Viewing Asset Information: Future Impact of Augmented Reality

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Abstract
Augmented reality shows digital information overlaid on a real-world view. As Building Information Modelling (BIM) makes increasingly large data-sets available to owners and operators, augmented reality can allow these data to be understood in context, providing both an intuitive interface and a means to compare and contrast digital sources with built infrastructure. This paper reviews augmented reality applications for infrastructure operations and maintenance, identifying potential needs and uses as a visual interface for asset information. It addresses the questions: What are the potential needs and uses of augmented reality in operations and maintenance? What are the likely impacts? What are the anticipated trajectories of technology development and practice over the next five years? It also identifies relationships with underpinning and related technologies, including Building Information Modelling (BIM), sensors and robotics, data capture and wearable computing; and potential longer term impacts from technology developments.

Keywords: augmented reality, asset information, visual interfaces

1 Introduction

More information is becoming available to owners and operators. New techniques for visualizing and using this information in decision-making are needed to meet aspirations for the built environment, such as the UK government targets for 50% lower emissions (BIS 2013). Building information modelling (BIM) and asset management are thus described as having a "mutually supportive relationship" (Pocock, Shetty et al. 2014). Collating and structuring information raises significant opportunities to monitor better and improve performance. This is recognized, with the UK government, for example, requiring project teams to deliver asset information through building information modelling (BIS/Industry Working Group 2011); promoting increasing use of BIM throughout a facility's lifetime and seeking to aggregate and combine its own data-sets, connecting them with Smart City and Digital Built Britain initiatives[1].

Moore's Law has correctly predicted an exponential rather than linear growth in computing power over the last 50 years. Yet we have also known for some time that having more information within the computer may not improve decision-making (Ackoff 1967). For example, Weick argues that, at the computer, people: *"act less, compare less, socialize less, pause less, and consolidate less when they work at terminals than when they are away from them. As a result, the incidence of senselessness increases when they work with computer representations of events"* (Weick, 1985, p. 56). As society becomes increasingly connected, with a growing use of mobile and wearable devices, there are rapid advances in techniques for mixing and merging real and virtual representations of built environment facilities within their natural environments. Overlaying data onto the built environment to which it relates may provide a better chance of these data being understood in context, providing both an intuitive interface and a means to compare and contrast digital sources

[1] see www.digital-built-britain.com.

with built infrastructure. The purchase by Apple of the augmented reality company Metaio in May 2015, experiments such as "Google glass", and the many consumer applications already available on smart phones[2] are suggestive of a world in which digitally enhanced vision is becoming the norm.

This paper reviews augmented reality applications for infrastructure operations and maintenance, identifying potential needs and uses as a visual interface for asset information. It is based on a desk-top review for a major rail infrastructure capital project "Crossrail" in the UK, and draws on our involvement in the working groups that developed the scope for BIM level 3 (DBB 2015) (which were led by the second author) and have a particular focus on use of BIM data in the operation of infrastructure. This work was motivated by considerations within this major rail infrastructure capital project of how the as-built info should best be configured and presented to allow (at least some) futureproofing for future use in railway operations. It was concerned with a combination of the current/developing commercial offerings and with current research which could lead to new, future commercial offerings. This is important as the commercial world is changing, for example through the UK government 'level 2' BIM mandate and 'level 3' strategy document) and new commercial requirements are developing which need new products/services, for which there is currently no appropriate or effective research-develop-manufacture-sell pipeline.

This paper hence contributes to a growing research literature that has begun to review applications and propose directions for research (e.g. Behzadan, Dong et al. 2015). As discussed above, augmented reality shows digital information overlaid on *"a predominantly real-world view"* (Wang, Kim et al. 2013). For example, a smart phone or tablet device with a camera may overlay information about built assets onto a mediated view of the physical world. The contribution here is to address specific questions: What are the potential needs and uses of augmented reality in operations and maintenance? What are the likely impacts? What are the expected trajectories in technology development and application over the next five years? In this paper we briefly describe what is meant by asset information in section 2, summarise the existing work in section 3, then outline the needs and uses for visual interfaces in operations and maintenance in section 4, using an example of a major UK infrastructure project. Potential impacts are discussed in section 5, and the trajectory from current practice in section 6. In the final section of the paper we provide some concluding remarks.

