Automation in Construction 33 (2013) 11–23

Contents lists available at SciVerse ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

InfoSPOT: A mobile Augmented Reality method for accessing building information through a situation awareness approach

Javier Irizarry [a], Masoud Gheisari [a,*], Graceline Williams [b], Bruce N. Walker [c]

[a] CONECTech Lab, School of Building Construction, Georgia Institute of Technology, Atlanta, GA, USA
[b] Digital Building Lab, College of Architecture, Georgia Institute of Technology, Atlanta, GA, USA
[c] School of Psychology and School of Interactive of Computing, Georgia Institute of Technology, Atlanta, GA, USA

ARTICLE INFO

Article history:
Accepted 9 September 2012
Available online 6 October 2012

Keywords:
Augmented Reality
Facility management
Situation awareness

ABSTRACT

The Architecture, Engineering, Construction, and Owner/Operator (AECO) industry is constantly searching for new methods for increasing efficiency and productivity. Facility Managers (FMs), as a part of the owner/operator role, work in complex and dynamic environments where critical decisions are constantly made. This decision-making process and its consequent performance can be improved by enhancing Situation Awareness (SA) of the FMs through new digital technologies. In this paper, InfoSPOT (Information Surveyed Point for Observation and Tracking), is recommended to FMs as a mobile Augmented Reality (AR) tool for accessing information about the facilities they maintain. AR has been considered as a viable option to reduce inefficiencies of data overload by providing FMs with a SA-based tool for visualizing their "real-world" environment with added interactive data. A prototype of the AR application was developed and a user participation experiment and analysis conducted to evaluate the features of InfoSPOT. This innovative application of AR has the potential to improve construction practices, and in this case, facility management.

Published by Elsevier B.V.

1. Introduction

Facility management as part of the Architecture, Engineering, Construction, and Owner/Operator (AECO) industry is constantly searching for new methods for increasing efficiency and productivity. The facility management profession depends heavily on archaic, time-consuming tasks and systems to accomplish its goals. The surge of new digital technologies provides great opportunities to make these tasks easier and allow Facility Managers (FMs) to solve problems faster. These professionals of the built environment require access to information about the facilities they maintain. There is so much information contained in our buildings that FMs have great difficulty in accessing the information needed at the right time or location inside the building. In this research, Augmented Reality (AR) has been used to help FMs with their daily inspection activities by providing them with an AR-based tool that would allow them to visualize their real-world environment with added interactive data. In order to assist FMs in accessing the information crucial for the task at hand, the concept of Situation Awareness (SA) is applied. The proposed research will fuse the area of AR and SA to solve the problem of providing the right information at the right time and location inside a facility.

Significant research has been done in the area of AR and the technology has advanced to a degree where consumer grade applications have started to be used by the public. AECO can utilize the low-cost mobile-device AR to optimize workflows for various purposes including quality control, safety management, scheduling, mocking up spaces for clients, training workers, construction education, and in this research for facility management. Due to its low-cost and the vast array of possible applications, mobile AR will likely have a significant impact on AECO operations in the next decade. Although consumers are beginning to see mobile AR integrated more and more in their daily lives, these applications are relatively simple in functionality, for static environments, and mainly for entertainment purposes that require little accuracy. The use of AR for facility management environments requires extreme accuracy and flexibility. The most significant challenge for researchers in facility management with an interest in AR will be to find solutions that are scalable and can change rapidly with the operation/maintenance environment. One of the issues in developing robust mobile AR tools for the facility management domain is Indoor Location Tracking. Current use of AR is mainly for use in outdoor settings where access to Global Positioning System (GPS) and Wireless Fidelity (Wi-Fi) technologies are available and relatively accurate. In contrast, AR applications for the facility management domain mostly require solutions for an indoor environment that might not have adequate GPS or wireless network access. This application also requires a high level of accuracy, within centimeters, and must be able to span long distances across several building stories. Another issue arises when integrating Building Information Models into mobile AR systems. Building Information Modeling is becoming the new standard in AECO. These information-rich

* Corresponding author. Tel.: +1 404 385 6779.
E-mail address: masoud@gatech.edu (M. Gheisari).

0926-5805/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.autcon.2012.09.002

models are overwhelmingly difficult to integrate into mobile AR solutions. In order to have seamless mobile AR solutions, guidelines will need to be created for how BIM models should be parsed and translated into a lower geometric and data resolution or partially loaded on display devices with only needed information. Considering all these challenges, Information Surveyed Point for Observation and Tracking (InfoSPOT) was developed as a prototype of a low-cost AR solution (tracking system + mobile application) to enhance the decision-making process of the FMs. InfoSPOT users (FMs) will be able to quickly install a Surveyed Point for Observation and Tracking (SPOT) mat and access the SA-based information through their mobile devices.

2. Situation awareness, applying a user-centered information assessment approach to facility management domain

In order to keep the human professional in charge and to enable him/her to solve meaningful problems in a manner that is as natural as possible, new approaches that are more user-oriented should be used to augment human capabilities. Systems have traditionally been designed and developed through a technology-centered perspective [1]. 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 (human). 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. Unlike the technology-centered approach, the very first issue that should be resolved in a user-centered perspective is whether the technology is usable considering the real users' information requirement and their experience in a specific domain. For understanding the information requirement part, Situation Awareness as an approach to user-centered design was used before system development and for investigating the users experience, a user-participation approach was recruited for evaluation purposes as a phase right after the system development.

A widely accepted definition of Situation Awareness (SA) is, “knowing what is going on so you can figure out what to do” [2]. Basically, SA is having awareness about what is happening around, in order to make decisions based on that information, now and in the future. In more detail, SA clarifies what is needed for reaching the goals of a specific job by understanding what important information is to be used in the decision-making process. Formally, SA has been defined by Endsley [3–5] as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future.” Improved SA can lead to better decision-making and performance [6]. As highlighted in Fig. 1, there is a relationship between environment, situation awareness, decision-making, and performance. Within the SA process, at the first level, the operator should perceive relevant information (Level 1 SA), then integrate this data with task goals (Level 2 SA), and at the end, predict future events based on his own understanding (Level 3 SA).

Various domains, such as fighter aircraft navigation, electronic systems and automation technology, driving and ground transportation, energy production and distribution, space operations, nuclear power plant management, and the medical field, have applied the SA methodology [5]. As an example, Son et al. [7] applied SA in a disaster response system. Their study found that for an effective situation-aware decision making process, IT-based systems should be designed to support individual responder as well as group decision making, considering complex socio-behavioral-technical interaction at the individual, team and inter/intra-organizational levels. They concluded that SA would support users' ability to get the required information on an as-needed basis under dynamic and complex conditions, which would result in improvements in decision-making and response efforts.

In this research, SA means understanding the information needs of facility management personnel in goal-oriented positions that are critical to the decision-making process in dynamic facility environments. Gheisari and Irizarry [8] took the initial steps in the application of SA in the facility management domain. The most recent definition of facility management is “a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process, and technology” which was presented by the International Facility Management Association (IFMA) [9]. This means FMs work in a complex environment in which they have to keep up with a large amount of information. FMs cannot easily filter and organize information in an accurate manner. This results in less than optimal decisions being made. The user, working on critical facilities or jobsites, should neither be overloaded with irrelevant information nor be hampered by inappropriate services and cumbersome input and output techniques. Gheisari and Irizarry [8] proposed a conceptual model based on the SA concept, which can help FMs to overcome the complexity of provided information in their working environment (see Fig. 2). SA can filter this large amount of information and provide the facility manager with organized and required information. The organized information requirements not only can shape the mental picture of the facility manager but also have the potential to be used as a basis for developing human-computer interfaces and applications. The improved mental picture together with human-computer interfaces can prosper the decision making process of FMs and can lead to the achievement of their goals in the facility management domain. Goals such as reducing errors and improving task performance can lead to the improvement of FMs’ practices in their working environment.

Based on the SA-centric outcome of the Gheisari and Irizarry [8] research, a human-computer application was developed to facilitate the decision making process of FMs. This human-computer application uses AR as a viable option to reduce data overload inefficiencies in facilities by adding interactive data to their real-world environment. FMs can use this application through their mobile devices.

3. AR, mobile AR, and InfoSPOT

According to Azuma [10], “AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real

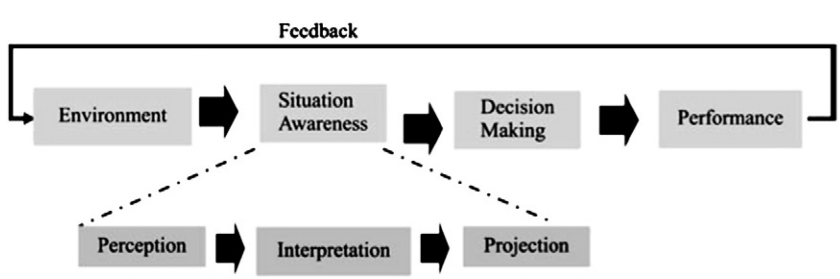


Fig. 1. Situation awareness feedback loop (adapted from [8]).

