Locating Building Components in a Facility Using Augmented Reality Vs. Paper-based Methods: A User-centered Experimental Comparison

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ABSTRACT

The Architecture, Engineering, Construction, and Operations (AECO) industry and specifically the facility management domain is searching for new methods for increasing maintenance efficiency and productivity where critical decisions are constantly made to maintain the facility. New digital technologies are capable of enhancing this decision-making process by providing better means of accessing required information. In this research, BIM, together with mobile Augmented Reality (AR) has been used for developing a system to access building information in facilities. AR has been considered as a viable option to replace the current approach of locating facility components using paper-based corrective/preventive maintenance work orders. The AR method was also assumed to reduce inefficiencies of data overload by providing facility managers with a BIM-based tool for visualizing their "real-world" environment with added interactive data. The hypothesis of this research is that bringing 3D BIM models of building components in an AR environment and making them accessible through handheld mobile devices would help the facility managers to locate those components easier and faster compared to facility managers' current approach of paper-based preventive/corrective maintenance work orders. A within-subjects user participation experiment and analysis was conducted to evaluate this hypothesis. The outcome of statistical analysis revealed that mobile AR-based environment would significantly enhance locating the right object in the facility in terms of the required time and number of errors. Although there were drift and registration problems while conducting the experiment participants significantly preferred the AR condition to the paper one.

INTRODUCTION

In the AECO domain it is often required to relate physical objects to associated information. This makes AR a good candidate to aid users within AECO practices with their routine tasks because their live view of a space can be supplemented by the information they need, all in one interface. Traditionally, those AECO-related users need to shift the domains they were working from the physical domain to a printed or digital manifestation of the information related to it. Moreover, since those AECO-related users are constantly moving through the spaces they are working in, having a portable, mobile device would be beneficial if they were to employ AR in their tasks. There are previous studies about Mobile Augmented Reality (MAR) application in the AECO domain. Shin and Dunston (2008) have studied the possible application areas of AR to the construction domain for enhancing performance. The majority of these studies and applications are in the outdoor environment (Behzadan 2008; Behzadan and Kamat 2005; Behzadan and Kamat 2007). They mainly focus on the design (Dunston et al. 2003) or construction (Chen and Huang 2012; Golparvar-Fard et al. 2009; Park et al. 2012; Wang and Dunston 2006) phases but there are also a few studies on MAR application in facility management (Irizarry et al. 2013 ; Irizarry et al. 2012) or indoor environment (Kuo et al. 2012).

In an indoor-based research of integrating Building Information Modeling (BIM) and MAR, Information Surveyed Point for Observation and Tracking (InfoSPOT) was developed (Irizarry et al. 2012). InfoSPOT is a low-cost non-image-based solution that leverages current MAR technology but focuses on its usability in the AECO context. It used a fixed location approach in which users were able to quickly install a Surveyed Point for Observation and Tracking (SPOT) and then the system would be able to serve the individuals by providing the required information or preferences in that specific location. Individuals would interact with augmented information on their real-world view of the environment and not on a still picture of their space. InfoSPOT demonstrated that it is possible to take an idealized building information model and integrate its data and 3D information in an MAR environment. A real-world experiment where participants used InfoSPOT to access data about physical objects was conducted to investigate how this system would be beneficial comparing to the traditional paper-based approaches of corrective or preventive maintenance in facility management practices.

Locating building components in a facility was the main task in this experiment. Based on the results of an online survey and feedback provided by facility managers, locating building components and 3D visualization are the most important applications of BIM within facility management practices (Gheisari 2013). The survey respondents also provided very positive feedback on accessing information in an AR environment. Considering these issues, the following hypothesis was developed for our experiment in this research: *"Bringing 3D building information models of facility components in an AR environment and making it accessible through handheld mobile devices would help the facility managers to locate those components easier and faster compared to facility managers' paper-based approach."*

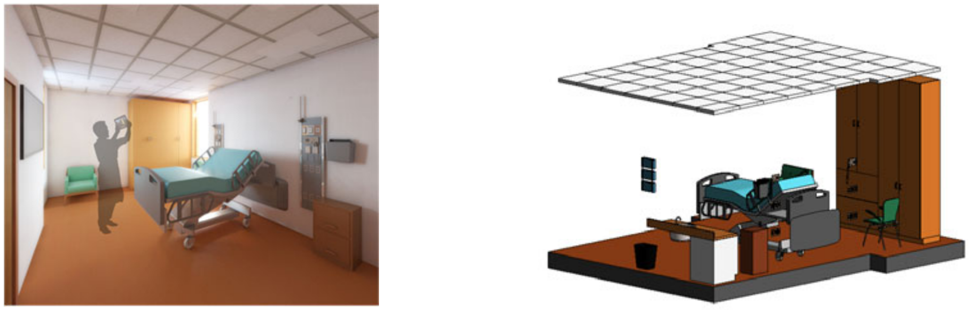
In the current approach of locating facility components, facility managers are usually provided with preventive or corrective maintenance work orders in which the location of the target building component has been recorded based on the previous maintenance tasks (preventive) or the calls/reports provided by other parties (corrective maintenance). As part of the experiment user performance and system usability were evaluated. The results showed that a MAR-based environment was relatively seamless and efficient for all participants in our study.

