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Review and analysis of augmented reality literature for construction industry

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Abstract

Research has identified various beneficial capabilities for augmented reality technologies in the AEC industry such as virtual site visits, comparing as-built and as-planned status of projects, pre-empting schedule disputes, enhancing collaboration opportunities, and planning/training for similar projects. This paper provides an expanded foundation for future research by presenting a statistical review of augmented reality technology in the AEC industry. The review is based on articles found within eight well-known journals in architecture, engineering, construction, and facility management (AEC/FM) until the end of the year 2012. The review further narrows the literature within these journals by considering only those 133 articles found through a key word search for "augmented reality." The selected journal articles are classified within the following dimensions: improvement focus, industry sector, target audience, project phase, stage of technology maturity, application area, comparison role, and technology. The number of articles within these dimensions are used to identify maturing and emerging trends in the literature as well as to synthesize the current state-of-the-art of augmented reality research in the AEC industry. In summary, the AR literature has increasingly focused on the demonstration of visualization and simulation applications for comparison of as-planned versus as-built statuses of the project during the construction phase to monitor project progress and address issues faced by field workers. In addition, the future trend is toward using web-based mobile augmented systems for field construction monitoring.

Keywords: Augmented reality; AEC industry; Project phase; Construction management; Literature review

Introduction

The complex nature of the architecture, engineering, construction, and facility management (AEC/FM) industry and its high demand for access to information for evaluation, communication and collaboration, increases the industry's need for information technologies. Recent visualization technologies such as virtual and augmented reality technologies are ideal in this environment.

Overview of augmented reality

Augmented reality gives a view of the real world where elements are superimposed by computer generated files such as graphics, sounds, videos, or digital information. From the first see-through head-mounted AR display developed in the 1960s by Ivan Sutherland at Harvard (Sutherland, 1968), to the enhanced HD^{4}AR and Mobile Augmented Reality System (MARS) developed by Golparvar et al. (Bae et al. 2012), augmented reality technologies have been used in various disciplines and arenas, e.g. engineering, entertainment, aerospace, medicine, military, and automotive industry, as a frontline technology to meet visualization difficulties in their specific domain (Behzadan and Kamat 2011).

Application areas

The AEC industry is also moving to embrace more AR technologies for improving various stages of construction projects. This advanced computer technology provides significant advantages through simulation and visualization of the construction industry, e.g., allowing the observer to interact with both the actual and the virtual objects and to monitor the construction progress by comparing the as-planned and as-built status of the project (Shin and Dunston 2008). AR technologies can benefit the AEC/FM industry in at least three levels: visualization, information retrieval, and interaction (Dong and Kamat 2013). Various applications of AR have been recommended for the AEC/FM industry by different researchers. Dunston and Wang (2005)

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proposed AR systems for AEC industry to support all phases of the constructed facility project life cycle. Wang et al. (2007) explore potential AR applications in heavy construction equipment operator training. Golparvar-Fard et al. (2009) developed a 4-dimensional AR model for automating construction progress monitoring, data collection, processing and communication in construction phase of the project. Behzadan et al. (2011) investigate a mobile 3-dimensional AR system for visualizing dynamic site operations during the construction phase. Waugh et al. (2012) developed a web-based augmented panoramic environment to document construction progress. Park et al. (2013) presented a conceptual framework that integrates AR with building information modeling (BIM) to detect construction defects. These applications demonstrate the potential of this technology for future use in this domain.

AR technologies

Although the application of augmented reality technologies in construction projects has tremendously increased in recent years, these technologies are still in the research stage and their full potential is not fully achieved. There are limitations that should be addressed before these technologies will become dominant in the AEC industry such as tracking technologies, and rendering software. Moreover, appropriate application areas for different types of AR will continue to evolve.

Historically, many AR technologies were not applied on construction sites due to tracking and alignment problems, instead they were generally used at the home office for simulation or collaboration during the design phase of a project. However as the technology developed in recent years, the majority of these technologies have been used on construction sites for progress monitoring and defect detection. Moreover, trend analysis shows that web-based and wireless network technologies are becoming more and more popular in recent years, and these types of AR technologies are interesting technologies for further research and application.

A list of various input mechanisms, output mechanisms, and tracking technologies for AR systems can be found in Wang (2009). Portable and mobile AR systems including: radio-frequency based tracking technologies such as GPS, WLAN, indoor GPS; infrastructure-dependent technologies such as fiducial markers; infrastructure-independent tracking technologies such as gyroscopes; and image-based tracking techniques have been studied in many research projects (Bae et al. 2013). Moreover, using cloud computing technologies for web-based and ubiquitous AR systems has been explored in recent years (Wang et al. 2013).

Related studies

Shin et al. (2008) study various application areas for augmented reality technologies in industrial construction based on technology suitability. The research assesses different work tasks from the human factors perspective and presents a comprehensive map, which identifies eight work tasks including layout, excavation, positioning, inspection, coordination, supervision, commenting, and strategizing out of seventeen classified work tasks which could potentially benefit from AR systems.

Wang (2009) gives a detailed review of AR in the AEC industry, and gives a review of several major research efforts prior to 2009, and categorizes various AR technologies with their advantages and disadvantages.

Wang et al. (2013) reviews 120 articles published between 2005 and 2011 in various journal and conferences databases with a focus on augmented reality technologies in the built environment. The paper classifies all available toolkits for augmented reality prototyping in five categories: 2D marker AR-PC and web-cam based, 2D marker AR-mobile, 3D object recognition-mobile, marker-less tools, GPS-compass based AR. In their research, AR literature is classified in three categories: (1) application area; (2) AR system layers: concept and theory (with four sub-layers including: algorithm and modeling, conceptual framework, evaluation framework, and technology adoption), implementation (with two sub-layers: software and hardware), evaluation (with two sub-layers: effectiveness and usability), and industry adoption; (3) other technical criteria. The paper explores state-of-the-art technologies in each category and proposes future research directions.

Chi et al. (2013) discusses trends in AR applications for the AEC/FM with a specific focus on four AR technologies: localization, natural user interface, cloud computing, and mobile devices. The paper reviews 101 articles and outlines future trends and opportunities for applying AR in the AEC/FM industry in six directions: (a) field exploration based on hybrid localization, (b) in-field gesture or kinesthetic control of AR interface, (c) integration with location-specific information, (d) accessing field information using ubiquitous services, (e) portable AR devices in the field, (f) context-aware augmented reality in AEC/FM fields.

Main contributions

To apply AR technologies in AEC projects efficiently and to achieve their full potential in this domain, it is essential to systematically identify application areas in which AR can be used for better performance. This statistical review seeks to answer to these questions: what are key AR application areas in the AEC industry based on suitability of AR technologies? what are the gaps in this area which can potentially benefit from AR technologies? Based on future trends, predict how AR technologies can be further improved for future applications?

This paper presents an in-depth statistical literature review of augmented reality technologies in construction industry over a fourteen-year period (1999–2012). The goals of this review are (1) to synthesize the current state-of-the-art and trends of augmented reality technologies for construction projects, and (2) to identify key application areas which could significantly affect the construction industry. These goals are accomplished by classifying the literature in categories defined by the authors found in the literature.

The scientific contribution of this review is the presentation of a comprehensive multi-dimensional categorization for specifying AR technology and characteristics in the AEC industry. This literature review gives the researcher a broad view of the stage of AR technology maturity in built environment, which can be used to guide new augmented reality system design as well as to help evaluate existing systems for the construction industry.

This paper offers construction practitioners and researchers an assessment of the application areas of augmented reality technologies including the purposes for which these technologies have been applied in different project phases. The paper qualitatively aggregates the results of 133 research studies of AR technologies in construction projects to show researchers and practitioners how augmented reality models have been applied to address project challenges. Based on the trend analysis that is conducted, past research is studied and future research directions are recommended.

Research method

The research methodology used in this paper is illustrated in Figure 1: (A) to select the journals and articles, (B) to review the selected articles, (C) to define relevant categories to classify the articles, (D) to classify the articles in the defined categories. Step (B) and step (C) iterate until the final results are achieved. Step (E) is described in section 6 and section 7 which presents discussion and conclusion.