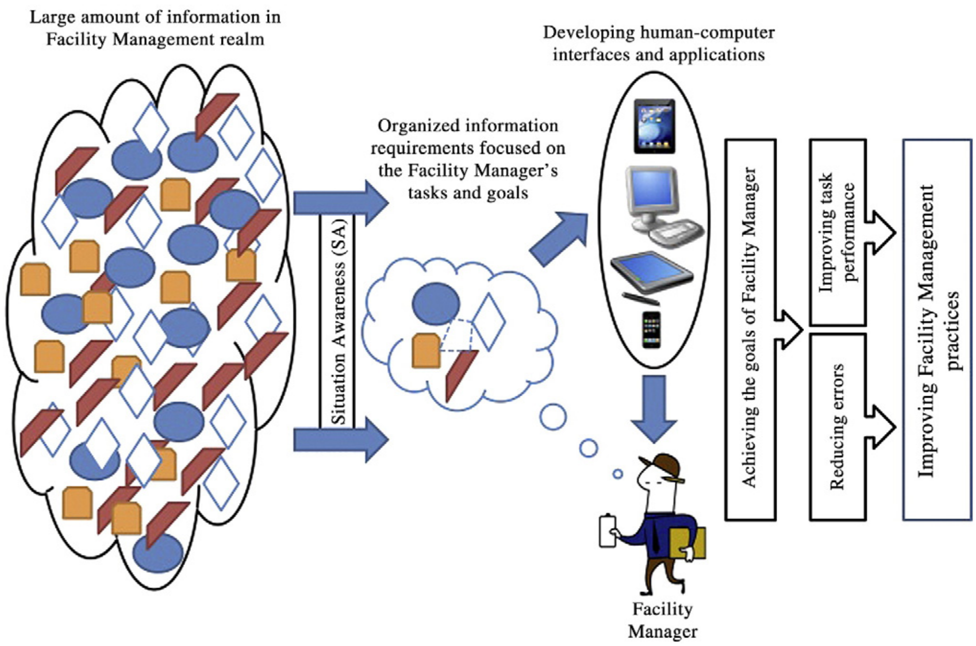


Fig. 2. The conceptual model of FM and SA integration [10].

world. Therefore, AR supplements reality, rather than completely replacing it." There are previous studies about AR application to AEC + FM domain. Shin and Dunston [11] 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 [12–14], focusing on design [15] or construction [16,17] phases. There are few studies in AR application in facility management as a phase that happens after the construction phase and usually in an indoor environment.

FMs are often required to relate physical objects to database-like text-based information. This makes AR a good candidate to aid FMs with their routine tasks because their live view of a space could now be supplemented by the database information they needed, all in one interface. Traditionally, FMs needed to shift the domains they were working in from the physical domain of the assets they managed to a printed or digital manifestation of the information related to those assets. As Henrysson and Ollila [18] pointed out in their study on Ubiquitous Mobile Augmented Reality (UMAR), AR can help solve real world problems because "there is no need for distracting domain switching."

Since FMs are constantly moving through the spaces they manage, having a portable, mobile device would be beneficial if they were to employ AR in their tasks. Mobile AR has been the topic of many research papers for decades evolving in complexity not only in terms of software but also in hardware. From Head Mounted Displays (HMDs) to tablet PCs to handheld mobile devices, the field of mobile AR is constantly changing as technology rapidly improves and makes AR more accessible to the consumer. Research by Feiner et al. [19] on a Touring Machine show early mobile AR development where users wore a HMD coupled with a secondary handheld display and a stylus to access information about the world around them. Several years later Wagner and Schmalstieg [20] deviated from HMDs and created the first self-tracking AR system on a Personal Digital Assistant (PDA) with an attached camera that utilized the AR Toolkit [21]. More recently several studies have been utilized AR and mobile phones [18,22]. As mobile phones and tablets replace the HMDs, great opportunities have been provided for AR applications that do not require bulky, socially unacceptable hardware.

As reported by eMarketer [23] , there is an estimated 34 million tablet users in the US with the Apple® iPad® taking a share of 28 million users. With such a significant user base with access to tablets and previous research indicating the benefits of hand-held mobile devices over HMDs, the iPad® was utilized as the testing device for the InfoSPOT prototype because it had a large screen that made augmentations easier to select, and it was also compatible with KHARMA, the software architecture used for developing InfoSPOT.

Developed by researchers at the Georgia Tech Institute of Technology, KHARMA [24] extends upon Keyhole Markup Language (KML), an Extensible Markup Language (XML) used to describe geo-referenced maps, images, and models, and utilizes HyperText Markup Language (HTML), JavaScript, Cascading Style Sheets (CSS), and Asynchronous JavaScript and XML (AJAX) techniques to provide augmentations to a mobile client. KHARMA was chosen because of its low-cost, ease of implementation, and its ability to utilize an indoor localization technique called GeoSpots.

Indoor tracking technologies generally fall into the following categories: sensor-based, vision-based, or hybrid. Sensor-based systems can rely on acoustical, optical, mechanical, inertial or magnetic sensors and "are analogous to open loop systems whose output is perceived to have error" [25]. Vision-based systems "calculate camera pose relative to real-world objects and so are analogous to closed-loop systems which correct errors dynamically" [26]. The GeoSpot technique was ultimately chosen because it utilizes sensor-based technology already integrated within our chosen device, but builds upon the strengths of the close-looped methods found in vision-based systems to overcome the limitations of the sensors.

Sensor-based systems employ methods like location fingerprinting as seen in Microsoft's RADAR [27] and a study on labor tracking on construction sites [28] , triangulation as seen in Intel's Place Lab [29], multilateration as seen in an implementation of MIT's Cricket System [30], proximity as seen in LANDMARC [31], and dead-reckoning as utilized in inertial and motion sensors [32] like gyroscopes. They calculate measurements like Received Signal Strength Indicators (RSSI), Time of Arrival (TOA)/Time Difference of Arrival (TDOA), and Angle of Arrival (AOA) or Direction of Arrival (DOA) [33,34]. But, they are error-prone due largely to component accuracy limitations. We found that solely utilizing a sensor-based system indoors would introduce significant error variables. The following explains the disadvantages of different types of sensor-based systems and the reason they were not implemented in this research.

Ultrasonic sensors like Cricket [35] are sensitive to temperature, occlusion, ambient noise, require significant infrastructure, and have a low update rate making errors frequent indoors [36]. Relying on GPS (Global Positioning System) without the ability to give a baseline measurement would cause significant errors indoors as GPS requires direct lines of sight from a user's receiver to at least 3 orbital satellites [36,37]. Infrared systems like Active Badge [38] suffer from short-range, signals only accurate in short distances, and are limited because of line-of-sight requirements which will be significant in an occupied indoor space that facility managers would be overseeing. While Radio Frequency (RF) systems (IEEE 802.11 and WLAN) do not have line-of-sight issues [37], they do require extensive infrastructure (base stations) to provide localization as seen in RADAR [27] and have a median accuracy of 2 to 3 meters which is not ideal for indoor FM situations where objects/items will be within centimeters of each other. RF Identification systems like SpotON [39] may also not be ideal for AECO environments as accuracy can be diminished due to static obstructions and due to the requirement of each object having its own RFID tag. The RFID approach also lacks in scalability. With thousands of objects/systems (some of which are obstructed from view) within a building, purchasing and maintaining RFID tags would not be practical. Unlike other RF technology, Ultra-wideband (UWB) systems overcome the multipath issues with signals being able to pass through walls and offer centimeter level positioning accuracy, but they still run into interference errors when metals or liquids are present and are relatively expensive to implement due to infrastructure costs running in the thousands of dollars [33,40]. Similarly, Indoor GPS systems provide centimeter-level accuracy, but require clear lines-of-sight and are even more expensive than UWB systems [37].

Other indoor tracking technologies can be categorized as vision-based (utilizing a camera/monocular vision system). In these systems, tracking of objects in the scene amounts to calculating pose, position and orientation [25], between the camera and the objects [41]. These systems are more reliable than sensor-based systems and can dynamically correct errors [26]. Vision-based systems can be classified as feature-based, or model-based [42]. Feature-based systems can track 2D features such as geometrical primitives, object contours, regions of interest or textures. Model-based systems track edges or textures as they relate to models of the tracked objects from 2D and 3D CAD/templates. Vision-based systems were not directly utilized for this study as the GeoSpot technique provides similar results. The following explains the disadvantages of vision-based systems and the reason they were not implemented in this paper.

Featured-based systems originated in marker-based tracking methods as seen in the ARToolKit library [21]. Marker-based systems rely upon easily identified artificial features (fiducials), and are not suitable for AECO scenarios as they are limited by line-of-sight and would require significant maintenance over a building life cycle. In AECO scenarios, marker-based techniques are also not scalable as some objects may be occluded from view or located within structural elements like walls, floors, or ceilings. Some featured-based systems track naturally occurring features (points, lines, edges, textures) as seen in [43,44]. These systems show a more robust method over markers and continue to track pose even after known visual features are established. But, accurately tracking naturally-occurring features depends on the system recognizing distinguishable “markers”. In indoor AECO scenarios where lighting conditions, clutter, and depths of spaces can vary greatly from space to space, solely relying on feature-based systems would provide inconsistent results.

Model-based systems can leverage existing natural features and extend the range of a tracking area [26]. But, these systems as seen in [41,42,45] can also suffer from errors due to occlusion and changes in illumination making them unsuitable for cluttered and varying AECO spaces.

According to Azuma [10], “one of the most basic problems currently limiting Augmented Reality applications is the registration problem”. In AR applications for facility management, it is crucial in a video-see-through approach (one where a user views augmentations through a live camera view) that augmentations align properly with the real world. Misalignment of augmentations could lead to inefficiencies in workflows and faulty asset management that made utilizations of GeoSpots beneficial for the InfoSPOT prototype. As stated by Bajura and Neumann [25], there are 4 causes of registration errors in combined real and virtual images:

1. The tracking system's origin is not aligned with the world coordinate system. In mobile augmented reality systems this could result when sensor-based systems fail to provide accurate readings due to issues like line-of-sight or calibration errors. All augmentations would be displaced from their proper positions.
2. The virtual origin-to-object transformation is not the same as the real origin-to-object transformation for a particular object. In the GeoSpot approach, this error would rarely occur.
3. The virtual camera position is not the same as the real camera position. This error might arise in some mobile augmented reality systems that employ inertial and motion based sensors resulting in misregistration and drift.
4. The virtual camera-to-image mapping doesn't accurately model the real camera. In mobile augmented reality, augmentations may misregister due to inaccurate calibrations of center of projection, field of view, or distortion.