EXPERIMENT DESIGN AND METHODS

A within-subjects experiment was used which consisted of using a tablet computer device (an Apple iPad) as a mobile AR tool versus using a paper format work order to locate problematic equipment in the test location. Simultaneously, an evaluator was measuring the time used and the number of errors made by the participants to successfully perform the tasks. The participants had to speak their thoughts aloud, and an observer was making notes about important events and participants' comments or concerns. Before starting the experiment, each participant was presented with an Informed Consent Form for him or her to read in agreement to participate in the experiment. Georgia Tech's Institutional Review Board (IRB) evaluated and approved the study protocol.

System Development (BIM2MAR Process). The developed method involves the integrated use of the different software applications. Autodesk Revit was used due to its widespread adoption in AECO and the ease of developing automation scripts using the Revit API. Google SketchUp was used due to its powerful Ruby API and integration with Google Earth. This project leverages SketchUp to automate the process of finding the geo-locations (latitude, longitude, elevation) of the BIM objects. Finally Argon 2, an Augmented Reality browser, which leverages Vuforia for vision-based tracking, Metaio for model-based tracking, THREE.js and WebGL, HTML5, and JavaScript, was utilized due to the ease of implementation and support from the developers of the project.

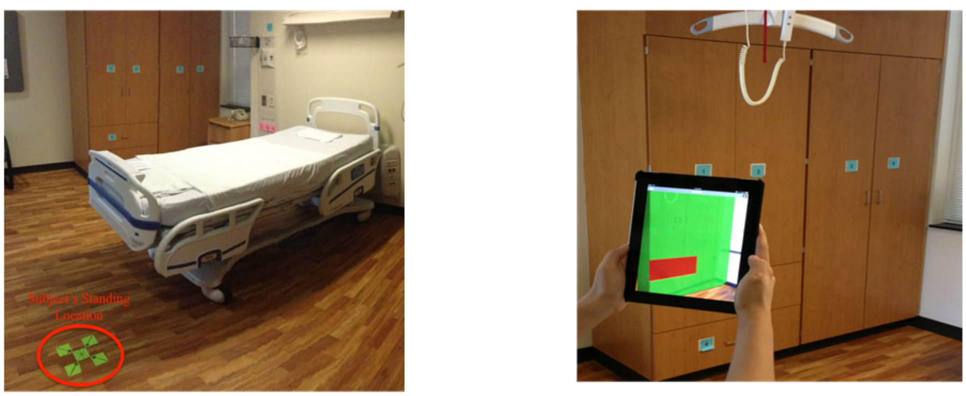
Test location. The experiment was conducted in a living laboratory setting (Intille et al. 2005) at the Shepherd Center in Atlanta GA, within a healthcare facility management context. This test location was chosen as an example of a complex and dynamic healthcare facility where facility managers are required to make critical decisions constantly. Since there was no 3D model of this facility, building documentation (architectural, structural, mechanical, electrical, and plumbing construction drawings and photographs) was gathered to develop a building information model in Revit. Since this was an active facility, the pilot study was restricted to one patient room (Room X). The building information model of Room X was created, and attributes were customized for each object based on the experiment task (Figure 1.a). As the experiment was facility management related, only the associated objects (Figure 1.b) were left visible for interaction within an augmented environment.



(a) BIM model of Room X in Revit (b) Experiment-associated objects in BIM model

Figure 1. Test Location

Test Conditions and Experiment Task. Considering the hypothesis that was mentioned in the Introduction, there were two conditions in this experiment: (1) Augmented Reality (AR) and (2) paper format. In the AR condition, participants stood on a fixed geo-spot location (InfoSPOT) previously defined in Room X (Figure 3-a) and were provided with an iPad to complete six different tasks. Each task indicated one object in the room that the participant should have located correctly. Participants could see the real-life view of the room through an iPad, but each object was highlighted using augmented 3D geometry of the same object from the BIM model (Figure 2-b). On their iPads, the target component in the facility appeared in red, while other components from the same family appeared in green.