This paper is an extension of our conference paper (Rankouhi and Waugh 2012); the research methodology is similar to the methodology used previously. Five new journals are added to our database: the ASCE Journal of Computing in Civil Engineering (CCE), the Journals of Advanced Engineering Informatics (AEI), the Journal of Computer Aided Civil and Infrastructure Engineering (CACIE), the Emerald Journal of Engineering, Construction and Architectural Management (ECAM), and the Emerald Journal of Construction Innovation Information, Process, Management (CIIPM). These journals cover a wider range of database in civil engineering research domain, and increase the number of selected articles. In addition, five new dimensions (research methodology, improvement focus, industry sector, comparison role, and location) and various new categories are added to our previous defined dimensions.

Selection of the journals and articles

Eight diverse academic journals (listed in Table 1) were selected within the domain of AEC/FM to record the evolution of AR technology in the AEC industry. Selection of these journals is based on their prominence in the English language field of information technologies in construction engineering and management research.

The articles were selected in two phases. In phase I, a total of 199 articles were found in these eight journals using the search phrase "augmented reality." In phase II, articles that were published in 2013 (due to the lack of a full year at the time when the search was conducted) and articles such as Calendars, Editors Notes, Subject Index, and Content of Volume were excluded. The total number of selected articles was reduced to 133. The number of articles found in each journal is listed in Table 1.

Review and identification of the article characteristics

This section describes statistics based on information provided by the authors, whereas the next section describes our interpreted categories. The number of articles by year and journal is depicted in Table 2.

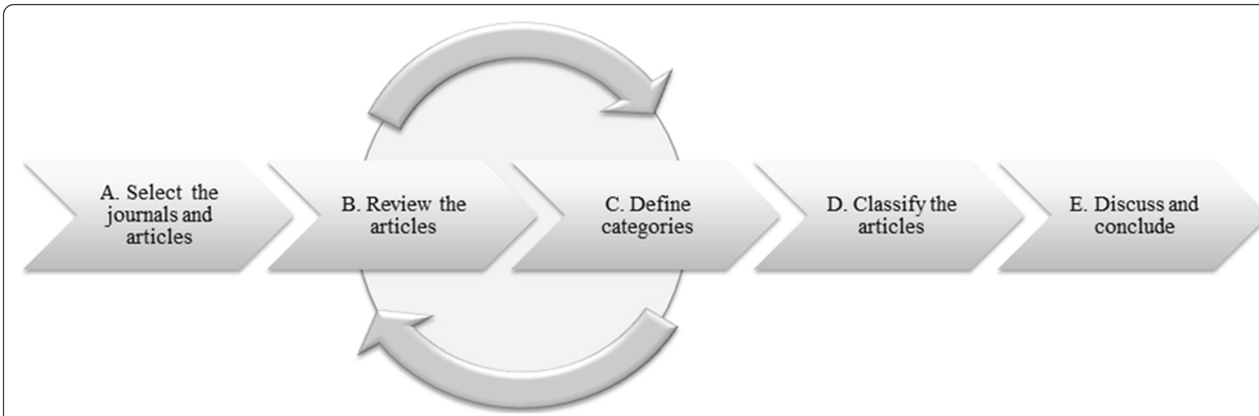


Figure 1 Research methodology.

Table 1 The number of selected journal articles during each phase

Journal	Phase I	Phase II
Journal of Automation in Construction (AIC)	87	43
Advanced Engineering Informatics (AEI)	31	24
ASCE Journal of Computing in Civil Engineering (CCE)	27	20
Journal of Information Technology in Construction (ITCON)	22	19
Journal of Computer Aided Civil and Infrastructure Engineering (CACIE)	14	11
ASCE Journal of Construction Engineering and Management (CEM)	13	11
Emerald Journal of Engineering, Construction and Architectural Management (ECAM)	4	4
Emerald Journal of Construction Innovation: Information, Process, Management (CIIPM)	1	1
Total	**199**	**133**

The distribution of articles by journal and year of publication is depicted in Figure 2. The maximum number of articles in a single year is published in both 2011 and 2012 (26 articles or 20%). The data shows highest numbers of articles for individual years in the AIC (11 articles in 2011), the ITcon (10 articles in 2008), and the CCE (8 articles in 2012) journals. The results show that the increasing trend in the number of articles is dominated by AIC, AEI, and CCE in recent year. Eighty-five percent of the articles were published in the most recent five years.

The final characteristic identified in this section is the percentage of articles based on the first author's country of residence which is shown in Figure 3. With 63 articles (47%), first authors residing in the USA have the highest number of the articles about AR technology in the AEC industry. The remaining counts show that Australia has the second place while both Canada and South Korea are in the third place.

Definition of categories

To better comprehend and further segregate the literature, we defined dimensions and categories to be used in this paper; each article was then compared to these defined dimensions for identification of its principal focus area or to determine the percentage of articles including reference to that classification. Table 3 shows the defined dimensions and the relevant categories. Each dimension is further explained in the following section.

Categorization of the articles

This section discusses the classification of the current state of AR technology literature in the AEC industry. For all but three sub-sections, the articles are classified based on their principal focus and each article is counted once. The exceptions to their approach are sub-sections 5.1, 5.4, and 5.8; in these sub-sections instead of selecting a single "principal focus," we identified the categories to which the article "made reference." In these three sub-sections only we report percentages and do not report counts.

Research methodology

In this section articles are classified based on their research methodology which is divided in five categories: case study, experimental/empirical study, proof of concept (or proof of principle study), questionnaire (survey/interview), and literature review.

A case study is a research method in which detailed consideration is given to the development of a particular case over a period of time. An experimental or empirical study is an empirical scientific method in which an experiment arbitrates between competing models or hypotheses. A proof of concept or a proof of principle study is a research method in which a certain method or model would be recognized to demonstrate its feasibility or to verify that a certain concept, theory, or prototype has the potential of being used. Questionnaires (as well

Table 2 Number of articles by journal and year of publication

	Total	%	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000	1999
AIC	**43**	**32%**	6	11	6	4	7	1	3	1	2				1	1
AEI	**24**	**18%**	7	7	6	3		1								
CCE	**20**	**15%**	8	1	2	5	2	1	1							
ITcon	**19**	**14%**	1	4		2	10	1			1					
CACIE	**11**	**8%**	3		2	2			3							1
CEM	**11**	**8%**	1	3	2	2	1			1					1	
ECAM	**4**	**3%**			1			2	1							
CIIPM	**1**	**1%**			1											
Total	**133**	**100%**	**26**	**26**	**20**	**18**	**20**	**6**	**8**	**2**	**3**	**0**	**0**	**0**	**2**	**2**
Cumulative			26	52	72	90	110	116	124	126	129	129	129	129	131	133
Percent			20%	39%	54%	68%	83%	87%	93%	95%	97%	97%	97%	97%	98%	100%

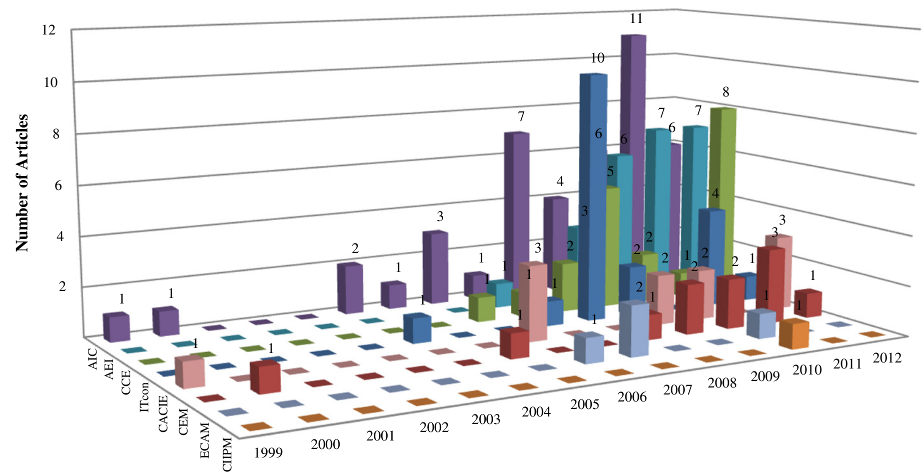


Figure 2 Distribution of articles by journal and year of publication.

as surveys and interviews) are research techniques in which qualitative and qualitative data analysis could be conducted based on the information gathered from research participants. Literature review (historical and documentary research, trend studies), is a research method which considers the critical points of current knowledge including substantive findings as well as theoretical and methodological contributions to a particular topic (Cohen et al. 2007).

Figure 4 depicts the percentages of articles based on their research method. Results show that large number of the articles use case studies to develop their research, while equal number of authors select an experimental method to conduct research in this area. Table 4, presents a list of selected reference articles for each category of research method dimension.