GeoSpots create geo-reference points of latitude and longitude associated with different descriptive information. Users can tell their device they are located at the GeoSpot and augmentations will be delivered to their screen relative to that GeoSpot. GeoSpots were a good solution for the InfoSPOT prototype because it made it possible to get more accurate registration and indoor localization than native iPad® hardware alone and eliminated the need for fiducial markers that would not really be feasible in a true facility management situation which might require thousands of unique tags for all objects in a managed space. Equipped with a three-axis gyroscope, accelerometer, Wi-Fi, and digital compass hardware, an iPad® utilizing the GeoSpots would reduce the problem of “when the real and virtual do not align properly the illusion is compromised” [10]. Previous research also validated that relying solely on the iPad® hardware alone would cause large registration and indoor localization issues, therefore the utilization of GeoSpots was necessary to maintain the AR illusion for users. Some iPads® come equipped with Global Positioning Technology (GPS) but even if these models were employed in our study, research has shown that no improvements would have been seen in registration or localization. A study by LaMarca et al. [29] in which users would carry GPS devices during different portions of their typical day demonstrated this point. The results showed that GPS devices showed low user coverage (4.5%). LaMarca et al. [29] surmised that this was likely due to users typically spending most of their time indoors where GPS technology suffers from multi-path effects, interference, and noise. Instead of GPS, the iPad® uses Wi-Fi for localization. As the same study by LaMarca et al. [29] indicates Wi-Fi had higher user coverage than GPS (94.5%) with an accuracy of 15–20 m. But, FMs often need to query and organize objects that are within centimeters of each other making standalone Wi-Fi unsuitable for this application. Although not employed in our prototype, other research indicates new techniques or implementation of other common built-in hardware found in today's mobile devices could become better sources for localization indoors in the future. A study by Bargh and Groote [46] implements a system that utilizes merely Bluetooth technology to locate someone indoors with 98% accuracy.

The downfall of the prototype is the requirement of full Bluetooth sensor coverage in a room and target devices needing to be stationary for long periods at a time (longer than a few seconds) that is unsuitable for facility management practices.

While developing InfoSPOT, it was realized that while GeoSpots allowed users to accurately position themselves initially, drift and lag caused by commodity grade sensors in the iPad® created registration errors after initialization which could only be avoided if the iPad® location was manually recalibrated every few seconds. One study in particular by Wither et al. [47] was used in this research to circumvent these tracking inaccuracies inherent in using only the iPad® hardware. Wither employs a “magic lens” approach to AR utilizing pre-prepared panoramas of specific locales and placing augmentations over them. Pre-prepared panoramas allow for consistent alignment of augmentations and removed registration errors found in the live video feeds used by typical mobile AR applications. Building upon Wither's research, the following three approaches were devised to mobile AR for facility management: (1) Augmented Reality I: Geo-referenced augmentation markers (InfoSPOTs) placed above a live video feed, (2) Augmented Reality II: InfoSPOTs placed above a 360 degree panorama of outlines of 3D object models above a live video feed, and (3) Virtual Model: Geo-referenced augmentation markers placed above a 360 degree panorama of a 3D model of object models and room architecture. The virtual model contains no video feed.

In addition to understanding AR, the InfoSPOT prototype also required a context for testing. Advances in AECO point to Building Information Modeling (BIM) as the new standard for CAD drafting in the AECO industry. BIM solutions are used mostly because of their three useful characteristics [20]; (1) they utilize digital databases, (2) they manage the interrelated databases so updates in one part result in the update of other parts, and (3) they store information that can be used later by other industry specific applications. These characteristics show that BIM is not only capable enough to be used in the design and construction phases but also can be applied in the latter stages of the life cycle. The disassociation between design/construction phase and facility management phase also can be improved using BIM solutions. BIM's Extension of Industry Foundation Classes (IFCs) can increase efficiencies and communication between stakeholders and managers throughout the lifecycle of a building, from design to management [21]. IFCs are an ISO (International Organization for Standardization) norm that describe object specifications and are interoperable between CAD software packages making them a good format for sharing data among various types of building stakeholders. This led us to using a real-world BIM example in our study in order to be able to determine the feasibility of implementing the InfoSPOT prototype in a real project. A BIM model had been generated and utilized for the design development and construction phases of the Hinman Research Building at Georgia Tech. For the sake of running an experiment in a controlled environment, from the entire 35,000 square foot of the Hinman building, the user participation test was run in a single modeled room (CONECTech Lab).

4. Overview of the project

As illustrated in Fig. 3, the first step in this research was developing an InfoSPOT system that is considered as a prototype of a fully functioning facility management data-accessing tool. Then a within-subjects experiment was designed to test the InfoSPOT with real subjects while performing a facility-manager-related-task under different conditions. In this experiment, the subjects would locate different objects in a room and then would answer one question about each object under three different conditions; (1) Augmented Reality I, (2) Augmented Reality II, and (3) Virtual Model. The time taken by experiment participants to perform the tasks as well as their responses to some qualitative questions was used as dependent

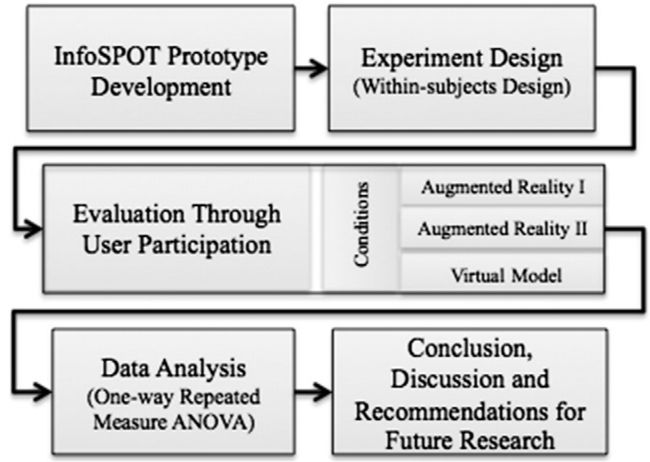


Fig. 3. Research methodology.

variables for comparing these three conditions. After performing the experiment, a repeated measures analysis of variance (ANOVA) was used to test whether there are statistically significant differences between these three conditions. After reporting the results of the statistical analysis, they are discussed and conclusions are made.

5. InfoSPOT development

The methods and procedures used to generate the InfoSPOT prototype have been illustrated in Fig. 4.

First, a BIM Model of the determined test area was acquired and checked for accuracy to built environment conditions. A few inconsistencies were present that the researcher resolved through surveying the test area and making adjustments to the BIM Model. Although a BIM Model of the entire 35,000 square foot building was obtained, the prototype required only a small portion of this model for experimentation. Therefore, the relevant geometry was isolated to increase graphics efficiency and reduce errors that could occur with a large model (Fig. 5).

Second, the BIM Geometry and Data was separated into two different files. The BIM Geometry was exported to the .fbx file format to use in a visualization-based 3D modeling software. BIM Geometry can be converted into many data formats including, but not limited to .fbx, .dxf, .dwg, etc. Testing was done on each of the geometry export options available through Autodesk® REVIT®. Each file format was measured against several variables that typically indicated errors in the format conversion process. The errors were stated by McHenry and Bajcsy [48] in a technical report and were likely due to software/hardware incompatibility and product data quality. After testing different file format conversions of the BIM Geometry, .fbx was found to be the most suitable for the InfoSPOT application. While some geometry did not translate over when converting to the .fbx format, the unique identifiers related to the objects remained which were useful when accessing the database for information. The BIM Data was exported to Open Database Connectivity. Each instance of geometry in the BIM model is associated with a unique identifier and corresponding data. Despite the lack of information relevant to FMs in the model acquired, it was decided that the BIM Data would still be stored for future research.

Third, the exported BIM Geometry was then optimized using several manual modeling techniques to reduce complexity. These techniques included welding overlapping vertices, eliminating unnecessary geometry, and mesh simplification.

Next, panoramas were generated with the purpose of replacing 3D models in the InfoSPOT prototype. The camera in the tablet device has a field of view of approximately 45 mm. As illustrated in Fig. 6, a

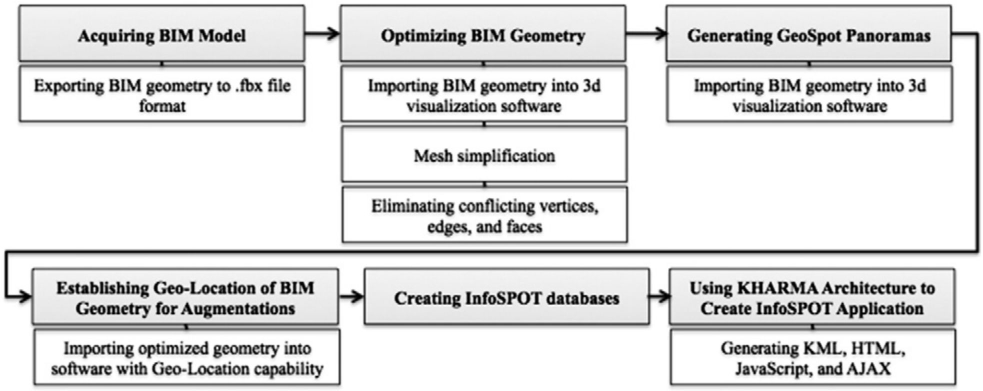


Fig. 4. InfoSPOT development diagram.

camera was placed in the 3D scene containing the optimized model and 360-degree panoramas were taken for use in the Augmented Reality II and Virtual Model conditions of the project.

Optimized geometry was then imported into Google Sketchup™ powered by Google Maps™ and Google Earth™ software to establish geo-referenced locations for augmentation markers (InfoSPOTs). Prior to import into the software, several InfoSPOTs were identified by the researcher. These InfoSPOTs were to represent graphic markers of several objects in the test area that users of the prototype could select to view more facility management related information about that object. The centroids of each InfoSPOT were observed and latitude, longitude, and altitude were recorded in a database. Additional data was also created and entered in the database that related to each InfoSPOT for use in the experiment. As mentioned above, the creation of new data was necessary due to lack of data in the original BIM model acquired for the experiment.