2 The need for visual interfaces to asset information

An asset may be a sub-system, assembly, sub-assembly, or component, but it is the smallest unit of an infrastructure facility maintained by an owner. Asset information is, therefore, information about an asset. This information may include the provenance, part types and serial numbers, design life, maintenance schedule, obsolescence risk and design rationale (Whyte, Stasis et al. 2015). This definition of asset as the smallest unit maintained by an owner, in common use by owners and operators, differs from the use in financing, management consulting and investment where infrastructure assets are discussed at a macro level.

Owners and operators have traditionally relied more on asset schedules, which are lists of assets, rather than drawings or models. The databases currently used for operation and maintenance have a limited visual interface, though this is changing with a number of major owner-operators using map information in Geographic Information Systems (GIS) as a graphic interface through which to access drawing, model and asset information. Case study evidence suggests a partial stepwise integration of systems (Korpela, Miettinen et al. 2015). Love, Matthews et al. (2015) argue that it is the financial investment and risks of interoperability with existing building management systems that have led to a lack of implementation of BIM by asset owners.

Questions remain about how to provide information to decision-makers in operations and maintenance in a way that supports their decision-making. Researchers have found that fast decision-makers use more, rather than less information (Eisenhardt 1989), suggesting that the ability to make information available and browsable should suit the working methods of experienced professionals and enable them to make good decisions rapidly within the working environment.

[2] for example augmented reality animations are on children's drink packaging; in the 2014 IKEA Catalogue App; and the HP Live Photo application allows you to view video by holding your phone over the photo.

3 Existing research on visual interfaces

There is a significant tradition of research on construction applications for augmented reality (Feiner, Webster et al. 1995), within which recent research has developed prototypes to investigate BIM and augmented reality (Kuula, Piira et al. 2012); GIS and augmented reality (e.g. Jang and Hudson-Smith 2012); the creation of point cloud models from site photographs to register digital information over the real-world scene (Bae, Golparvar-Fard et al. 2013); and visualizing energy performance (Bae, Golparvar-Fard et al. 2013). Such work extends a long interest in visualization within the literature (e.g. Bouchlaghem, Shang et al. 2005), within which there is prior research on using virtual or augmented reality in the built environment, or indeed in operations and maintenance (e.g. Whyte 2002), and a broader range of current work, including developments in immersive visualization (e.g. Hayden, Ames et al. 2014; Parfitt and Whyte 2014).

Recent work has also conducted trials. Augmenting the natural view *"with text, labels, arrows, and animated sequences"*, Henderson and Feiner (2010) tested the ability of professional mechanics on 18 tasks, including installing and removing fasteners, indicator lights and connecting cables. Augmented reality was found to provide better satisfaction and performance than two baseline conditions, untracked text and graphics in the display and a fixed flat panel display with an improved version of current documentation. Augmented reality has also, if less systematically, been used within a university campus, to reduce the time required to collate and understand facility information (Koch, Neges et al. 2014)

The volume and variety of data in use in the delivery of the built environment, as well as recent developments in computing, have also brought about a recent and growing literature reviewing augmented reality applications and proposing directions for research (e.g. Behzadan, Dong et al. 2015). While this paper does not provide a detailed technical review, we note that current solutions providing such a visual interface to asset information research on underpinning computer vision technologies and software libraries, and broader developments in tracking, information management, mobile and display technologies.

3.1 Computer vision technologies and software libraries

There has been rapid development in the underpinning computer vision technologies and software libraries available for use in the development of augmented reality applications. As digital information must have the same alignment, perspective and illumination as the real world view, researchers have developed techniques to calibrate these (Tuceryan, Greer et al. 1995), addressing related field of view, image resolution, luminance, contrast, depth resolution, vertical alignment, accommodation, shadowing and viewpoint dependence issues (Drascic et al., 1996) as well as human factors (Huang, Alem et al. 2013). While early work used black and white markers, techniques are now being developed to recognize objects in the scene (Huang, Hui et al. 2013).

Software libraries for the development of augmented reality applications have been made available for both research and commercial applications. The most used of these came out of research at the HITLab in Washington, USA in the late 1990s/ early 2000s (Billinghurst, Kato et al. 2001). VTT in Finland used and developed this, making its library (Harviainen, Korkalo et al. 2009)[3].