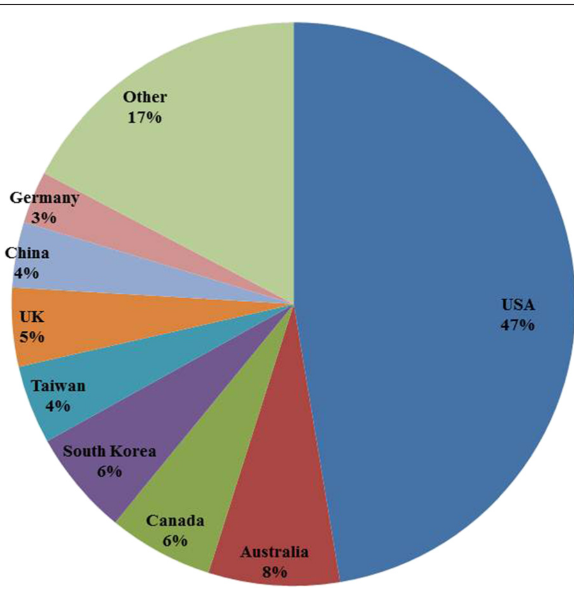


Figure 3 Number of articles by first author's country of residence.

Improvement focus

Articles are classified in four categories based on where the improvement which the article proposes would occur: (1) AEC industry, (2) organization, (3) projects, and (4) individuals. Moreover the organization category

Table 3 Defined dimensions and their categories

Dimensions	Categories
Research methodology improvement focus	Case study, Experimental/empirical study, Proof of concept, Questionnaire, Literature review
	AEC industry, Organization (Facility owner, Contractor, Designer), Projects, Individuals
Industry sector	Building commercial, Municipal/infrastructure, Heavy/highway, Residential, Industrial
Target audience	Design team, Project manager, Worker/technician, Inspector, Project end user, Building systems engineers, Student, Other
Project phase	Initiation, Design, Procurement, Construction, Maintenance
Stage of technology maturity	Theory, Framework, Sub-system technical issues, System development, System application
Application area	Simulation/visualization, Communication/collaboration, Information modeling, Information access/evaluation, Progress monitoring, Education/training, Safety/inspection
Comparison role	Comparison modes (Model vs. model, Model vs. reality, Reality vs. reality),
	Comparison purpose (Progress monitoring, Defect detection, Evaluation the model, Updating the model, Validating the model)
Technology	User perspective (immersive, non-immersive), Device (mobile, non-mobile), Delivery (web-based, standalone)
Location	Home-office, Field

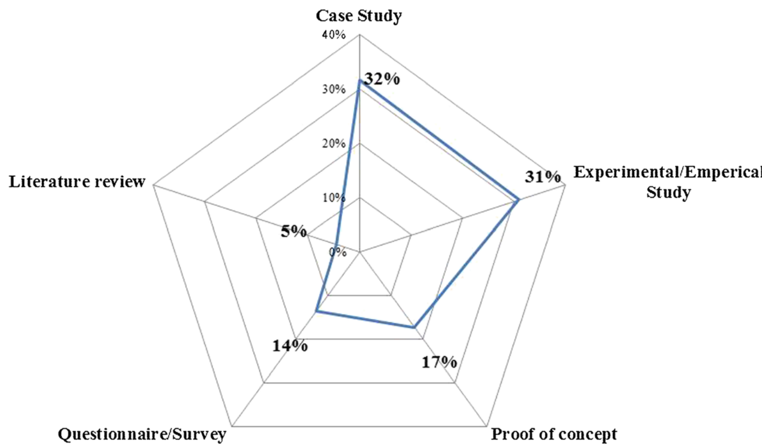


Figure 4 Percentage of articles based on the research method.

is divided into three subcategories of organization type including: (a) facility owner, (b) designer, and (c) contractor.

Figure 5 illustrates the number of articles within each improvement focus category. As shown, 69 articles (52%) have a principal focus on projects, while 27 articles (20%) have a principal focus on individuals in the construction industry. In addition, 19 articles (14%) and 12 articles (10%) have a principal focus on the AEC industry and the organization level, respectively.

Industry sector

In the construction industry various project types can benefit from AR technologies including: (1) municipal/infrastructure, e.g., evaluation of dynamic city models and an emission model for transportation (Aschwanden et al. 2012), (2) residential, e.g., virtual and augmented reality for designing and customizing mass housing (Duarte 2005), (3) building/commercial, e.g., visualizing high-rise building construction strategies (Russell et al. 2009), and virtual and augmented reality technologies for maintenance of exterior closures and interior finishes of walls and in the construction of buildings (Sampaio et al. 2012), (4) heavy/highway, e.g., developing virtual reality system for optimized simulation of road design data (Kang L. S. et al. 2010), and segmentation and recognition of highway assets using image-based 3D point clouds and semantic Texton forests (Golparvar-Fard et al. 2012), and (5) industrial, e.g., application areas for augmented reality in industrial construction (Shin and Dunston 2008).

Figure 6 presents the number of articles within each industry type category. As shown, 34 articles (26%) have a principal focus on building/commercial as an industry type for AR technology. Municipal/infrastructure, heavy/highway, industrial, and residential categories have 18 articles (14%), 14 articles (11%), 13 articles (10%) and 8 (6%) articles respectively. Thirty-six articles focus on multiple areas while these categories were not applicable for 10 articles. Table 5, presents a list of selected reference articles for each category of industry sector dimension.

Table 4 Reference article for research methods dimension

Research method	Reference
Case study	Dai et al. (2011), Turkan et al. (2012), Peña-Mora et al. (2012)
Experimental/empirical study	Wang and Dunston 2006, Wang et al. (2008), Behzadan and Kamat (2008)
Proof of concept	Roh et al. (2011), Yabuki et al. (2011), German et al. (2012)
Questionnaire/survey	Wang and Dunston (2006), Kuo et al. (2011), Chi et al. (2012)
Literature review	Malkawi et al. (2004), Wang et al. (2013)

Target audience

Due to the complexity of construction projects and the collaborative nature of the AEC industry, the application of AR systems has a wide range of target audiences. To classify these articles the following audiences were chosen partially based on Muramoto et al. (2008): (1) worker, e.g., machine operators and technicians, (2) design team, e.g., architects, interior and exterior designers, (3) schedule and budget professional, in particular referred to as project manager, (4) building systems engineer, e.g., structural, mechanical, and electrical engineers, (5) inspector, e.g., project safety officers (6) engineering student, (7) project end user, e.g., building occupants, office employees, (8) other stakeholder, e.g., clients, and building owners. If an article proposed a change in, or enhancement of, the work of one of these audiences, it was classified in that category.

As noted above, in this section instead of giving the number of articles with a "principal focus on" a category, we report the percentage of articles "including reference to" that category, since in this section each article may refer to more than one category. Figure 7 presents the

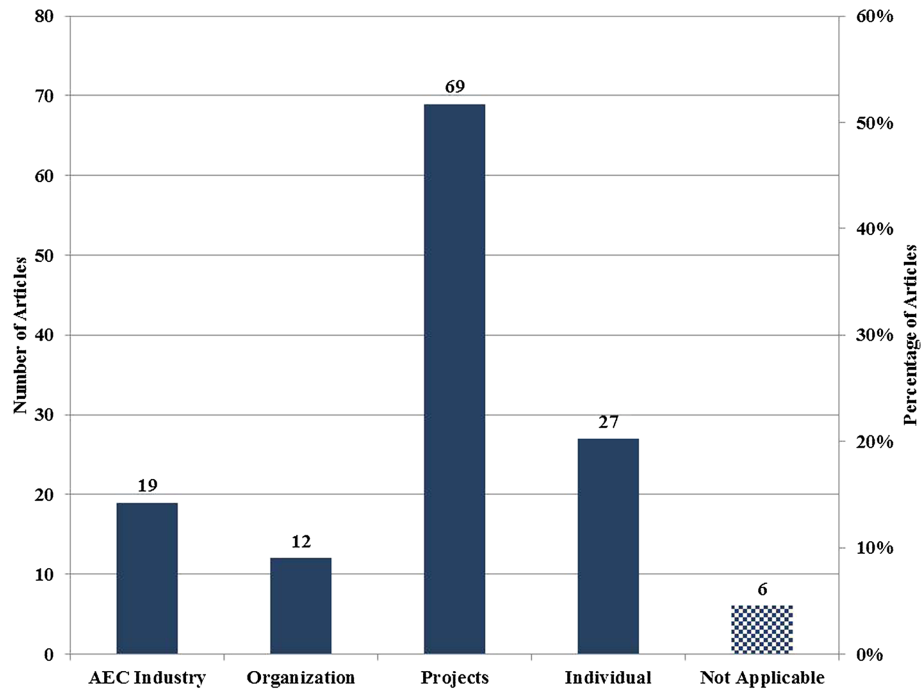


Figure 5 Number of articles by improvement level.

percentage of articles by target audience. The results indicate that the largest number of articles include reference to workers as the target audience. A list of selected reference articles for each category of target audience dimension is shown in Table 6.