Last, the KHARMA architecture was utilized to create the InfoSPOT prototype. A mixture of KML, XML, HTML, JavaScript, and AJAX was utilized to generate augmentations for users to view inside the augmented reality browser, Argon. Fig. 7 illustrates the sample code for InfoSPOT prototype development. The InfoSPOT prototype can be viewed through the Argon Browser for mobile devices. The Argon Browser utilizes the KHARMA Architecture. Fig. 8 illustrates the systems architecture of the InfoSPOT.

6. Challenges in InfoSPOT development

Working with a real world example of a BIM model, several unexpected issues changed the approach to creating the augmentations and visualizations for the InfoSPOT prototype. Early in the study, the contractor/architect BIM model was obtained and checked for inconsistencies or errors. This process exposed the lack of pertinent

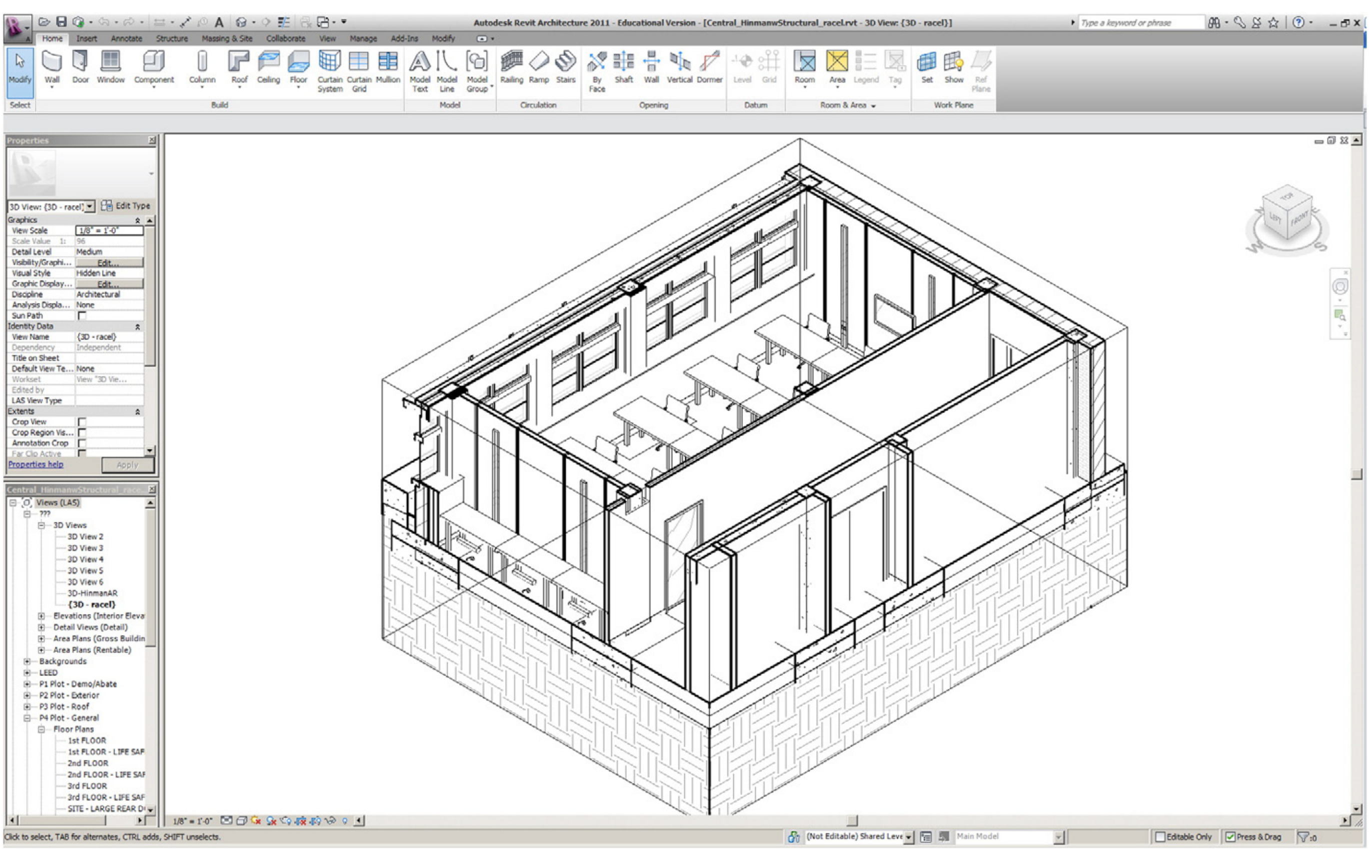


Fig. 5. BIM model of test area.

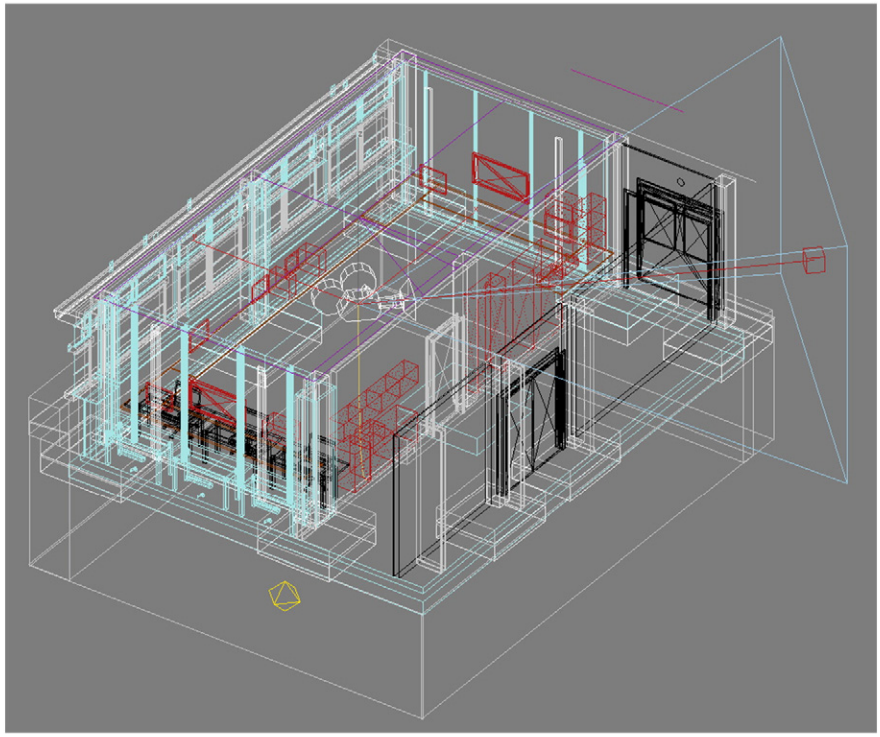
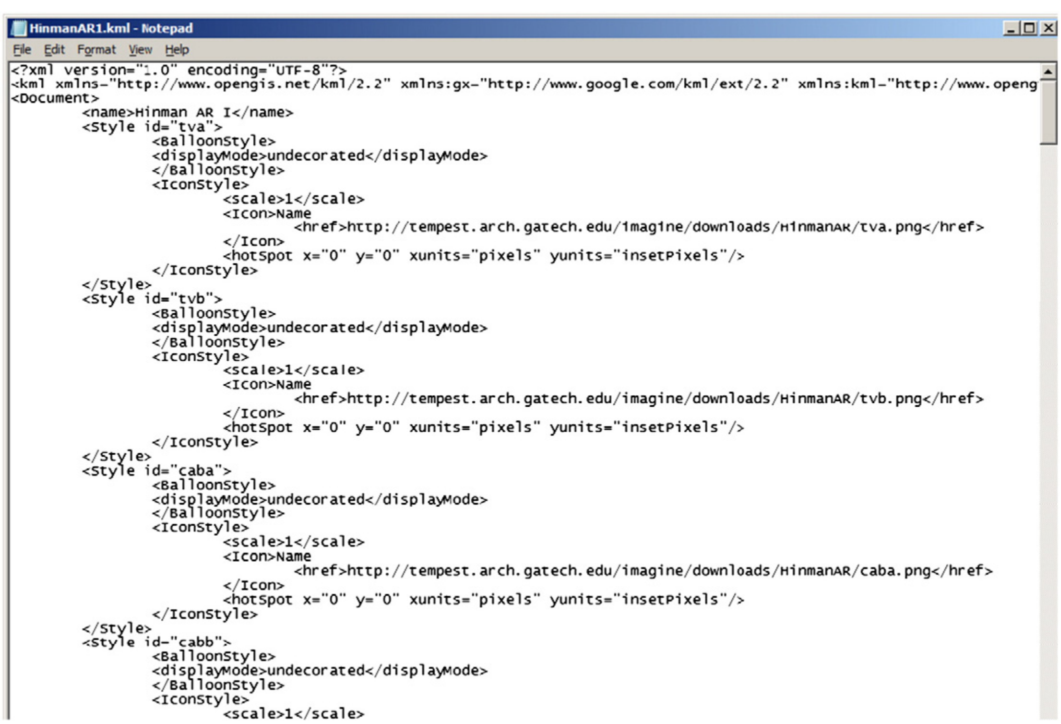


Fig. 6. Panoramic camera in 3D scene of optimized BIM geometry.

database information embedded in the model. While architectural features, structural features, and furniture were all present in the BIM model, any useful information for facility managers was lacking. To try and ascertain if the models received were the final as-builts, several meetings were held with the contractors and architects of the building. Through our discussions we discovered that the BIM model we received was only utilized through the design development phase by the architect alone. During the construction phase, the contractor and sub-contractors had generated their own working drawings in various other file formats and CAD software. These files were not made available to our group during the time of the study. This discovery led us to question the accuracy of the BIM model, and surveys of the test area were conducted. Results of the surveys indicated the BIM model was inconsistent with the built environment.



