Architecture in an Age of Augmented Reality:

Opportunities and Obstacles for Mobile AR in Design, Construction, and Post-Completion.

By Rana Abboud
NAWIC International Women's Day Scholarship Recipient 2013

March 2014

Contents

Abstract

This paper explores the Opportunities and Obstacles for Mobile Augmented Reality across the Design, Construction, and Post-Completion phases of architectural practice. It identifies high-level uses for Mobile AR (MAR) across these phases, and explains the challenges currently preventing MAR's uptake by Australian architectural industry. Written primarily as an introduction to Mobile Augmented Reality for practicing architects in Australia, the paper may also interest professionals within the Architecture, Engineering, and Construction (AEC) industries globally, as well as AR developers producing applications for Architectural uses. The paper's appendix includes a **Glossary of Literary Terms**, and brief introduction to the **Components of a Simple Augmented Reality System**.

In **Design,** MAR may augment a real site with proposed virtual models at full scale, and overlay physical presentation media with 4D content. MAR applications may inform the design process by bringing greater contextual awareness during design review, and communicate architectural narrative. In **Construction,** MAR applications may geo-locate BIM data directly on the construction site to aid site set-out. Task support applications may guide users through complex assembly procedures; and MAR applications for real-time field reporting can allow geo-tagging of elements directly on site. Use of MAR may extend to site navigation and way-finding; while in **Post-Completion**, MAR has applications in facilities management and maintenance. State-of-the-art MAR Use Cases ground each **Opportunity** discussed in the paper, drawn from work by AR researchers; AEC industry leaders; academics; software providers; and AR developers worldwide.

The **Obstacles** preventing MAR uptake by architectural industry today encompass technological challenges, human factors, and financial constraints. Technological hurdles range from hardware limitations- such as MAR displays and tracking challenges- to difficulties in the preparation of virtual data. Human factors also hinder MAR's uptake, such as disillusionment with AR following news media hype; user resistance to change; user safety considerations; and privacy factors. Finally, financial constraints play a significant role in slowing the uptake of MAR by architectural professionals in Australia.

Introduction

Augmented Reality's potential for Architecture is huge. *AR* is any system that 'augments', or overlays, the real world with digital information that seems to co-exist with the real world.[1] Over the past few decades, this once theoretical field has matured into a mass medium[2] with applications spanning countless industries. Today, AR has captured the imagination of construction industry professionals and researchers worldwide. As the technology and business case for AR develops, its use in the construction sector will become standard, much like Building Information Modelling (BIM).[3]

This paper focuses on a subset within the AR spectrum known as 'Mobile Augmented Reality' (MAR). Mobile AR applies the concept of AR in truly mobile settings, '*away from the carefully conditioned environments of research laboratories and special-purpose work areas.*[4]*'* With MAR, displays are portable, and range from smartphones, to tablets, to wearable Head-Mounted Displays (HMDs).

Today's MAR applications hint at a future to come: virtual furniture may be overlaid in real time to check its size and appearance in a room;[5] 'see-through' walls on a construction site allow builders to view pipes and mechanical ducting behind,[6] and overlays of past and future buildings render the city a canvas for virtual data. As tech giants race to release wearable interfaces for ever greater augmentation of the physical world,[7] the number of worldwide users consuming AR via portable media devices is expected to exceed 1 billion users by 2020.[8]

The rapid change underpinning AR technology means that those working within the field are continuously adapting their explorations to a shifting infrastructure. The speed of AR's evolution will soon make this paper obsolete, as new <u>Opportunities</u> are uncovered and existing <u>Obstacles</u> resolved. In this context, the paper serves as a snapshot of the emerging uses, prototypes and challenges facing Mobile Augmented Reality (MAR) for Architectural applications in early 2014.

---

1 Refer to the <u>Glossary</u> for the industry standard definition, Azuma, "A Survey of Augmented Reality."
2 Toni Ahonen contends that AR is the 'Eight Mass Medium of our Time'. *Augmented Reality - the 8th Mass Medium*.
3 (Xiangyu Wang, 2009)
4 Höllerer and Feiner, "Mobile Augmented Reality." The <u>Glossary</u> elaborates on the meaning and componentry of Mobile AR. Augmented Reality may also be used within fixed locations (ie: as a communication platform, building on the 'virtual conference room' of today). These custom, fixed location applications are not the topic of this paper.
5 (Butcher, 2010)
6 "Constructech Magazine | Augmented Reality in Construction."
7 Both Google and Apple have wearable interfaces in the works (refer: *You Will Want Google Goggles - MIT Technology Review*; Strange, "Apple Granted Patent for Head-Mounted Computing Device | News & Opinion | PCMag.com.")
8 *Augmented Reality - the 8th Mass Medium*.