Project phase

The life cycle of a construction project consists of a sequence of steps or project phases to be completed in order to reach project goals and objectives. These phases are defined by N. Dawood (2009) as: (1) initiation and

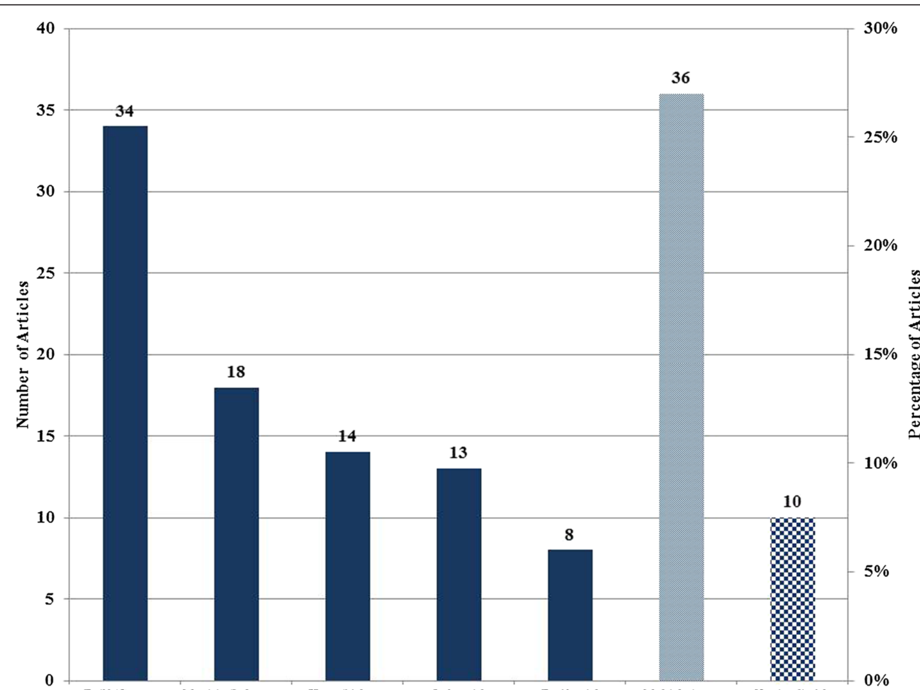


Figure 6 Number of articles by industry sector.

Table 5 Reference article for industry type dimension

Industry type	Reference
Building/commercial	Behzadan and Kamat (2008), Akhavian and Behzadan (2012)
Municipal/infrastructure	Dai et al. (2011), Fathi and Brilakis (2011)
Heavy/highway	Esch et al. (2009), Jordon et al. (2012)
Industrial	Shin and Dunston (2008), Shin and Dunston (2009)
Residential	Wang et al. (2012)

outline design, (2) design development, (3) [procurement], contract and pre-construction, (4) construction, and (5) maintenance. The number of the articles by project phase is depicted in Figure 8. A list of selected reference articles for each category of project phase dimension is shown in Table 7.

Figure 9 illustrates the number of articles for each project phase by year of publication. In this diagram articles with a focus on multiple phases are excluded (reducing the total to 98 articles). The highest number of articles in a single year is for the construction phase in the year 2012. The focus on the design phase of a project reached its highest number (5 articles) in the year 2008. Figures 8 and 9 show that the highest number of articles occur in the construction phase of a project for AR technologies and applications.

Stage of technology maturity

From a stage of technology maturity perspective, the articles are divided into five categories: (1) theory, (2) framework, (3) sub-system technical issues, e.g., investigation of tracking, positioning and orienting issues for AR-based technology for steel column inspection (Shin and Dunston 2010), (4) proposed system development, e.g., development of ARVISCOPE (AR animation scripting language) and ROVER a mobile computing framework for information modeling and simulation of construction operation (Behzadan et al. 2011), and (5) system application demonstration and production, e.g., application of D^{4}AR for construction progress monitoring (Golparvar-Fard et al. 2011a), application of AR Training System for training the operation of heavy construction equipment (Wang et al. 2007).

Figure 10 illustrates the number of articles within each stage-of-technology-maturity category. Results also show that only four articles (3%) have a principal focus on AR theory, while six articles (5%) have a focus on multiple areas (i.e., more than one of the previous stages); these multiple areas are typically a combination of application demonstration and proposed system development. A list of selected reference articles for each category of stage of technology maturity dimension is shown in Table 8.

Application area

Augmented reality technology has many applications in the AEC industry. We classify AR application areas in the AEC industry as follows: (1) visualization or simulation, (2) communication or collaboration, (3) information modeling, (4) information access or evaluation, (5) progress monitoring, (6) education or training, and (7) safety or inspection.

Figure 11 presents application areas for AR technologies in the AEC industry. As shown, 26 articles (20%) have a principal focus on visualization and simulation as an application area for AR technology. Thirteen articles focus on multiple application areas, while these subcategories were not applicable for 8 articles. A list of selected reference articles for each category of AR application area dimension is shown in Table 9.

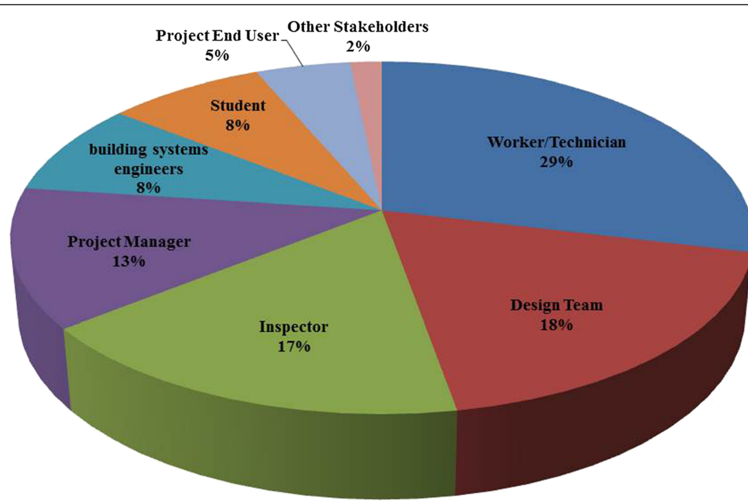


Figure 7 Percentage of articles by target audiences.

Table 6 Reference article for target audience dimension

Target audience	Reference
Worker/technician	Lucas and Thabet (2008), Chi et al. (2012)
Design team	Leicht et al. (2009), Gu et al. (2011)
Inspector	Shin and Dunston (2010), Zhu and Brilakis (2010)
Project manager	Golparvar-Fard et al. (2011b), Roh et al. (2011)
Building system engineers	Lee and Akin (2011), Shin and Dunston (2008)
Student	Wang et al. (2007)
Project end user	Jang et al. (2008), Wang et al. (2012)

Comparison role

Construction participants use augmented reality technologies to compare different statuses of a project. Articles that "make reference" to the comparison role of AR technologies are divided in two categories; (1) comparison modes: (a) reality versus reality, e.g., comparing two construction site 360 degree panoramas at two different times for virtual reality documentation of Inuvik Super School (Waugh et al. 2012), (b) model versus reality, e.g., integrating sequential as-built and as-planned representation with D4AR tools (Golparvar-Fard et al. 2011a), and (c) model versus model, e.g., the application of Experimental Virtual Environment (EVE) (Savioja et al. 2003); and (2) comparison purpose, e.g., progress monitoring, defect detection, validating the model, updating the model, and evaluating the model.

Sixty-two articles (47% of articles) have reference to the comparison role of augmented reality technologies in construction industry. For these 62 articles only, Figure 12 illustrates the number and the percentage of articles within each comparison mode category. A list of selected reference articles for each category of comparison mode dimension is shown in Table 10.