HinmanAR1.kml - Notepad

File Edit Format View Help

```
<?xml version="1.0" encoding="UTF-8"?>
<kml xmlns="http://www.opengis.net/kml/2.2" xmlns:gx="http://www.google.com/kml/ext/2.2" xmlns:kml="http://www.openg
<Document>
	<name>Hinman AR I</name>
	<Style id="tva">
		<BalloonStyle>
		<displayMode>undecorated</displayMode>
		</BalloonStyle>
		<IconStyle>
			<scale>1</scale>
			<Icon>Name
				<href>http://tempest.arch.gatech.edu/imagine/downloads/HinmanAR/tva.png</href>
			</Icon>
			<hotSpot x="0" y="0" xunits="pixels" yunits="insetPixels"/>
		</IconStyle>
	</Style>
	<Style id="tvb">
		<BalloonStyle>
		<displayMode>undecorated</displayMode>
		</BalloonStyle>
		<IconStyle>
			<scale>1</scale>
			<Icon>Name
				<href>http://tempest.arch.gatech.edu/imagine/downloads/HinmanAR/tvb.png</href>
			</Icon>
			<hotSpot x="0" y="0" xunits="pixels" yunits="insetPixels"/>
		</IconStyle>
	</Style>
	<Style id="caba">
		<BalloonStyle>
		<displayMode>undecorated</displayMode>
		</BalloonStyle>
		<IconStyle>
			<scale>1</scale>
			<Icon>Name
				<href>http://tempest.arch.gatech.edu/imagine/downloads/HinmanAR/caba.png</href>
			</Icon>
			<hotSpot x="0" y="0" xunits="pixels" yunits="insetPixels"/>
		</IconStyle>
	</Style>
	<Style id="cabb">
		<BalloonStyle>
		<displayMode>undecorated</displayMode>
		</BalloonStyle>
		<IconStyle>
			<scale>1</scale>
```

Fig. 7. Sample code for InfoSPOT prototype.

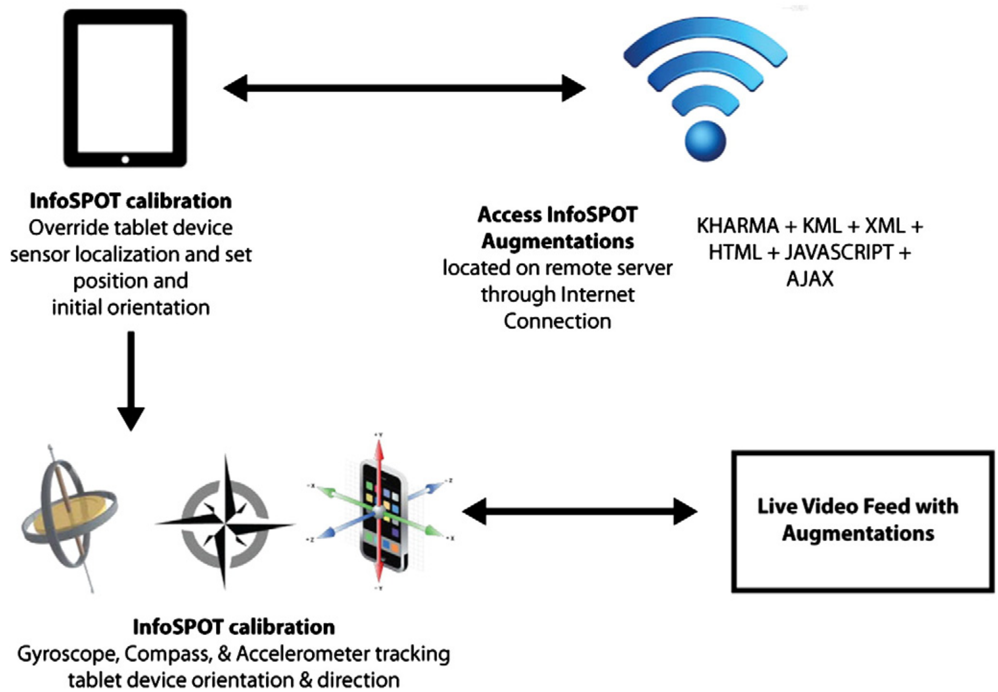


Fig. 8. The InfoSPOT system architecture.

Architectural elements and furniture were off by several meters. Due to the amount of information in the BIM model and minimal control of how geometry topology is created in BIM modeling software, it was determined that the entire BIM model of our building was too complex to display in a mobile device without geometry optimization. As a result of these issues, the 3D geometry was separated from the database information and optimized in modeling software, Autodesk® 3Ds max®, where the researcher was able to better control the complex geometry . To further increase the efficiency and reduce errors in the prototype, the optimized 3D geometry was used to generate 3D panorama images that would load faster than 3D models in a mobile device with limited processing power.

7. Evaluation through user participation

The experiment consisted of using a tablet computer device (an Apple® iPad® was used in the experiment) as a mobile AR tool to access some inventory information about different objects in a test area (CONECTech lab at Georgia Tech). The lab was used as a test location for the experiment. The user's task was to locate some objects in the room and then answer a question about each of them. Simultaneously the experimenter was measuring the time taken by the participants to perform each task. Note that having access to an inventory of different objects in a facility is one of the basic information needs of FMs. Before starting the experiment each subject was presented with an Informed Consent Form for him or her to read and sign in agreement to participate in the experiment. Georgia Tech's Institutional Review Board (IRB) evaluated and approved the study protocol. The subjects were also required to fill out a demographic information form before starting the experiment.

7.1. Study design and methods

A within-subjects experimental design was employed, in which each subject participated in three “location finding + data extraction” conditions. The subject would sit on a chair over the InfoSPOT mat and was provided with a tablet device as an interaction tool to go through different scenarios and perform the required tasks (Fig. 9).

There were three different scenarios (conditions) for performing the tasks. The conditions were different based on the models provided in the tablet device; Augmented Reality I (ARI), Augmented Reality II (ARII), and Virtual Model (VM). In the ARI condition, the participant had a real life view of the room while an augmented icon was tagged to each object in the room (Fig. 10a). In the ARII condition, the participant not only had the augmented icon used in the real life view of the room (ARI) but also the outline of each object was highlighted using augmented lines (Fig. 10b). It was assumed that having augmented outlines of each object could help the subjects to perform their locating-the-right-object task easier when they were faced with drift problem or information overloads/overlays in the object-congested-areas of the room. In the VM condition, the participant had a virtual model view of the room while an augmented icon was tagged to each object in the model (Fig. 10c). It was assumed that having the VM could be used as a non-location-based alternative providing the users with natural interactive experience of accessing the inventory data wherever they are.

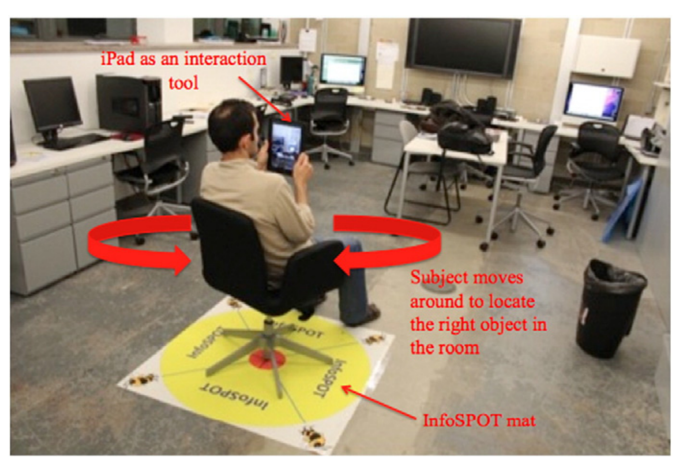


Fig. 9. Experiment setup.

Each scenario included five different tasks. Each task considered one object in the lab and had two parts; (1) locating the correct object and (2) answering one question about the located object. Table 1 shows an example of one of the five tasks in each scenario. The experimenter asked the questions orally and also measured and wrote down the time taken on each task. Subjects were not required to write down any answer but they had to state them aloud so the experimenter could verify it. As soon as the experimenter said the word "START" at the end of each question, it meant the time measurement had started. Afterwards, if the subject stated aloud the right answer, the experimenter would say "STOP" as well as stopping the stopwatch. If the participant did not provide the right answer, the experimenter would say "NOT CORRECT" and the subject had to keep looking until finding the right answer. At the end of each condition, the experimenter would add up all the times for the five tasks to get the total time required for performing each scenario. This total time was used for the purpose of statistical analysis.

By touching the augmented red icon tagged to each object, a table of information about that object would pop up (Fig. 11). This table was the source from which the subjects could get the information to answer experimenter's questions. The list developed using the Gheisari and Irizarry [7] research on SA-based data requirements for FMs and consisted of information such as product manufacturer, support person in charge, installation date, anticipated life of the product, warranty expiration date, average replacement cost, and last inspection date. This information had been provided almost for all the objects in the lab but the questions in the scenarios were only about the ones that were illustrated in the schematic plan of CONECTech Lab (Fig. 12): (1) two TVs, (2) four desktop Apple® iMacs®, (3) two PCs (Case + Monitor), (4) two wardrobes, and (5) two printers.

Before starting the experiment, the tablet had to be calibrated for the test location. To indicate that the tablet device was at a GeoSpot location, the researcher first placed the tablet device on a calibration marker (Fig. 13). After placement, the researcher was prompted to enter several parameters to override sensor localization and select one of the three conditions of the experiment.