3.2 Tracking, information management, mobile and display technologies

Work on augmented reality has benefited from wider IT developments, including mobile hardware, data capture technologies (laser scanning, image recognition and heat mapping), ground positioning system (GPS), radio frequency identification (RFID) tags, wireless and sensor networks; and related technologies such as wearable computing, 3D/4D modelling, gesture devices, machine vision learning algorithms, big data, cloud computing and the Internet of Things. MIT's recent work on 'smart objects' (Heun, Kasahara et al. 2013) extends such interests in ubiquitous computing.

Tracking has always been a particular issue in augmented reality, and continues to be a topic of ongoing work in the underpinning areas of computer science, though research attention is

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[3] ARToolkit (http://artoolkit.sourceforge.net/); ALVAR (http://virtual.vtt.fi/virtual/proj2/multimedia/alvar/) available. Today, there are more than seventy software development kits (sdks), across mobile and laptop platforms (http://socialcompare.com/en/comparison/augmented-reality-sdks) with available construction-related apps including ARGON (http://argon.gatech.edu/); Smart reality (http://smartreality.co/) and MARS (http://www.parworks.com/mars-aec/).

increasingly shifting from registration of the user into the screen to more advanced topics such as the matching of virtual shadows onto real world objects (Kolivand, Kolivand et al. 2015); and the provision of both day and night situational awareness (Gans, Roberts et al. 2015). In different applications users can tolerate different levels of (in)accuracy and latency in the tracking.

4 Needs and Uses of Asset Information in Operation and Maintenance

In the operation of major infrastructure, operators and maintainers need access to appropriate asset information in a timely manner, so that they can make effective decisions. As part of a smart infrastructure, visual interfaces can focus attention on relevant information for asset management, maintenance, auditing, and operations, and mobile augmented reality techniques can filter and make context-relevant information available to the operative at their place of work. It can also give managers a rapid overview of a site during a walk around, or help emergency services and rapid response teams to make time-critical decisions.

4.1 Uses as a visual interface to asset information during delivery

Contractors have recognized the benefits of augmented reality as a visual interface to asset information on site during their construction work, with applications in the international research literature including construction defect management (Parka, Lee et al. 2013), piping assembly (Hou 2013), uncertainty aware excavating (Xing Su, Sanat Talmaki et al. 2013), bridge information systems (Bae, Lee et al. 2013), dynamic visualization using GPS (Behzadan 2008; Moore 2013), energy performance augmented reality (Bae, Golparvar-Fard et al. 2013; Ham and Golparvar-Fard 2013) and related work on drawing augmentation (Fiorentino, Monno et al. 2009) and augmented teleoperation (Livatino, Banno et al. 2012).

This work suggests 1) a need for augmented reality in infrastructure operations to be simple to use, and integrated into personal and protective equipment (PPE), enabling operatives to access information and also work with their hands-free, and 2) that for such complex or data-rich applications, real-time querying of and connectivity with a data server becomes important. Examples of commercial uses of augmented reality include work on the M1 Junction 12 (Fiatech 2013) and London Bridge (Building 2013), both in the UK, and Bentley's research on panorama-based augmented reality (Côté, Trudel et al. 2013).

Two challenges for professional applications of augmented reality in engineering are accurate location of digital information on the real-world view, and interaction with the model server and/or other operational databases (where challenges include security – in terms of reliability of use and also, separately, cyber security – and rapidity of access). Some research involves taking photos on site, which are then augmented in a few seconds, using a process that involves generating 3D models from photographs, to locate related information from server data-bases (Bae, Golparvar-Fard et al. 2013).

4.2 Crossrail as an example

Crossrail is a new high-capacity railway across central London, which extends out from central twin bore tunnels to overground lines to the east and west of the city. Its route spans from Reading and Heathrow Airport in the west to Shenfield and Abbey Wood in the east, a total of 118 kilometres. The project is intended to deliver a 10% increase in the rail capacity of London, a city in which the majority of commuters already travel by rail. Operational in 2018, the new railway is forecast to carry 20 million passengers a year. It will have 24 trains an hour through the central section. Delivery costs £13bn.