Figure 13 depicts the percentage of articles within each comparison purpose category for these 62 articles. As shown, 32% refer to comparison for progress monitoring, 28% for defect detection, 16% for evaluating the model, 13% for updating the model, and 11% for validating the model. A list of selected reference articles for each category of comparison purpose dimension is shown in Table 11.

Technology

Augmented reality technology, which typically layers virtual information on a real scene, utilizes different hardware (personal computers (PC), laptops, head mounted displays (HMD), GPS, data gloves, smart boards, etc.) and software (AutoCAD, Photoshop, AC3D, 3D Studio, building information model (BIM), etc.). From a technology perspective articles are classified into three categories: (1) user experience: (a) immersive or (b) non-immersive, i.e., desktop-based; (2) device: (a) mobile, (b) stationary or non-mobile; (3) delivery: (a) web-based, (b) standalone.

Devices such as HMD and data-gloves create immersive AR systems, in which users feel immersed in a

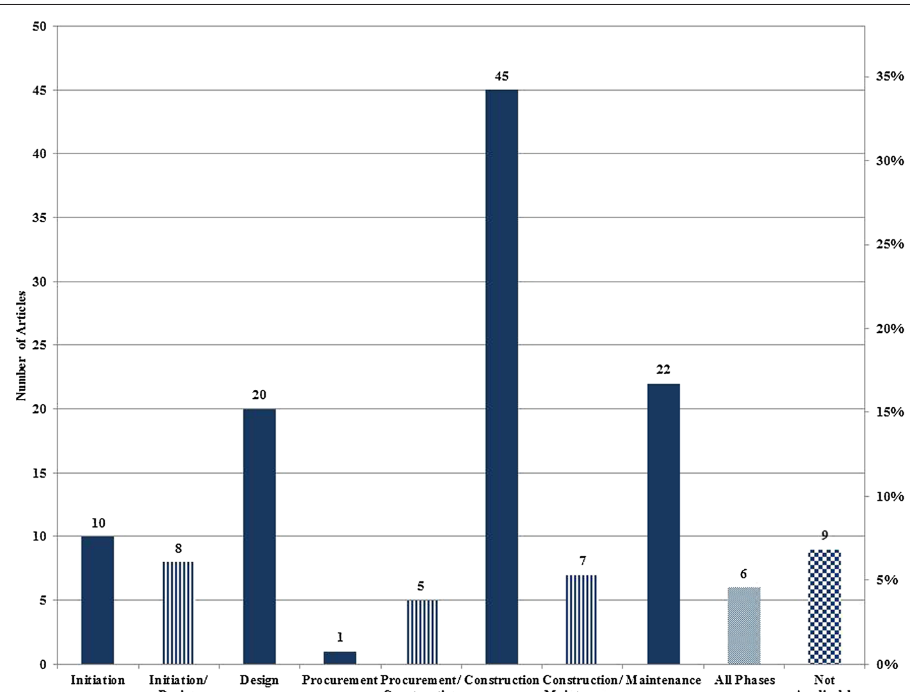


Figure 8 Number of articles by project phase.

Table 7 Reference article for project phase dimension

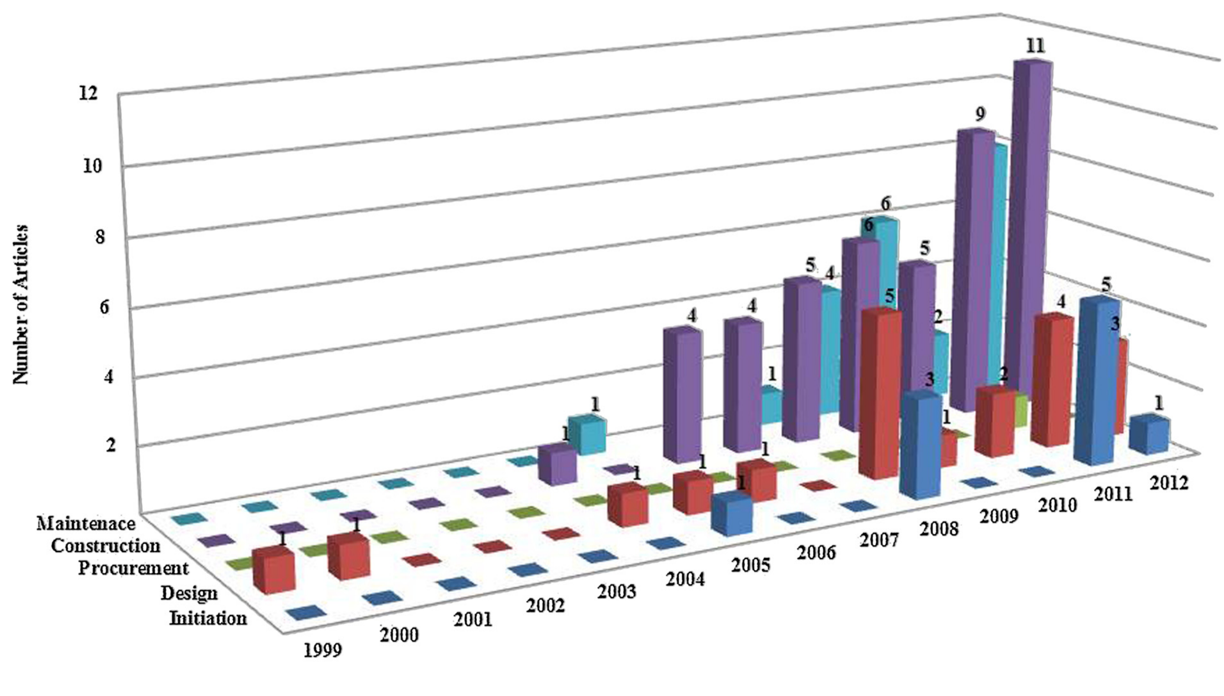
Project phase	Reference
Initiation	Dunston and Wang (2005), Gu et al. (2011)
Design	Kang et al. (2010), Germani et al. (2012)
Procurement (procure.)	Ajam et al. (2010)
Construction (constr.)	Behzadan and Kamat (2008), Golparvar-Fard et al. (2011b)
Maintenance	Zhu and Brilakis (2010), Victores et al. (2011)

virtual environment just as they usually feel in a real environment. Due to the improving performance of handheld devices and recent solutions to technical difficulties such as tracking, there is an opportunity for augmented reality systems to become portable, as well there is a growing interest in the use of mobile AR applications. Web-based augmented reality technologies can deliver project information to remote locations and are very useful to manage virtual projects around the globe. Finally, due to the wide range of AR applications, these technologies can be used both on-site for progress monitoring and in an office (not-on-site) for design control.

From the user experience perspective, 32 articles have a principal focus on immersive AR technologies, 76 articles (57%) have a principal focus on non-immersive or desktop-based AR technologies, while 25 articles were not applicable. Figure 14 presents the number of articles with immersive and non-immersive technologies as a principal focus by year.

Figure 15 presents the number of articles within the device category that had a principal focus on mobile and non-mobile AR technologies in the AEC industry. The diagram implies an increasing trend in mobile AR technologies in AEC industry. Of the selected articles, one was published in 2000 that discussed mobile AR technology; while 7 articles (5%) focus on mobile AR technologies in both year 2011 and year 2012; 41 articles were not applicable to this category.

Figure 16 depicts the number of articles within the delivery category that had a principal focus on web-based and on standalone AR technologies in the AEC industry. Fifty-two articles (40%) were not applicable to this category. A list of selected reference articles for each category of technology dimension is shown in Table 12.



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Initiation							1			3			5	1
Design	1	1				1	1	1		5	1	2	4	3
Procurement													1	
Construction						1		4	4	5	6	5	9	11
Maintenace							1			1	4	6	2	8

Figure 9 Number of articles by project phase and year (articles spanning multiple phases are excluded).