The experiment lasted approximately thirty minutes per participant. After performing the tasks under any specific condition, participants were asked to fill out a usability questionnaire to get their feedback and comments on each condition. A statistical analysis was performed on the outcome of the experiment as well as the questionnaires. The purpose of this experiment was to see whether there are statistically significant differences between these three conditions considering time and qualitative dependent variables.

Table 1
An example of one of the five tasks in each scenario.

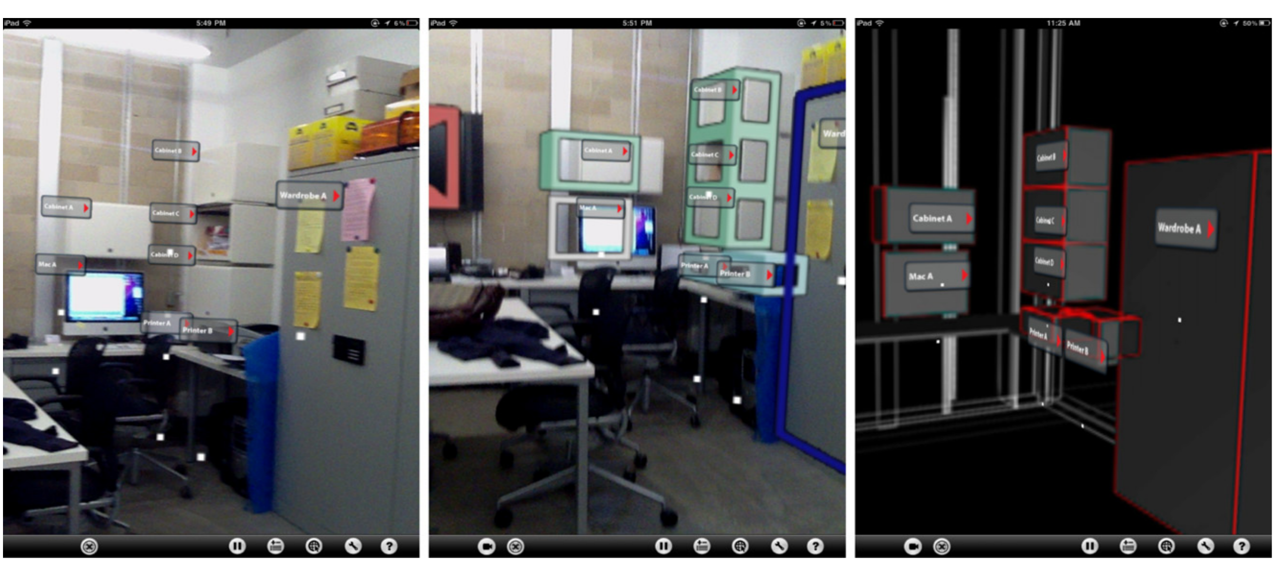
Question	Answer	Time
Locate the printer with the following support person in charge: Reza Chen	B	–:–.–
What is the last Inspection date for Printer B?	10/08/10	–:–.–

7.2. Participants

Thirty participants (21 male and 9 female) took part in the experiment. All participants reported normal or corrected to normal vision. The majority of subjects (20) had heard about AR and only 9 had previously used any AR-based tool, device, or application. Argon, Yelp, Layar, and Junaio were the AR-based systems previously used by those subjects. Table 2 provides an overview of the collected demographic information.

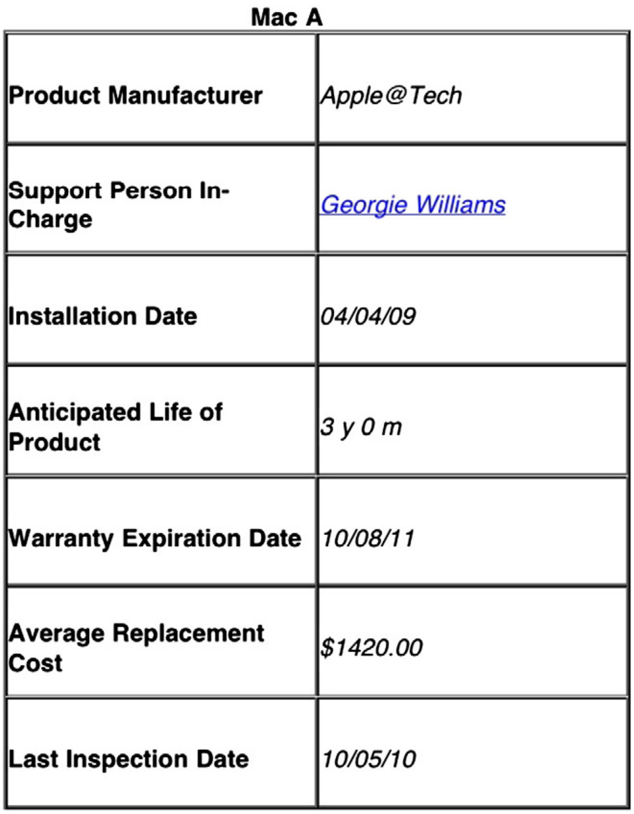
7.3. Statistical analysis results

Analysis of the data collected includes reporting descriptive statistics as well as performing a one-way repeated measure ANOVA. Some parts of the IBM Post-Study System Usability Questionnaire (PSSUQ) [49] were combined with other qualitative variables to develop a new After-Scenario Questionnaire (ASQ) for this experiment. The new questionnaire consisted of 18 questions while questions 1 to 12 were extracted from PSSUQ and questions 13 to 18 were based on some qualitative issues that were of interest to the research group. As same as the PSSUQ methodology [49], the new ASQ requires combining different items in it to make three new overall items; Overall Usability (average of questions 1 to 12), System Usability (average of questions 1 to 8), and Interface Quality (average of questions 9 and 10). The items requested participants to express their level of agreement with the statements presented using the 7-point Likert Scale provided. Table 3 demonstrates the Means, Standard Deviations (SD), and different Likert scales of all the ASQ items based on the subjects' experiment conditions.



a) Augmented Reality I b) Augmented Reality II c) Virtual Model

Fig. 10. Experiment conditions.



Mac A

Product Manufacturer	Apple@Tech
Support Person In-Charge	Georgie Williams
Installation Date	04/04/09
Anticipated Life of Product	3 y 0 m
Warranty Expiration Date	10/08/11
Average Replacement Cost	$1420.00
Last Inspection Date	10/05/10

Fig. 11. An example of augmented table of information tagged to one object (Mac A).

Table 4 also demonstrates the means, standard deviations (SD), minimums, and maximums for the dependent variable of time based on subjects' experiment conditions.

Time and all different variables in the ASQ were analyzed using a one-way repeated measures ANOVA with Greenhouse–Geisser correction when necessary, and alpha level of $p = .05$. Planned comparisons were used to compare condition means. Table 5 displays the results of the one-way repeated measures ANOVA. INTERQUAL and Question 14 were statistically significant between different conditions of InfoSPOT experiment.

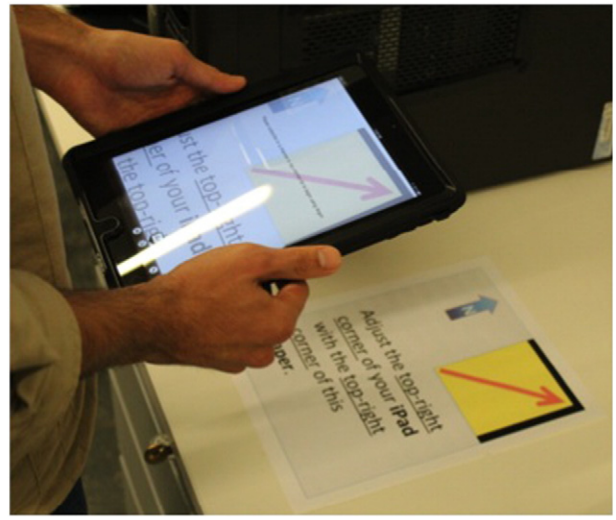


Fig. 13. Calibration process.

8. Discussion

The results show that the general pattern is similar which means items were scored almost identically low or high in each of the three conditions. On average the subjects indicated a positive response to all the questions under three conditions of the InfoSPOT system. Individuals' comments in the ASQ also supported the findings.

In the case of Interface Quality (average of questions 9 and 10 in ASQ), the users liked the interface of InfoSPOT system under all three conditions while comparing those conditions they scaled the interface of ARI (2.07) and ARII (2.30) statistically better than VM (2.81). Having VM as least preferred interface comparing to AR ones was supported by comments such as “not pleasant User Interface [UI]”, “not realistic interface”, and “dark black and red [UI] is not very appealing.” Also considering the question 14, the users agreed that using the InfoSPOT under any condition was not physically demanding and comparing those three conditions they statistically scaled VM (6.13) more physically demanding than ARI (5.80) and ARII (5.77). There were some negative comments on physical problems that were identical for some subjects. For example one user noted his physical problem that “my arms got a little tired by the

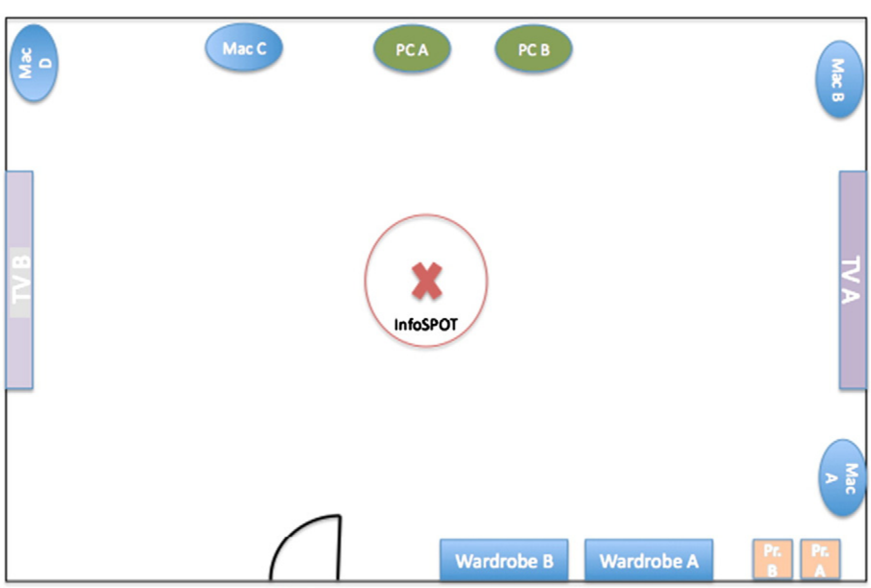


Fig. 12. Schematic plan of CONECTech lab.