Fig 1. *Superimposing virtual IKEA furniture to check its scale in a room*[9]

Fig 2. *Exploring mechanical systems behind existing walls at the Braunhofer Institute*[10]

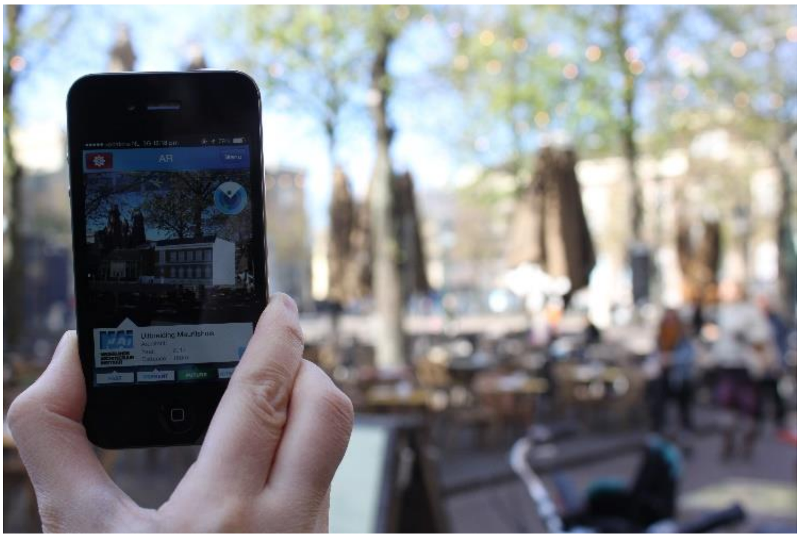

Fig 3. *UAR Underground app, showing past and future buildings in Den Haag*[11]

9 *The New IKEA Catalog App*.
10 *Augmented Reality for Building Technology*.
11 *UAR Underground*.

Research Question

Architects in Australia today are largely unaware of MAR's opportunities for architectural practice, and the prototypes being developed by AR researchers worldwide.[12] This paper makes a small contribution to closing the knowledge gap between Australian architectural industry, and the researchers and AR professionals developing and promoting MAR globally. The paper asks:

What are the Opportunities and Obstacles for Mobile AR in key phases of architectural practice - namely, Design, Construction, and Post-Completion?

The paper is divided into four sections. The first three explore the **Opportunities** for Mobile AR across key Architectural phases, while the fourth considers the **Obstacles** currently preventing MAR's mass uptake by architectural industry.

[12] Defined simply *'as those circumstances that make it possible to do something,'* refer **Glossary.**

Research Methodology

The paper synthesises discourse from the fields of Architecture and Augmented Reality. From a philosophical standpoint, the paper is grounded in phenomenology.[13] All research is qualitative in nature, and the research methodology follows four key steps.

Step 1: Literature Review of MAR applications in AEC
The author began research by conducting a literature review of MAR prototypes across the AEC industries. Primary research material stemmed from online conference proceedings, journals, media articles, and videos of MAR prototypes. The novelty of MAR applications in AEC uses means that this subject has yet to be fully researched. Much research in the overlapping AR/AEC realm has been undertaken by academics with a special interest in Augmented Reality, whose publications are geared to those with prior knowledge of this technology.

Against this framework, a non-technical overview of state-of-the-art AR prototypes is likely to appeal to industry professionals- this paper's target audience. For readers new to AR, the paper's **Appendix** includes a **Glossary of Literary Terms** to define key terms, along with an introduction to the **Components of a Simple Augmented Reality System.** A **Bibliography** references all material cited.

Step 2: Categorising Opportunities for AR within Established Architectural phases
The paper is structured around key phases of Architectural practice, drawing from the author's knowledge of this field, and Architecture's ability to straddle the fields of Engineering and Construction. The paper references literature by professional Architecture Institutes (i.e.: AIA, RIBA) to establish project stages within Architectural practice as **Design**, **Construction**, and **Post-Completion**.

Often an ***Opportunity*** for MAR is applicable across multiple project phases: for instance, visualising a design in-situ at full scale may be useful during both Design and Construction. Where this occurs, the paper discusses the Opportunity under its primary phase (i.e.: where it is most commonly used), and uses bullet points within the below table to indicate additional phases for application.

Phases	*D*	*C*	*P-C*
Application	●	●	

D*: Design;* C: *Construction;* P-C: *Post-Completion*
i.e.: Useful during both the Design and Construction Stages

While some ***Opportunities*** may seem foreign to the role of the architect now, with new technologies come new possibilities. Architects already using BIM workflows may expand their professional services to encompass MAR offerings, either by partnering with an AR developer to design custom apps, or by licensing existing platforms.