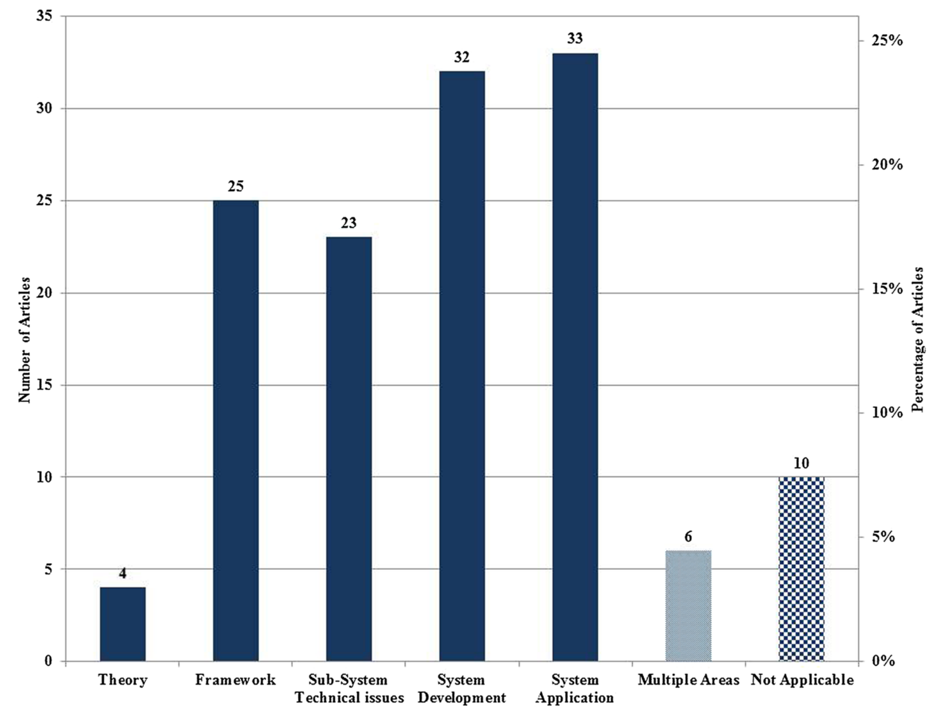


Figure 10 Number of articles by stage of technology maturity.

Location

Augmented reality technologies can be applied in different locations during a construction project. From a location perspective, AR technologies can be classified in two categories: (a) field, e.g., using robot-aided tunnel inspection and maintenance system on construction site (Victores et al. 2011), (b) home office, e.g., virtual environments for synchronous and remote collaborative design (Germani et al. 2012).

Figure 17 depicts the number of articles within the technology category that had a principal focus of on-site and on not-on-site. The diagram implies an increasing trend in the on-site application of AR technologies in construction projects. The highest number of articles in a single year is for the on-site technologies in the year 2012. Twenty-two articles (17%) were not applicable to this category. A list of selected reference articles for each category of location dimension is shown in Table 13.

Table 8 Reference article for stage of technology maturity dimension

Stage of technology maturity	Reference
Theory	Dunston and Wang (2011), Pradhan et al. (2012)
Framework	Dunston and Wang (2011), (Wang et al. 2010)
Sub-system technical issues	Zhu and Brilakis (2010), Huang et al. (2012)
System development	Liang et al. (2011), (Golparvar-Fard et al. 2011a)
System application	Jang et al. (2008), Roh et al. (2011)

Review

Discussion

Figure 18 shows the total number of articles in defined dimensions and categories, in which increasing trends over the period are indicated by an up arrow and dominant categories are indicated by bold font.

The following results are concluded for the categories defined in this research.

- Journals: *Automation in construction* has the highest overall number of articles among the journals. The maximum number of AR technology articles published in these eight journals in a single year, occurred both in 2011 and 2012. Eighty-three percent of the articles were published in most recent five years.
- First authors: *USA*, with more than half of articles, is the dominant residence of the first authors.
- Research methodology: *Case studies* and *experimental studies* with 32% and 31% respectively, are the most frequent research method among selected articles.
- Improvement focus: The majority of the articles focus on *projects* rather than on the AEC industry, organization or individual level.
- Industry sector: *building/commercial* with 35% have the highest number of articles, whereas, *residential* have the least number of articles.

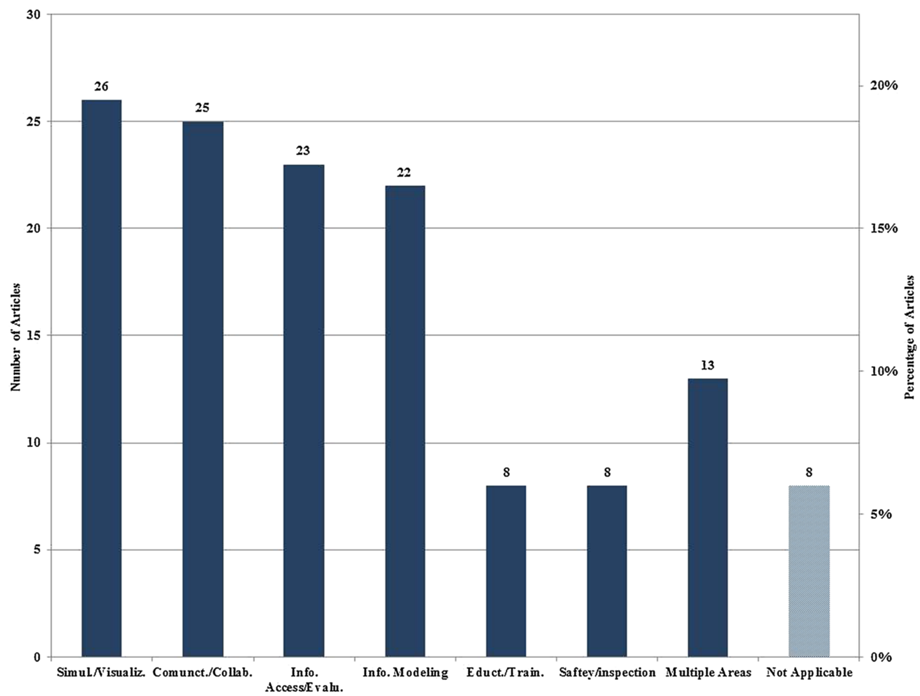


Figure 11 Application areas for AR technology.

- Target audience: The most frequent focus is the *workers* (e.g., machine operators and technicians), whereas the least focus is on project end users.
- Project phase: The most frequent focus is the *construction phase* with the maintenance phase being next with approximately half as many articles. Twenty-six articles cover two phases (e.g., initiation/ design) or all phases. Procurement phase shows a lack of focus in the area of AR systems.
- Stage of technology maturity: The most number of articles focus on AR *system application* rather than system development or sub-system technical issues.
- Application areas: Approximately half of the articles had a principal focus on *visualization/simulation* or *communication/collaboration*, and just a few articles focus on education/training and safety/inspection.

Table 9 Reference article for AR application area dimension

Application area	Reference
Simulation/visualization	Kang et al. (2010), Liang et al. (2011)
Communication/collaboration	Hammad et al. (2009), Gu et al. (2011)
Information access/evaluation	Zhu and Brilakis (2010), Khoury and Kamat (2009)
Information modeling	Behzadan and Kamat (2011), Styliadis (2008)
Education/training	Wang et al. (2007), Jardón et al. (2012)
Safety/inspection	Zhu et al. (2012), Li and Liu (2012)

- Comparison role: 47% of the articles made reference to the comparison role of augmented reality technologies for comparing different statuses of projects. More than half of those articles focused on comparing a *model with a reality* to monitor progress and detect construction defects. Comparing model vs. model captured the least attention in this area. In addition, majority (%60) of the comparison

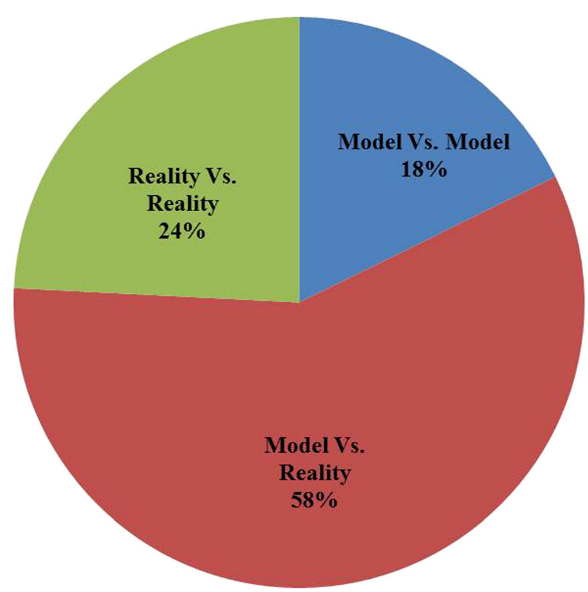


Figure 12 Number and percentage of articles by comparison modes.