Table 2
Demographics of participants.

Variables		Frequency (percentage)
		Total # of subjects = 30
Age	19–25	11 (37%)
	26–30	11 (37%)
	31–40	8 (26%)
Gender	Male	21 (70%)
	Female	9 (30%)
Occupation	Student	27 (90%)
	Other	3 (10%)
Field of study for highest degree	Civil Eng.	8 (27%)
	Architecture	19 (63%)
	Other	3 (10%)
Academic Rank	Undergraduates	5 (17%)
	Master	6 (20%)
	PhD/Faculty	19 (63%)
Previous experience in the AEC + FM Industry?	Yes	18 (60%)
	No	12 (40%)
Previously heard about AR?	Yes	20 (67%)
	No	10 (33%)
Previously used any AR-based tool, device, or application?	Yes	6 (20%)
	No	24 (80%)
Play videogame?	Yes	13 (43%)
	No	17 (57%)

end". Some other subjects indicated the same problems in other words by saying "the tablet" was "heavy," and "too wide" to be able to "hold [it] with one hand and manipulate the screen with the other [one] (safe clicking)" in an "awkward angle."

Considering the total time for performing each scenario, on average it took more than a minute in all three conditions. Participants on average achieved the fastest time in ARI (01:15.51), followed by ARII (01:19.53) and VM (01:22.85) respectively. Participants indicated they somewhat agreed or liked the Overall Usability (average of questions 1 to 12 in ASQ) of InfoSPOT's three scenarios. In this experiment, participants slightly liked the ARI (mean response out of 7, M = 3.03), more than ARII (3.10) and VM (3.14). In the case of System Usability (average of questions 1 to 8 in ASQ), participants were satisfied with easiness, simplicity, affectivity, efficiency, and comfortability of InfoSPOT under the three conditions. ARI and ARII both with 1.77, as their mean response, satisfied the subjects slightly more than VM (1.82). The users indicated their general positive interest on the InfoSPOT system using comments such as "I had a short, very short learning curve" or "very intuitive, everything was well labeled." But comparing the three conditions, they had very different perspectives. For example, one individual noted, "I preferred the ARI setting" while on the other hand, one commented, "ARI is a little bit harder than the ARII." Some users preferred AR systems to VM; "[VM] was easy, but AR was making it easier," "[VM was] not as quick as the ones with the AR," or "[VM was] slightly more difficult than the [AR] in my opinion". Some others preferred the VM and supported their scaling by stating, "[VM] was simple and clear enough to perform well," or "[VM] is easier to locate objects." Interestingly one subject mentioned the intended purpose of having the augmented outline of each object in the ARII as a facilitator by stating, "[I] liked ARII the best! The outline for each product highlighted what exactly I was looking at." Also another user touched on the intended purpose of having VM as a non-location-based alternative by stating, "[In VM], it seems like you wouldn't have to be in the space and still accomplish the tasks."

Considering the questions 13, the scores indicated that the subjects did not believe that using InfoSPOT was mentally demanding under the three scenarios. In the case of question 15, although some subjects indicated that they "felt rushed because [they] were being timed" or "the START and GO [words for timing] put a bit of pressure [on them]" but the scores shows that participants believed that the pace of the task almost was not rushed while using InfoSPOT under three conditions. In the case of being successful in performing the required tasks (question 16) subjects on average believed that they were successful in accomplishing what they were asked to do and comparing the three conditions, they scaled augmented reality models (ARI (1.93), and ARII (1.90)) somewhat better than VM (1.77). Also they indicated that they didn't need to work hard to accomplish their level of performance (question 17). Moreover they were not insecure, discouraged, irritated, stressed, or annoyed with the tasks while using InfoSPOT (question 18). Interestingly under all these three qualitative statements, ARII was scaled somewhat better than ARI and VM.

Although the InfoSPOT system was scaled almost well under all three conditions it seems that "these three scenarios all [had] the drift problem". One subject stated, "[user interface] would be off its coordinates if I move too fast" and another one noted, "it seems that [all conditions] are susceptible to drift [problem]". Also another user declared that there is "less drift problem in VM". The subjects also provided different recommendations such as embedding "voice function" in the system, "having search feature to filter out unnecessary objects", "having an arrow that shows the amount of rotation we need to reach the object", and testing the InfoSPOT under "different light conditions" or for "different viewing angles".

9. Conclusion

InfoSPOT as a human-computer application was developed to facilitate the decision making process of FMs. This low-cost AR-based tool reduces data overload inefficiencies in facilities by adding interactive data to their real-world view. Using the KHARMA architecture, the InfoSPOT prototype was developed. The augmentations were

Table 3
Descriptive statistics for the after-scenario questionnaire.

Question #	Variables	Likert scale	Experiment conditions		
			Augmented reality I	Augmented reality II	Virtual model
			Mean (SD)	Mean (SD)	Mean (SD)
1 to 12	Overall (overall usability)	1 = Strongly Agree to 7 = Strongly Disagree	3.03 (.68)	3.10 (.78)	3.14 (.55)
1 to 8	SYSUSE (system usability)	1 = Strongly Agree to 7 = Strongly Disagree	1.77 (1.04)	1.77 (1.22)	1.82 (.86)
9 and 10[a]	INTERQUAL (interface quality)	1 = Strongly Agree to 7 = Strongly Disagree	2.07 (1.27)	2.30 (1.55)	2.81 (1.58)
13	How mentally demanding was the task?	1 = Very Demanding to 7 = Not Demanding	6.10 (1.18)	6.07 (1.38)	5.97 (1.40)
14[b]	How physically demanding was the task?	1 = Very Demanding to 7 = Not Demanding	5.80 (1.73)	5.77 (1.70)	6.13 (1.48)
15	How hurried or rushed was the pace of the task?	1 = Very Rushed to 7 = Not Rushed	5.53 (1.70)	5.67 (1.60)	5.50 (1.70)
16	How successful were you in accomplishing what you were asked to do?	1 = Very Successful to 7 = Very Unsuccessful	1.93 (1.28)	1.90 (1.63)	1.77 (1.01)
17	How hard did you have to work to accomplish your level of performance?	1 = Very Hard to 7 = Not Hard	6.17 (1.34)	6.33 (.84)	6.17 (1.05)
18	I was insecure, discourage, irritated, stressed and annoyed with the task.	1 = Strongly Agree to 7 = Strongly Disagree	6.40 (1.22)	6.60 (.77)	6.40 (.93)

[a] Indicates marginally significant differences.
[b] Indicates statistically significant differences.

Table 4
Descriptive statistics for the dependent variable of time.

Quantitative variable		Experiment conditions		
		Augmented reality I	Augmented reality II	Virtual model
Time (mm:ss.ss)	Mean	01:15.51	01:19.53	01:22.85
	Standard deviation	00:19.88	00:27.66	00:20.39
	Minimum	00:33.90	00:39.30	00:44.80
	Maximum	01:53.10	02:36.60	02:08.00

Table 5
One-way repeated measures ANOVA results.

Variables	Mauchly's test Sig.	F	Sig.	Variables	Mauchly's test Sig.	F	Sig.
Time	.42	1.50	.23	Question#14	.15	3.13	.05
OVERALL	$p<.01$*	.33	.64	Question#15	.02*	.36	.65
SYSUSE	$p<.01$*	.04	.89	Question#16	.05*	.18	.84
INTERQUAL	.03*	2.78	.08	Question#17	.03*	.41	.62
Question#13	.03*	4.25	.66	Question#18	$p<.01$*	.65	.47

* Mauchly's test statistic is significant ($p<.05$) so the condition of Sphericity has been violated. In this case, degrees of freedom for the reported F values have been corrected using Greenhouse-Geisser method.

developed in the InfoSPOT application through KML, XML, HTML, JavaScript, and AJAX codes. Also Argon browser was utilized for viewing inside the augmented reality space. One of the main development challenges was related to the accuracy and relevant data in the BIM model. Without an accurate BIM model, augmentations like those found in ARI and ARII that are dependent on surveyed locations are difficult to align to their real world counterparts. After the development process, InfoSPOT was tested by real subjects through a totally within-subject experiment under three different conditions; (1) Augmented Reality I, (2) Augmented Reality II, and (3) Virtual Model. The outcome of the statistical analysis revealed that on average the subjects indicated a positive response to all the questions under the three said conditions. On average the results for overall usability, system usability and interface quality were positive. Furthermore, InfoSPOT almost was not physically or mentally demanding but there were some comments on facing physical problems while using the iPad® tablet as an interaction tool. Also the subjects indicated that they were not supposed to really work hard to successfully accomplish the required level of performance, and they didn't feel rushed, hurried, irritated, stressed and annoyed while using the InfoSPOT. Performing this experiment did provide us with valuable feedback and revealed real problems that should be considered in future stages of this research. The drift problem, choosing an appropriate interaction tool, and developing a user-friendly interface should be considered as major issues of developing a sophisticated AR-based facility management assistant tool. InfoSPOT serves as the first mobile AR solution for facility managers. It also helps support that a "magic" lens approach to AR could be suitable for FMs needs and database querying tasks.