(a) Participant's standing location (InfoSPOT) (b) Target wood cabinet in red while others in green

Figure 2. Augmented Reality (AR) Condition

In the paper-format condition, the participants were provided with a very similar set of six preventive/corrective maintenance work orders but in the exact paper format that facility managers were using at the Shepherd Center. The participants started the experiment at the starting location point (Figure 2-a), but unlike in the AR condition, they had to move about the room to find the correct objects. In this condition, the participants were required to go through the work orders and, using the sections related to the location of the target building component, locate the right object in the room. For this purpose, the participants not only needed to focus on the location-related sections of the work order to approximately locate the area of the target object but they also had to check the serial number or manufacturer information on the work order using the table of information provided under the numbered labels to make sure they have located the correct object.

RESULTS AND STATISTICAL ANALYSIS

Eight participants (5 male and 3 female) took part in the experiment. All participants reported normal or corrected-to-normal vision. The majority of subjects (75%) had not heard of AR, and only 1 had previously used any AR-based tool, device, or application. Analysis of the data collected includes reporting descriptive statistics as well as performing a paired-samples-T-test and a 95% confidence interval of the paired differences. A Shapiro-Wilk test (appropriate for small sample sizes) with an alpha level of $p = .05$ was also used to assess the normality of collected data under two different conditions. The collected scores were normally distributed under both conditions. A set of seven question adopted from IBM Post-Study System Usability Questionnaire (PSSUQ) (Lewis 1995) were used as an after-scenario usability questionnaire (ASQ) for this experiment. The items asked participants to express their levels of agreement with the statements presented using the 7-point Likert Scale (1=Strongly Disagree to 7=Strongly Agree) provided. Table 1 demonstrates the Means and Standard Deviations (SD) for time and number of errors as well as all the ASQ items based on the participants' experiment conditions. The table also displays the results of the 2-tailed paired-samples-T-test and the 95% confidence interval. As illustrated in this table, all results were statistically significant except Question 3, which was marginally significant.

Table 1. Descriptive statistics, paired-samples t-test and 95% confidence interval results

Variables	Test Conditions		95% Confidence Interval of the Paired Difference		t	Sig.
	AR	Paper				
	Mean (SD)	Mean (SD)	Lower	Upper		
Time (mm:ss)	02:08 (00:52)	05:36 (01:23)	-0:04:42	-0:02:13	-6.600	.000
Number of errors	1 (1.07)	19.38 (12.29)	-29.062	-7.688	-4.066	.005
Q1: Overall, I am satisfied with the ease of completing this task	6.50 (0.53)	3.63 (2.39)	0.956	4.794	3.543	.009
Q2: It was simple and quick to use this approach	6.63 (0.52)	3.38 (2.56)	1.119	5.381	3.606	.009
Q3: It was easy to learn to use this approach.	6.63 (0.74)	5.25 (1.39)	-0.103	2.853	2.200	.064
Q4: I believe I could become productive quickly using this approach	6.75 (0.46)	4.50 (2.14)	0.421	4.079	2.909	.023
Q5: Whenever I make a mistake using the approach, I could recover easily and quickly	6.38 (1.06)	4.50 (1.77)	0.299	3.451	2.813	.026
Q6: It was easy to find the information I needed	6.63 (0.74)	3.50 (2.27)	1.487	4.763	4.511	.003
Q7: Overall, I am satisfied with this approach	6.50 (0.76)	3.63 (2.45)	0.956	4.794	3.543	.009

Discussion of Results. The results indicate that the general pattern is similar, meaning items were scored significantly better in the AR (Augmented Reality) condition (see Table 1). Individuals' comments in the after-scenario questionnaire

(ASQ), as well as issues declared by participants in the think-aloud process during the experiment, also supported the findings.

Considering the total time for performing each condition, participants completed the experiment task faster with the AR system (Mean=02:08, Min=01:09, and Max=03:21) than with the paper documents (Mean=05:36, Min=04:00, and Max=07:50). Further, participants in AR condition (Mean=1.00, Min=0, and Max=3) had fewer errors in locating the correct object in the test room than when using paper-based maintenance forms (Mean=19.38, Min=7, and Max=39). Participants made similar comments in favor of the AR approach and against the paper condition, supporting the result of time and number of errors. "[Paper approach] could lead to lots of errors easily", [Paper approach] was "confusing," "very unreliable," and "time consuming." One participant noted that "it was not easy to find the location [of the correct object in the paper condition] because it was taking a lot of time to match information [between paper forms and objects' data table]."

