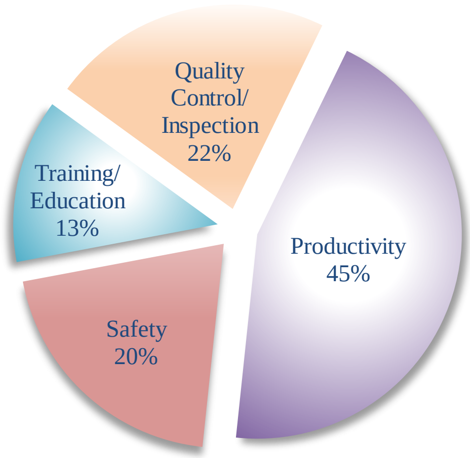

FIG. 10: The distribution of articles that propose an AR improvement focus (N = 69)

5. THEORETICAL FRAMEWORK FOR AR APPLIED TO UNDERGROUND UTILITY PROJECTS

This paper proposes a conceptual framework for using AR applied to underground utility construction. The key element of this framework is a cloud-based GIS that can be shared between all stakeholders. The framework ensures a real-time information flow between utility owners and contractors and is illustrated in Fig. 11. In Steps 1 to 4, the contractor pre-marks the excavation area using traditional methods of white paint or flags, and then registers the new proposed line using the AR system. The new lines are uploaded onto a cloud database and stored for future access. Thereafter, the contractor requests a dig ticket from the One-Call center. In Steps 5 and 6, the One-Call center informs individual utility owners of the contractor's request who then send field locators to mark the approximately location of their respective utility. In Steps 7 to 9, the utility locators use the AR system for guidance regarding the exact location of the new line proposed by the contractor in Step 3 to mark-out the job site using both traditional methods and the AR system. The captured utilities are uploaded to the cloud database and shared with the contractor. Finally, in Step 10, excavators start digging using the AR system to update the depth of the utilities. This step assists in building a reliable database that can be shared among underground utility stakeholders.

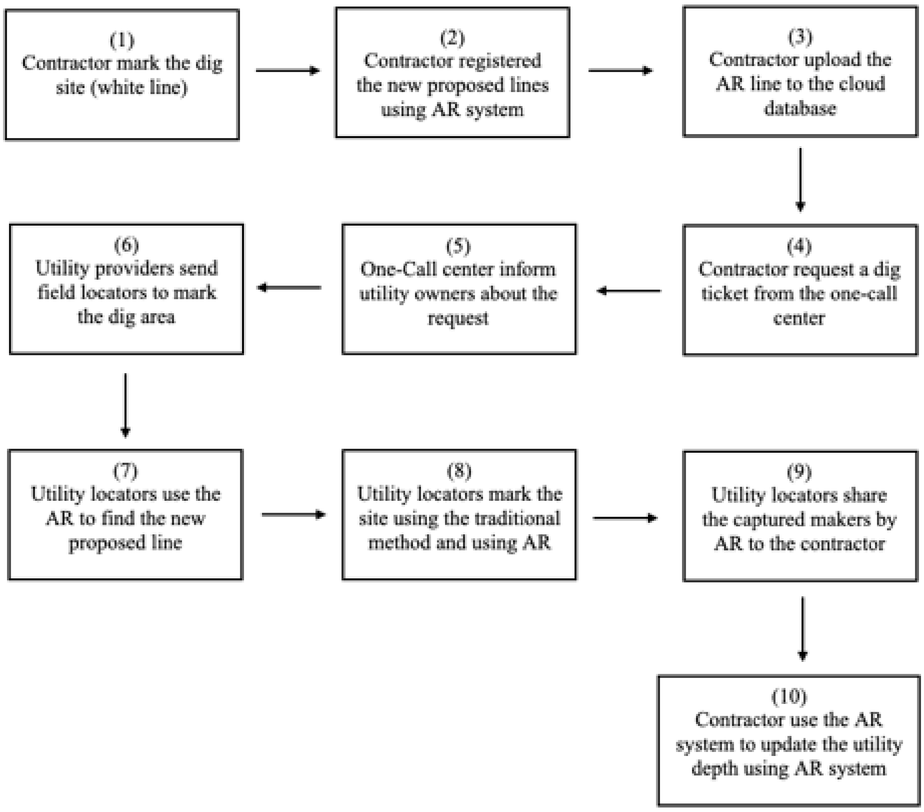

FIG. 11: The proposed theoretical framework using AR for underground construction sites

6. CONCLUSIONS

This paper provided a systematic literature review of the use of augmented reality (AR) in the construction industry. It identified and analysed challenges and investigated technical approaches to addressing the fundamental challenges that prevent the technology from being usefully adopted in the underground construction industry. The structured methodology was used to identify sixty-nine articles on the topic of augmented reality from ten well-recognized indexed construction industry journals. The review of research trends from the literature enabled the identification of challenges in AR development that could result in better application to underground utility construction.

There is a critical need to protect existing underground utilities during excavation. The implementation of an AR system enables equipment operators, as well as other site personnel, to view virtual models of subsurface utility pipes at the construction site. Experiments with hardware and software systems have proven the feasibility of the idea of creating real-time visualizations of computer models on top of live video backgrounds. Such visual information support can significantly reduce the risk of damaging buried utilities by enhancing the contractor's display of the work site. By building on existing technologies, the main contribution of this research is proposing a theoretical framework that provides guidance in the development of AR applications aimed at visualizing the accurate location of existing underground utilities.

The American Society of Civil Engineers (ASCE) has estimated that in the United States, a total of $2.2 trillion is needed to overhaul the entire country's infrastructure system over the next few years. Water (D) and wastewater (D+) pipelines were given failing grades in the 2017 ASCE Infrastructure Report Card (ASCE 2017). Installing new utilities and replacing old ones are all necessary as part of the required maintenance. This research is very timely and important, especially given that the proposed framework would allow excavation contractors to visually observe buried utilities from the surface and could also help to reduce time and cost over-runs, while significantly improving safety.

AR is both a needed and useful technology for the construction industry. It has been applied in practice to confront various logistical problems associated with construction. In underground construction applications, AR technology could aid in locating existing utilities or any other significant hindrances, thereby reducing potential risks of striking these lines. Furthermore, considerable time and money savings could be realized.

It is recommended that future studies be conducted to identify best practices for the application of AR and measuring productivity when using this technology to locate existing utilities. For example, the use of AR could help to reduce the amount and time for potholing to expose underground utilities prior to installing a new utility line. It is also recommended to develop an integrated system using GIS and AR to more efficiently input data in the field.

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