The InfoSPOT prototype, as a low-cost solution that leverage current AR technology, would show that it is possible to take an idealized BIM model and integrate its data and 3D information in an MAR environment. This inexpensive solution will help facility managers with their routine tasks because their live view of a space could now be supplemented by needed information, all in one interface while there will be no need for distracting domain switching. The integrated solution in the testing bed of Facility Management would be considered as the adoption of BIM together with MAR in the Facility Management domain. Moreover, the user participation experiment using the InfoSPOT system helped to quantify the effect of natural user interfaces on information access in an AR environment through usability evaluation; and identify barriers to information access in such an environment. The overall methodology of this research is an innovative and Human-Computer-Interaction-based approach in the Facility Management domain. This will be a paradigm shift for researchers and practitioners in the Facility Management domain from a technology-centered approach to a user-centered one that considers user requirements when adopting new technologies in this domain. This research is extremely helpful for the AECO industry that thrives on efficiency and efficacy to provide quality services at a low cost because it shows that AR solutions can be easy to calibrate/setup and costly/timely hardware installations are not necessary for a successful AR application.

References

[1] M.R. Endsley, B. Bolte, D.G. Jones, in: Designing for Situation Awareness: An Approach to Human-Centered Design, 1 edition, CRC Press, 2003, p. 344.
[2] E.C. Adam, Fighter cockpits of the future, in: Digital Avionics Systems Conference, 1993. 12th DASC., AIAA/IEEE, 1993.
[3] M.R. Endsley, Design and Evaluation for Situation Awareness Enhancement, Human Factors and Ergonomics Society, 1988.
[4] M.R. Endsley, Toward a theory of situation awareness in dynamic systems, Human Factors: The Journal of the Human Factors and Ergonomics Society 37 (1) (1995) 32–64.
[5] M.R. Endsley, Theoretical underpinnings of situation awareness: a critical review, in: Situation Awareness analysis and Measurement, 2000, pp. 3–32.
[6] M.R. Endsley, D.J. Garland, Situation Awareness: Analysis and Measurement, CRC, 2000.
[7] J. Son, Z. Aziz, F. Pena-Mora, Supporting disaster response and recovery through improved situation awareness, Structural Survey 26 (5) (2008) 411–425.
[8] M. Gheisari, J. Irizarry, Investigating facility managers' decision making process through a situation awareness approach, International Journal of Facility Management 2 (1) (2011).
[9] IFMA, Website of the International Facility Management Association (IFMA). [cited 2009 June 2009]; Definition of facility management]. Available from: www.ifma.org, 2009.
[10] R.T. Azuma, A survey of augmented reality, Presence-Teleoperators and Virtual Environments 6 (4) (1997) 355–385.
[11] D.H. Shin, P.S. Dunston, Identification of application areas for augmented reality in industrial construction based on technology suitability, Automation in Construction 17 (7) (2008) 882–894.
[12] A.H. Behzadan, ARVISCOPE: Georeferenced Visualization of Dynamic Construction Processes in Three-Dimensional Outdoor Augmented Reality, ProQuest, 2008.
[13] A.H. Behzadan, V.R. Kamat, Visualization of Construction Graphics in Outdoor Augmented Reality, Winter Simulation Conference, 2005.
[14] A.H. Behzadan, V.R. Kamat, Georeferenced registration of construction graphics in mobile outdoor augmented reality, Journal of Computing in Civil Engineering 21 (2007) 247.
[15] P. Dunston, et al., Mixed reality benefits for design perception, in: NIST Special Publication SP, 2003, pp. 191–196.
[16] X. Wang, P.S. Dunston, Compatibility issues in augmented reality systems for AEC: an experimental prototype study, Automation in Construction 15 (3) (2006) 314–326.
[17] M. Golparvar-Fard, F. Pena-Mora, S. Savarese, Application of D4AR,ÄìA 4-Dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication, ITcon, 2009.
[18] A. Henrysson, M. Ollila, UMAR: Ubiquitous Mobile Augmented Reality, ACM, 2004.
[19] S. Feiner, et al., A touring machine: prototyping 3D mobile augmented reality systems for exploring the urban environment, Personal and Ubiquitous Computing 1 (4) (1997) 208–217.
[20] D. Wagner, D. Schmalstieg, First steps towards handheld augmented reality, in: Wearable Computers, 2003. Proceedings. Seventh IEEE International Symposium on, 2003.
[21] H. Kato, M. Billinghurst, Marker tracking and HMD calibration for a video-based augmented reality conferencing system, in: Augmented Reality, 1999. (IWAR '99) Proceedings. 2nd IEEE and ACM International Workshop on, 1999.
[22] A. Henrysson, M. Billinghurst, M. Ollila, Face to face collaborative AR on mobile phones, in: Mixed and Augmented Reality, 2005. Proceedings. Fourth IEEE and ACM International Symposium on, 2005.
[23] eMarketer, One in Three Online Consumers to Use a Tablet by 2014. [cited 2011 December 2011]; Available from: http://www.emarketer.com/Article.aspx?R=1008701, 2011.
[24] A. Hill, et al., KHARMA: an open KML/HTML architecture for mobile augmented reality applications, in: Mixed and Augmented Reality (ISMAR), 2010 9th IEEE International Symposium on, 2010.
[25] M. Bajura, U. Neumann, Dynamic registration correction in video-based augmented reality systems, IEEE Computer Graphics and Applications 15 (5) (1995) 52–60.

[26] Z. Feng, H.B.L. Duh, M. Billinghurst, Trends in augmented reality tracking, interaction and display: a review of ten years of ISMAR, in: Mixed and Augmented Reality, 2008. ISMAR 2008. 7th IEEE/ACM International Symposium on, 2008.
[27] P. Bahl, V.N. Padmanabhan, RADAR: an in-building RF-based user location and tracking system, in: INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE, 2000.
[28] S. Woo, et al., Application of WiFi-based indoor positioning system for labor tracking at construction sites: a case study in Guangzhou MTR, Automation in Construction 20 (1) (2011) 3–13.
[29] A. LaMarca, et al., Place lab: device positioning using radio beacons in the wild pervasive computing, in: H. Gellersen, R. Want, A. Schmidt (Eds.), Springer, Berlin / Heidelberg, 2005, pp. 301–306.
[30] M. Popa, et al., Combining cricket system and inertial navigation for indoor human tracking, in: Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE, 2008.
[31] L.M. Ni, et al., LANDMARC: indoor location sensing using active RFID, Wireless Networks 10 (6) (2004) 701–710.
[32] C. Fuchs, et al., Indoor tracking for mission critical scenarios: A survey, Pervasive and Mobile Computing 7 (1) (2011) 1–15.
[33] G. Deak, K. Curran, J. Condell, A survey of active and passive indoor localisation systems, Computer Communications, 2000.
[34] L. Hui, et al., Survey of wireless indoor positioning techniques and systems, IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews 37 (6) (2007) 1067–1080.
[35] N.B. Priyantha, A. Chakraborty, H. Balakrishnan, The Cricket location-support system, in: Proceedings of the 6th annual international conference on Mobile computing and networking, ACM, Boston, Massachusetts, United States, 2000, pp. 32–43.
[36] J.P. Rolland, L.D., Y.B., A survey of tracking technology for virtual environments, in: Fundamentals of Wearable Computers and Augmented Reality (1), 2001, pp. 67–112.
[37] H.M. Khoury, V.R. Kamat, Evaluation of position tracking technologies for user localization in indoor construction environments, Automation in Construction 18 (4) (2009) 444–457.
[38] R. Want, et al., The active badge location system, ACM Transactions on Information Systems 10 (1) (1992) 91–102.
[39] J. Hightower, R.W., G. Borriello, SpotON: An Indoor 3D Location Sensing Technology Based on RF Signal Strength, in: UW CSE Technical Report #2000-02-02, University of Washington, Department of Computer Science and Engineering: Seattle, WA, 2000.
[40] S. Gezici, et al., Localization via ultra-wideband radios: a look at positioning aspects for future sensor networks, IEEE Signal Processing Magazine 22 (4) (2005) 70–84.
[41] A.I. Comport, et al., Real-time markerless tracking for augmented reality: the virtual visual servoing framework, IEEE Transactions on Visualization and Computer Graphics 12 (4) (2006) 615–628.
[42] M. Pressigout, E. Marchand, Hybrid tracking algorithms for planar and non-planar structures subject to illumination changes, in: Proceedings of the 5th IEEE and ACM International Symposium on Mixed and Augmented Reality, IEEE Computer Society, 2006, pp. 52–55.
[43] U. Neumann, S. You, Natural feature tracking for augmented reality, IEEE Transactions on Multimedia 1 (1) (1999) 53–64.
[44] L. Vacchetti, V. Lepetit, P. Fua, Combining edge and texture information for real-time accurate 3D camera tracking, in: Mixed and Augmented Reality, 2004. ISMAR 2004. Third IEEE and ACM International Symposium on, 2004.
[45] G. Reitmayr, T.W. Drummond, Going out: robust model-based tracking for outdoor augmented reality, in: Mixed and Augmented Reality, 2006. ISMAR 2006. IEEE/ACM International Symposium on, 2006.
[46] M.S. Bargh, R.d. Groote, Indoor localization based on response rate of bluetooth inquiries, in: Proceedings of the first ACM international workshop on Mobile entity localization and tracking in GPS-less environments, ACM, San Francisco, California, USA, 2008, pp. 49–54.
[47] J. Wither, Y.-T. Tsai, R. Azuma, Indirect augmented reality, Computers and Graphics 35 (4) (2011) 810–822.
[48] K. McHenry, P. Bajcsy, An Overview of 3D Data Content, File Formats and Viewers, 2008.
[49] J.R. Lewis, IBM computer usability satisfaction questionnaires: psychometric evaluation and instructions for use, International Journal of Human Computer Interaction 7 (1) (1995) 57–78.