Table 10 Reference article for comparison mode dimension

Comparison mode	Reference
Model vs. Model	Wang et al. (2008), Gu et al. (2011)
Model vs. Reality	Shin and Dunston (2009), Behzadan and Kamat (2011)
Reality vs. Reality	Zhu and Brilakis (2010), Brilakis et al. (2011)

Table 11 Reference article for comparison purpose dimension

Comparison purpose	Reference
Progress monitoring	Bohn and Jochen (2009), Golparvar-Fard et al. (2011a)
Defect detection	Zhu and Brilakis (2010), Shin and Dunston (2010)
Evaluating the model	Gül et al. (2008)
Updating the model	Gu et al. (2011)
Validating the model	Isikdag and Underwood (2010)

articles focus on field audience (for progress monitoring and defect detection), while less than half of the comparison articles focus on home office audience (for model improvement).

- Hardware system: From the user-experience perspective most of the articles discussed *non-immersive technologies*. From the delivery perspective, most of the articles discussed *standalone technologies*, and from device perspective, most of the articles focus on *non-mobile* technologies. A spike in the number of articles focusing on mobile technologies occurred in 2011.
- Location: The most frequent focus is AR technologies which can be applied in the *field* (rather than in the home-office). The field category included almost 80% of those articles which referred to a location.

Future trends

Table 14 provides a list of the categories for which there was a significant and consistently-increasing trend in the most recent five years. There were no categories for which the number of articles was consistently-decreasing over the 14 year period.

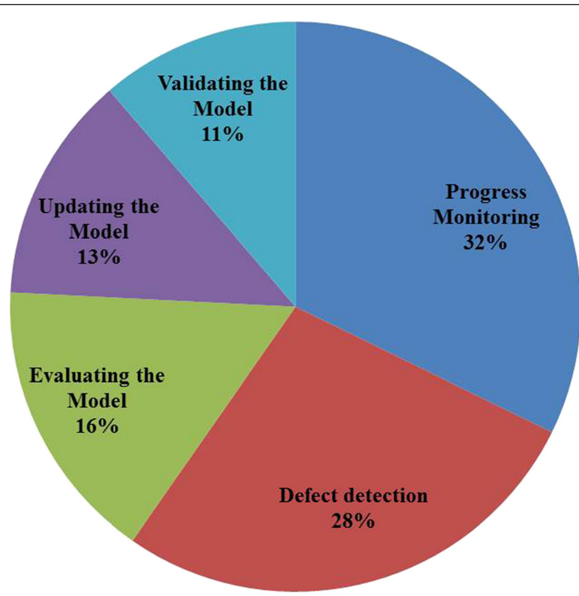


Figure 13 Number and percentage of articles by comparison purpose.

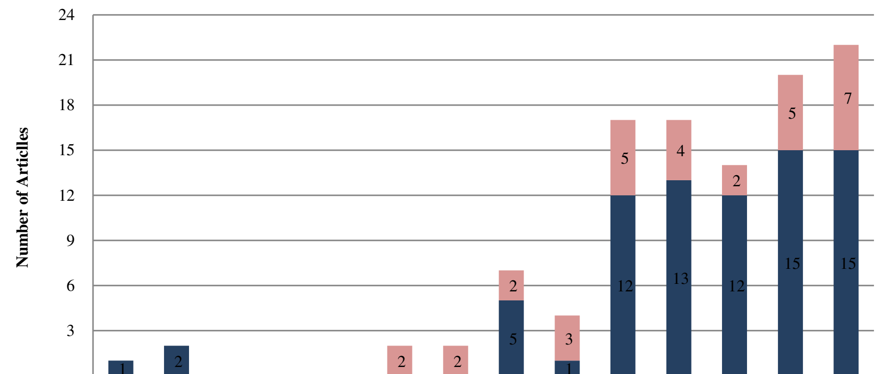
AR technologies provide proven benefits especially in the areas of visualization/simulation and communication/collaboration, however these benefits are not yet widely adopted by AEC industry participants nor have they been incorporated into industry-wide workflow processes. As a result, industry participants choose to pilot (i.e., system development and application) AR technologies on a few projects rather than adopting or piloting the technology across their organization.

Building/commercial projects provide a good test bed for visualization and communication of different perspectives of a project, since these projects typically entail more complexity and more need for integration than an infrastructure, heavy/highway, or residential projects. However, the trend in the most recent five years shows that heavy/highway projects are getting an area of focus for new AR technologies. We also predict that use on industrial projects will grow rapidly as technologies are improved and confidence is gained.

We predict expansion of AR technologies from a principal role in the construction and maintenance phases to other phases (especially the design and procurement phases) as the ability to compare virtual models with previous virtual models (and realities with previous realities) to monitor project progress and detect construction defections, rather than the narrow focus of comparing a current construction phase reality with a final design phase model.

The uniform distribution of target audiences among the design team, the project management team, and on-site personnel reflects integration being the essential purpose of AR technologies.

We predict continued growth in the use of internet and web-based devices to enhance integration of perspectives. Collaborative, ubiquitous, and internet-based AR systems enable users to update and synchronize the information from a remote location. Cloud computing technologies could help next generation construction professionals to access massive amount of



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Immersive						2	2	2	3	5	4	2	5	7
Non-immersive	1	2						5	1	12	13	12	15	15

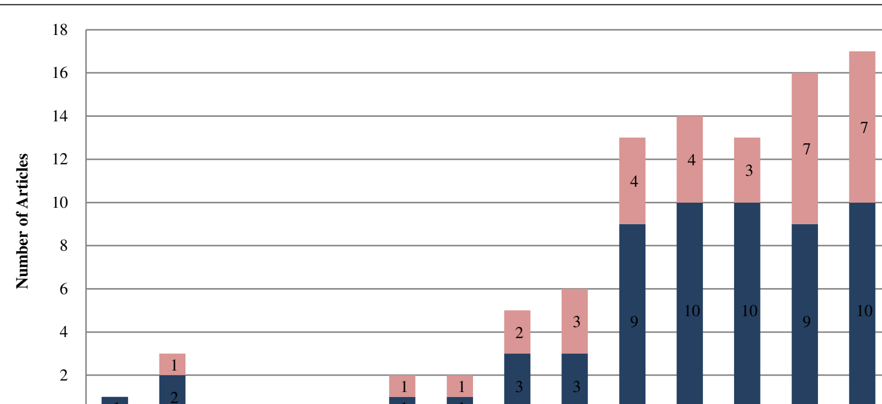
Figure 14 Immersive and non-immersive AR technology by year.

field information such as BIM rapidly and conveniently (Chi et al. 2013).

We also predict continued growth in the use of mobile and portable multi-user AR devices to display (and capture) models and realities. The next generation mobile technologies are likely to have natural user interface (Wang et al. 2013), which would be controlled by human movement and gestures, and makes it easy for field workers to use AR systems on construction sites. It is also predicted that next generation mobile AR systems would have context-aware and location-aware applications. We also speculate that the cost of immersive hardware is, and will continue to be, an impediment to its widespread use.

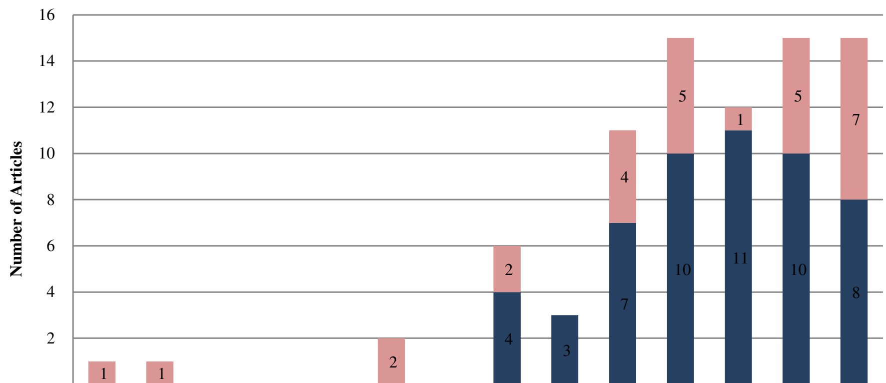
Conclusion

A structured methodology was used to identify 133 articles on the topic of augmented reality from eight prominent AEC industry journals. The first article was published in 1999; a significant increase in the number of articles on this topic occurred during the year 2008. In addition to statistics on the counts of articles by year and the first author's country of residence, ten interpreted dimensions were developed for classification of these articles. Literature show field workers and project managers have high interests in using non-immersive and desk-top standalone (individual) AR technologies during construction phase of a project to compare as-planned versus as-built statuses to monitor progress and defect detection. Whereas, it is predicted that future trend, is more toward using collaborative and internet based mobile AR systems which have applications not only in construction phase, but also in procurement and maintenance phases of a project. Due to various benefits of AR technology for construction industry, the application of AR systems for initiation and procurement



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Mobile		1				1	1	2	3	4	4	3	7	7
Non-mobile	1	2				1	1	3	3	9	10	10	9	10

Figure 15 Number of articles for mobile and non-mobile AR technology by year.