On the Crossrail delivery project there are pilots of 4D augmented reality on Bond Street station (Fiatech 2013; Johnson 2013). As the project is handed over to operators, the asset tags being located within assets in Crossrail can be expected to become used as part of the positioning system for augmented reality in the operational phase. Within the delivery phase, closely related work includes the broader trials of mobile technologies on Crossrail; including Formotus Based Observation Reports and Field Supervisor (Pawsey, O'Keefe et al. 2013); work on configuration management, including the Asset Painter (Dentten 2013), the pilot of the Mission Room at Paddington Station. As GPS is not sufficiently accurate (and sometimes not available), to locate positions on sites there is a use of matching of the view with 'point cloud data'. This is being used alongside markers and inertial sensors. There are trials using Bluetooth low energy with positional mobile device management software that may benefit augmented reality (Pawsey, O'Keefe et al. 2013).

5 What are the Impacts in Operation and Maintenance?

The potential impacts of visual interfaces on asset information include the reduction of the time wasted by operatives walking back to the office, reduction in maintenance hours, and better ability to make effective, safe and sustainable decisions about installed assets. It is expected that these potential uses and impacts of using context-sensitive data in the operation phase will bring benefits at the point of use of the operative or maintainer and help owners to meet government performance targets. Potential areas of impact, derived from our discussions of augmented reality with industry participants, are:

- Smarter real-time inspection imaging;
- Locating and accessing relevant information from maintenance and operation manuals at site;
- Accessing up-to-date information on track geometry and tunnel geometry;
- Alerts to highlight relevant information from safety manuals;
- Energy performance analysis and wildlife management;
- Accessing data on modelled, historical and real-time passenger flow;
- Ensuring sufficient access for safe and effective maintenance, refurbishment and replacement activities, in relation to people and tools/equipment/parts;
- Training for difficult, hazardous or time-critical operations; and
- Remote operation using augmented video feed from robotic operators.

An augmented reality interface may also be used to make detailed engineering information available to managers and policy makers viewing a physical model in corporate offices, for example when considering strategies and budgets or discussing issues with wider stakeholder groups.

6 Trajectory from current practice

There is currently rapid prototyping of augmented reality in construction, and developments in underpinning research and related technologies, which suggest radical changes in the potential applications in the next 5 years. These include:

1) **An unmediated real-world view** – augmented reality will no longer require a video-stream of data from the real-world onto which the digital information is overlaid. Operatives' safety glasses may come with embedded interfaces to enable the real-world view to be directly augmented with digital information, which can then be accessed through a gesture-based interface. Or digital information may be projected directly onto surfaces in the real world[4]. Projective augmented reality could be used to view models and simulations from drawings. Military research has also developed contact lenses that bring distant images, and polarised near-field digital images simultaneously into view (http://innovega-inc.com/).
2) **Dynamic and interactive information displays** – At present dynamic data that is shown in augmented reality displays is generated offline, because of the computational resources that would be needed to generate dynamic data in real-time. There is expected to be a growth of bandwidth, with Wireless broadband 4G+ and cloud technology, better latency and more sophisticated tools for querying large engineering data-sets and merging data from different sources to view new simulations and data-sets, including data from smart sensor networks. The operative would be expected to be able to update the server-side data from the field. Such technologies will be combined with improved tracking technologies, through improvements in photogrammetry, heat mapping and ground penetrating radar (Rogers, Hao et al. 2012). Such data need to be critically examined by the operative, and here the types of people that become

[4] While such glasses exist as "Google glass", and vuzix M100 and STAR 1200 (http://www.vuzix.com/augmented-reality/), the associated wearable computing and projected augmented reality continues to be rapidly developed. Metapro glasses (https://www.spaceglasses.com/, see also http://www.youtube.com/watch?v=LuMv29nKo2k) developed by a start-up with augmented reality pioneer Steve Feiner as advisor, and Daqri http://hardware.daqri.com/smarthelmet/features are suggestive of developments in glasses; while a rich display for table-top use is demonstrated by LuminAR (http://fluid.media.mit.edu/sites/default/files/poster-final-small.pdf) and CastAR (http://technicalillusions.com/?page_id=197).

operatives and their skill-sets will affect interpretation of data, but such data could provide a wealth of contextual information that could improve decision-making.