In terms of the qualitative after-scenario questions, the users were more satisfied with the ease of completing the experiment task under the AR condition (mean response out of 7, Mean=6.50) than the paper-based checklists (3.63). One participant stated, "even a kid can handle the task [using the AR system] as there was not much to do beside looking around [through the iPad] and find the right object [in the test room]". The participants also believed that the AR approach was simpler and quicker to use (6.63) than the paper-format (3.38). Participants also indicated that it was easier for them to learn the AR approach (6.63) than the paper forms (5.25). They also believed that AR (6.75) made them productive more quickly than the paper condition (4.50). Using the AR system (6.38), when the participants made a mistake, they could recover more easily and faster than with the paper-based approach (4.50). In terms of finding the information, participants indicated that it was easier for them to find the information required to locate the correct object in the test room under AR condition (6.63) than in the paper format (3.50). Overall, participants were more satisfied with AR condition (6.50) than the paper format (3.63).

Although the AR system was rated more highly than the paper condition, the majority of participants made several comments about drift problem. One participant stated, "The [AR] system is very intuitive but sometime there is a mismatch between the objects and the augmentations," and another one noted that "[the augmentations] were not exactly matching [on the right object], but I could easily guess the right answer." As a part of the experiment under paper condition, the participants were required to climb a ladder to check the information behind the HVAC tiles that were numbered with labels. This led to several comments such as "the AR is much more reliable and safer [than paper condition]," and "AR approach is easier and less risky than climbing ladders in a hospital and it has less trial and error." The participants also provided different recommendations/comments such as "[AR] is simple and easy to locate the objects but just having green and red colors to represent right and wrong objects [in the test room] is not intuitive," and "I don't like touching objects in hospital and having AR system helped me not to do that."

There were some other issues observed while participants were performing their tasks. In paper condition, most of the participants were initially confused with the tasks but learned how to do so after completing the first. They made comments such as “I don’t know what I am doing,” or “I am not sure where I can find the right object in the room.” In AR condition, the system crashed several times, and the most important comments made by users in their thinking aloud process was about the drift issue. They made comments such as “… It is difficult to find…align, please,” “It is not matching,” and “It is not totally matched, it is 1 meter away.” Another issue observed several times in the AR condition was that participants had to look at the iPad and the real world (switching the domains) to locate the right object. This issue might be due to the drift problem or the transparency and size of the augmented geometry of the object. Some other general observations in the AR condition are as following: (1) some users were leaning back on their standing point to see some augmented information, (2) users were generally identifying the color first and then deducing from geometry, (3) after a short time, users would translate errors in drift and could begin to interpolate the correct answer, (4) due to drift, users felt as though they were guessing which object was the correct one, (5) some users were trying to align digital information before stating which object needed to be maintained, (6) some users moved their bodies extensively, and (7) some users had to look back and forth from the screen to call out the number.

CONCLUSION

This research is the first rigorous study on bringing BIM to an AR environment while conducting a user-centered experiment to considering the users requirements in design, development, and evaluation phases. Systems have traditionally been designed and developed through a technology-centered perspective. In such a perspective the designers would accept the technology as is and would try to apply the very same technology in different domains without considering the very important element of the ultimate end user. In a technology-centered perspective, the end user and all its requirements would be considered improperly identical in different domains. In this research, a user-centered approach was employed. In a user-centered perspective the technology should be considered while investigating the real users’ experience and their own requirements in any target specific domain. This user-centered usability-based step would provide a foundation for understanding the requirements for practical application of the technology in a domain.

An important challenge of AR application for facility management practices is the drift problem meaning virtual augmentations would not exactly match on the real object. Solving this issue is a main avenue of research in the Computer Science domain. There are different approaches for reducing the drift issue to minimum amount but most of them are costly and not scalable for real applications in AECO practices. Through the user-participation experiment that was conducted, it was understood that even having the drift issue, significantly better outcomes were achieved under AR condition compared to the paper-condition. Accepting drift issues and investigating human computer interface requirements that would minimize the matching requirement and would enhance the user experience in an AR environment would be of great value for AR applications using the current technological infrastructure in the market (e.g. tablet computers and handheld mobile devices). Unfortunately there is no design guideline for AR for use in any handheld, projective, or head-worn tools. The next phases of this research should be investigating what would be the design requirements for AR application in AECO practices. Each phase of a building life cycle (design, construction, or facility management) might have its own requirement that should be studied in detail. The applicability of an AR environment within each of those phases of the building life cycle and comparing it to similar methods such as augmented picture or augmented panoramic views would be other issues that should be investigated as future steps of current research.

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