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Web-based	1	1				2		2		4	5	1	5	7
Standalone								4	3	7	10	11	10	8

Figure 16 Number of articles for web-based and standalone AR technology by year.

phase of a project to compare model vs. model and reality vs. reality is recommended. Moreover, lightweight mobile and immersive AR systems are also recommended for field personnel due to dynamic environment of construction fields.

Based on this review, our recommendation for researchers in the area of AR technology is that the current trial systems should have narrow applications and there is an essential need for more comprehensive systems. There is an opportunity for more research on the application of AR systems during the procurement phase of construction projects, since literature shows a lack of research in these phases of project. In addition, the assessment of success of developed systems should be validated by researcher and practitioner from academy and industry. From a theory and framework perspective, integration of multiple projects (within an organization) and integration of multiple organizations (within the industry) could be a considered for future research in the area of AR systems. Integration might be easier in less complex types of work, i.e., residential projects. Comparisons are fundamental to AR system within the AEC industry to be able to monitor projects and defect detections, therefore, our testing of five comparison purposes (progress monitoring, defect detection, evaluating the model, updating the model, validating the model) need to be further investigated.

We assume that construction industry practitioners would assess an AR system based on the system contents, features, and value. From the content perspective they would seek current (possibly real-time) information as well as a historical record that may be integrated with traditional project information (e.g., BIM). From a feature perspective, they would seek a user friendly interface (possibly internet-based) that can be integrated into their content workflow process and that facilitate the comparison of project statuses over time. From the value perspective, they would seek an affordable cost (initial and ongoing) for which the payback period is short. We assume the benefits of AR contribute to this payback are virtual site visits, defect detection, pre-empting dispute resolution, photographic as-built, and training of personnel. Currently, most

Table 12 Reference article for technology dimension

Technology	Reference
Immersive	Behzadan and Kamat (2011)
Desktop-based	Golparvar-Fard et al. (2009), Wang and Dunston (2008)
Mobile	Khoury and Kamat (2009), Behzadan and Kamat (2011)
Stationary	Gül et al. (2008), Bohn and Jochen (2009)
Web-based	Muramoto et al. (2008)
Standalone	Styliadis (2008), Lee and Akin (2011)

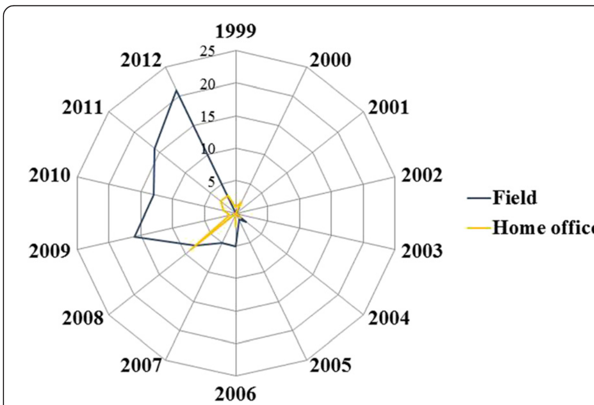


Figure 17 Number of articles for field and home-office AR technology by year.

Table 13 Reference article for location dimension

Location	Reference
Field	Kamat et al. (2011), Golparvar-Fard et al. (2011a), Lee and Akin (2011)
Home-office	Muramoto et al. (2008)

Table 14 Significant trends

Dimension	Category	2008	2012	Factor
Journal	AIE	0	7	∞
Industry sector	Heavy/highway	1	5	5.0
Project phase	Maintenance	1	8	8.0
Delivery	Mobile	4	7	1.8
Location	Field	8	21	2.6
Total number of articles	All categories	20	26	1.3

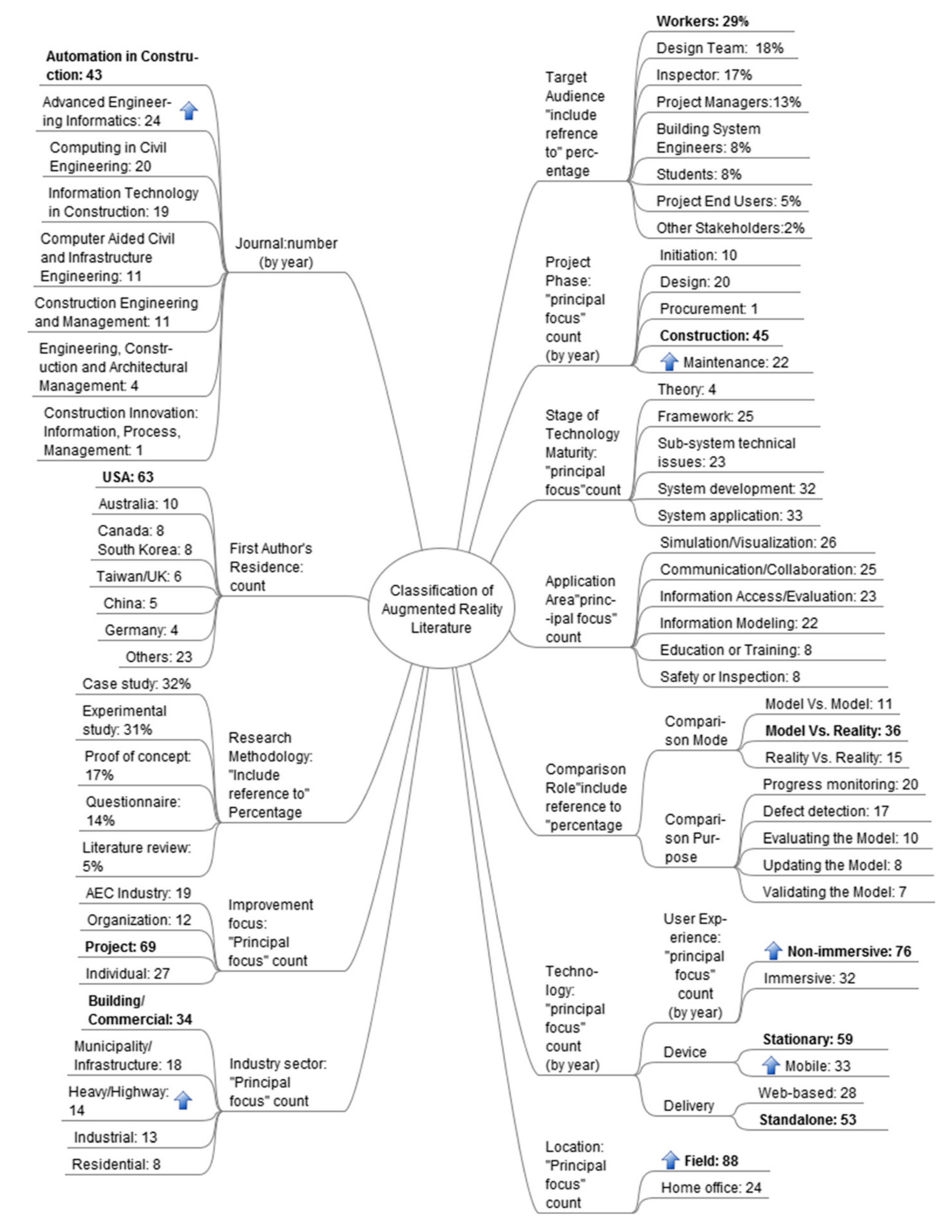


Figure 18 Literature review summary.

of systems found in the literature are trial/demonstration, hence they are developed for specific purposes they do not have all of the above criteria, however some new systems offers some valuable feature and may provide a competitive advantages. As the technology is rapidly evolving, it is recommended to the construction participants to monitor this developing area closely in order to get the latest update.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
Both authors contributed extensively to the work presented in this paper. SR searched the databases, selected the articles, reviewed and analyzed the literature, and prepared the manuscript. LW defined dimensions and categories, supervised the overall review, and edited the manuscript. Both authors read and approved the final manuscript.

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