3) **More established augmented reality use in construction and operations** – The current work in delivery is developing protocols for the use of augmented reality in construction, and there is expected to be more sophisticated guidance and training developed on use in the next 5 years, that will allow for safe use of mobile augmented reality in all locations where operatives currently use a pencil. There may be a need to keep things simple. Work on augmented reality should also benefit from data standards being developed through the broader BIM initiative. Knowledge may be developed on the levels of accuracy suitable for different applications in operations and where there is a need to stream larger amounts of data for real-time image positioning and viewing. Monitoring and nuanced work on the impact of technologies is important, noting that research on use of augmented reality in surgery found issues going unnoticed in both augmented reality and not augmented reality supported groups, with the augmented reality group being more accurate, but less likely to identify significant unexpected findings, and a need to compensate for this effect (Dixon, Daly et al. 2013). Over the next 5 years, parts of the construction workforce may also develop a familiarity of augmented reality technologies, gained through gaming, driving or other augmented activities.

There is a well understood shift from PCs to mobile devices that enables augmented reality to be used through a range of wearable or pocket computing devices. According to Jeff Bradley, Senior Vice President at AT&T, speaking in 2012, by 2020 mobile devices will have 28 GHz of processing power, embedded storage of 64 terabytes and a 500 Mbps connection to the mobile data network (http://www.mobilefutureforward.com/). This convergence is well recognized in the computing industry: a major augmented reality conference, Augmented World Expo, now combines discussion of augmented reality, virtual reality, Internet of things and wearable computers.

7 Conclusions

There is the potential for augmented reality techniques and devices to be used as intuitive visual interfaces to asset information in both the delivery and operation of infrastructure. We expect that they will enable users to act more, compare more, socialize more and consolidate more than they do at terminals, hence reducing the senselessness that Weick notes occurs with computer representations. Mobile augmented reality techniques can filter and make context-relevant information available to the operative at their place of work. They can also give managers a rapid overview of a site during a walk around, or help emergency services and rapid response teams to make time-critical decisions. The likely impacts of augmented reality include the reduction of the time wasted by operatives walking back to the office; reduction in maintenance hours; and better ability to make effective, safe and sustainable decisions about installed assets.

There is the potential to learn from other areas that use advanced image-guidance systems, such as surgery, aviation, the military, the civil nuclear sector and digital manufacturing. A challenge for future work is the risk of patents, a possible VHS vs Betamax type situation among providers and the dynamics of commercial competition, inhibiting rather than promoting innovation in this area. Large projects need to be able to mobilise new technologies through an effective research-develop-manufacture-sell pipeline, and as these techniques become used in practice then it would be useful to measure their effects to refine the next generation of construction applications.

Acknowledgements

To be added.

References

Ackoff, R. L. (1967). "Management misinformation systems." *Management Science* **14**(4): B147-156.

Bae, H. J., Golparvar-Fard, M. and White, J. (2013). "High-precision Vision-based Mobile Augmented Reality System for Context-aware Architectural, Engineering, Construction and Facility Management AEC/FM Applications." *Journal of Visualization in Engineering* **1**(3): 1.

Bae, S.-H., Lee, G.-Y. and Lee, H. (2013). Augmented reality bridge information system using smart phone. *Ubiquitous Information Technologies and Applications: CUTE 2012*. Y.-H. Han, D.-S. Park, W. Jia and S.-S. Yeo**:** 621-629

Behzadan, A. H. (2008). ARVISCOPE: Georeferenced Visualization of Dynamic Construction Processes in Three-Dimensional Outdoor Augmented Reality. *Civil Engineering*, University of Michigan. **PhD**.

Behzadan, A. H., Dong, S. and Kamat, V. R. (2015). "Augmented reality visualization: A review of civil infrastructure system applications." *Advanced Engineering Informatics* **29**(2): 252–267.

Billinghurst, M., Kato, H. and Poupyrev, I. (2001). " The MagicBook: A Transitional AR Interface." *Computers and Graphics*: 745-753.

BIS (2013). Construction 2025: industrial strategy for construction - government and industry in partnership. London, Department for Business Innovation and Skills, BIS/13/955.

BIS/Industry Working Group (2011). Building Information Modelling (BIM) Working Party Strategy Paper. London, Government Construction Client Group

Bouchlaghem, D., Shang, H., Whyte, J. and Ganah, A. (2005). "Visualisation in architecture, engineering and construction (AEC)." *Automation in Construction* **14**(3): 287-295.

Building (2013). BIM inititative of the year 2013. *Building Magazine*. http://www.building.co.uk/bim-initiative-of-the-year-2013/5053560.article

Côté, S., Trudel, P., Desbiens, M.-A., Giguère, M. and Snyder, R. (2013). *Live Mobile Panoramic High Accuracy Augmented Reality for Engineering and Construction*. Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, London, UK 30-31 October 2013. http://itc.scix.net/data/works/att/convr-2013-27.pdf

DBB (2015). Level 3 Building Information Modelling - Strategic Plan, UK Government document published via Digital Built Britain and available from www.digital-built-britain.com.

Dentten, R. (2013). *Information Mobility for the Crossrail Smart Railway*. Bentley Year in Infrastructure Conference, London, UK 29-31 October

Dixon, B. J., Daly, M. J., Chan, H., Vescan, A. D., Witterick, I. J. and Irish, J. C. (2013). "Surgeons blinded by enhanced navigation: the effect of augmented reality on attention." *Surgical Endoscopy* **27**(2): 454-461.

Eisenhardt, K. M. (1989). "Making Fast Strategic Decisions in High-Velocity Environments." *Academy of Management Journal* **32**(3): 543-576.

Feiner, S., Webster, A., Krueger, T., MacIntyre, B. and Keller, E. (1995). "Architectural anatomy." *Presence: Teleoperators and Virtual Environments* **4**(3): 318-325.

Fiatech (2013). Advanced Asset Knowledge through the use of Augmented Reality Technologies, Fiatech. https://custom.cvent.com/F0D3FC83AB884EE1BAAC045EEDBF06C1/files/d3c9c30dcb3549759aa63289c3bc1979.pdf

Fiorentino, M., Monno, G. and Uva, A. E. (2009). "Tangible digital master for product lifecycle management in augmented reality." *International Journal on Interactive Design and Manufacturing (IJIDeM)* **3**(2): 121-129.

Gans, E., Roberts, D., Bennett, M., Towles, H., Menozzi, A., Cook, J. and Sherrill, T. (2015). *Augmented reality technology for day/night situational awareness for the dismounted Soldier*. Proc. SPIE 9470, Display Technologies and Applications for Defense, Security, and Avionics IX; and Head- and Helmet-Mounted Displays XX, 947004 May 21, 2015

Ham, Y. and Golparvar-Fard, M. (2013). "EPAR: Energy Performance Augmented Reality models for identification of building energy performance deviations between actual measurements and simulation results." *Energy and Buildings* **63**: 15-28.

Harviainen, T., Korkalo, O. and Woodward, C. (2009). "Camera-based interactions for augmented reality." *ACE '09 Proceedings of the International Conference on Advances in Computer Entertainment Technology* 307-310.

Hayden, S., Ames, D., Turner, D., Keene, T. and Andrus, D. (2014). "Mobile, Low-Cost, and Large-Scale Immersive Data Visualization Environment for Civil engineering Applications." *Journal of Computing in Civil Engineering*.

Henderson, S. and Feiner, S. (2010). "Exploring the Benefits of Augmented Reality Documentation for Maintenance and Repair." *Visualization and Computer Graphics* **17**(10).

Heun, V., Kasahara, S. and Maes, P. (2013). *Smarter objects: using AR technology to program physical objects and their interactions*. CHI '13 Extended Abstracts on Human Factors in Computing Systems 961-966

Hou, L., Wang, X., and Truijens, M. (2013). "Using Augmented Reality to Facilitate Piping Assembly: An Experiment-Based Evaluation." *Journal of Computing in Civil Engineering*.

Huang, W., Alem, L. and Livingston, M., Eds. (2013). *Human Factors in Augmented Reality Environments*, Springer.

Huang, Z., Hui, P., Peylo, C. and Chatzopoulos, D. (2013). Mobile Augmented Reality Survey: A Bottom-up Approach, HKUST Technical Report-20130903-182109-4052 (arXiv:1309.4413).

Jang, S. H. and Hudson-Smith, A. (2012). *Exploring Mobile Augmented Reality Navigation System for Pedestrians*. GISRUK 2012, Edinburgh

Johnson, M. (2013). Bechtel BIM 4D-AR Study: Practical deployment of augmented reality at Bond Street, London, Crossrail Project. London, Bechtel.
Koch, C., Neges, M., Markus Königa and Abramovici, M. (2014). "Natural markers for augmented reality-based indoor navigation and facility maintenance." *Automation in Construction* **48**: 18-30.
Kolivand, H., Kolivand, M. and Sunar, M. S. (2015). "Interactive Virtual Shadows on Real Objects in Augmented Reality." *International Journal of Information Technology & Computer Science (IJITCS)* **19**(2): 74.
Korpela, J., Miettinen, R., Salmikivi, T. and Ihalainen, J. (2015). "The challenges and potentials of utilizing building information modelling in facility management: the case of the Center for Properties and Facilities of the University of Helsinki." *Construction Management and Economics* **33**(1): 3-17.
Kuula, T., Piira, K., Seisto, A., Hakkarainen, M. and Woodward, C. (2012). *User requirements for mobile AR and BIM utilization in building life cycle management.* Proceedings of the 12th International Conference on Construction Applications of Virtual Reality (CONVR2012), Taipei, Taiwan 203-211
Livatino, S., Banno, F. and Muscato, G. (2012). "3-D Integration of Robot Vision and Laser Data With Semiautomatic Calibration in Augmented Reality Stereoscopic Visual Interface." *Industrial Informatics, IEEE* **8**(1): 69 - 77.
Love, P., Matthews, J. and Lockley, S. (2015). "BIM for Built Asset Management." *Built Environment Project and Asset Management* **5**(3).
Moore, N. J. (2013). A contextual AR model based system on-site construction planning, Wolverhampton University. **PhD**.
Parfitt, M. R. and Whyte, J. (2014). *Developing a Mobile Visualization Environment for Construction Applications.* ICCCBE and W78 Construction, Florida, USA, 23-25 June
Parka, C.-S., Lee, D.-Y., Kwon, O.-S. and Wang, X. (2013). "A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template." *Automation in Construction* **33**: 61-71.
Pawsey, N., O'Keefe, T. and Smith, S. (2013). *Making Crossrail Mobile.* COMIT 2013, London Slides 84-102. http://www.comit.org.uk/projects#!conference/cs05
Pocock, D., Shetty, N., Hayes, A. and Watts, J. (2014). "Leveraging the relationship between BIM and asset management." *Infrastructure Asset Management* **1**(1): 5 -7.
Rogers, C. D. F., Hao, T., Costello, S. B., Burrow, M. P. N., Metje, N., Chapman, D. N., Parker, J., Armitage, R. J., Anspach, J. H., Muggleton, J. M., Foo, Y., Wang, P., Pennock, S. R., Atkins, P. R., Swingler, S. G., Cohn, A. G., Goddard, K., Lewin, P. L., Orlando, G., Redfern, M. A., Royal, A. C. D. and Saul, A. J. (2012). "Condition Assessment of the Surface and Buried Infrastructure - A Proposal for Integration." *Tunnelling and Underground Space Technology* **28**(1): 202-211.
Tuceryan, M., Greer, D. S., Whitaker, R. T., Breen, D., Crampton, C., Rose, E. and Ahlers, K. H. (1995). "Calibration Requirements and Procedures for a monitor-based augmented reality system." *IEEE Transactions on Visualization and Computer Graphics* **1**(3): 255-273.
Wang, X., Kim, M. J., Love, P. E. D. and Kang, S.-C. (2013). "Augmented Reality in built environment: Classification and implications for future research." *Automation in Construction* **32**: 1-13.
Whyte, J., Stasis, A. and Lindkvist, C. (2015). "Managing change in complex projects:configuration management; asset information and big data." *International Journal of Project Management* **forthcoming**.
Whyte, J. K. (2002). *Virtual Reality and the Built Environment.* Oxford, Architectural Press.
Xing Su, Sanat Talmaki, Hubo Cai and Kamat, V. R. (2013). "Uncertainty-aware visualization and proximity monitoring in urban excavation: a geospatial augmented reality approach." *Visualization in Engineering* **1**(2).