Step 3: Conversing with Thought Leaders to identify MAR Use Cases
The author discussed the opportunities and challenges for MAR first-hand with thought leaders worldwide while on a 4-week international study tour. Those approached included AEC industry leaders; AR developers and consultants; software researchers; academics; and pioneers of AR in

[13] A discussion of the central tenets of this philosophical framework lies beyond the scope – and intent- of this brief paper.

construction applications.[14] The study tour uncovered a broad spectrum of Use Cases and prototypes relevant to architecture across Oceania, North America, and Europe.

Cities visited on study tour included San Francisco (speaking to representatives from Metaio, IdeaBuilder, and the Autodesk Gallery); Seattle (visit to Boeing); Vancouver (trialling the Museum of Vancouver's AR app in-situ); Boston (visit to MIT's Media Lab); New York (a visit to Columbia University's CGUI lab); Zurich (visiting the ETH ValueLab); London (speaking to BIM experts at Laing O'Rourke); Manchester (visiting the University of Salford's ThinkLab); the Dutch cities of Amsterdam, Rotterdam and The Hague (speaking to directors at ARLab and DPI Holdings; visiting the New Institute; and trialling the UAR app in-situ); and Christchurch (visiting the HITlab at the University of Canterbury). Following the study tour, short videos and photos of Use Case applications and prototypes were uploaded as **blog posts onto the author's website**.

The search for Use Cases in AEC applications proved elusive. Given AR's commercial promise, many pioneers in the field today are reluctant to share their Intellectual Property with those outside their organisations, fearing loss of competitive advantage. Whereas academic contacts and researchers spoke openly about their work, contacts within private companies (such as Boeing and Autodesk) were reluctant to share their AR research and prototypes. Direct access to commercial AR developers for this paper was limited to those keen to market their work to AEC professionals.

Step 4: Research Synthesis

Following conversations with MAR thought leaders, key Opportunities and Use Cases identified in Step 3 were categorised within the architectural phases of Design, Construction, and Post Completion. MAR's challenges in the context of Architectural applications comprise the **Obstacles** section.

Often, MAR's affordances were hard to separate from the underlying technology's ability to encompass other features; for example, the ability to directly facilitate public commentary via mobile devices is based on an app being online. This paper embraces these 'accidental opportunities,' reasoning that the most successful AR platforms are those that combine numerous functionalities, and are true *'Apps with AR'*, rather than one-dimensional '*AR apps.'*

[14] Please refer to the **Acknowledgements** section for a list of people who contributed their time and thoughts.

1. Opportunities: Design

MAR's most familiar use today is in design visualisation, but Augmented Reality will increasingly inform the design process itself. AR's combination of real and virtual elements provides the ideal context for a design team to examine spatial problems in a collaborative setting.[15] With AR, multiple users may share the same physical space and perceive the 'spatial presence' of a digital object. The following sections discuss high-level uses for MAR across the architectural Design stage.

The *Design* phase in architecture encompasses *Schematic Design* and *Design Development.* The architect develops a design to meet a client's brief, and visually communicates this to project members, from the client; to local authorities and specialist consultants; and increasingly, the public. *Schematic Design* presumes that basic decisions regarding brief, budget and client requirements have already been established between the client and architect. The architect produces spatial solutions to address these requirements using a variety of media, and presents these to the client for assessment and selection. The coordination of a selected design with specialist consultants occurs during *Design Development*, where the project develops from its early schematic design. Drawings and models take on greater detail, and a local authority is typically involved to comment on and approve the scheme, prior to proceeding to the next phase of practice.[16] Mobile AR can contribute to multiple activities during this important phase.

1.1 Full Scale Design Visualisation in Situ

Phases	*D*	*C*	*P-C*
Application	●	●	

MAR's most widespread and familiar use is in overlaying a real site with an intended virtual design at full-scale. A growing number of AR developers and visualisation providers now offer AR platforms that enable 'walking tours' of a virtual building, from early design through to construction.[17]

Design visualisation using MAR more intuitively conveys the intended appearance, scale, and features of a proposed design to project team members. It is ideal for large-scale urban proposals, where a complex project must be communicated to a large number of people. Those from backgrounds outside the construction industry often struggle to decode technical planning documents, or interpret 2-dimensional drawings to understand their 3-dimensional implications.[18] MAR applications bypass traditional 'coding' and 'translation' models of spatial communication, reducing 'transmission errors' between design professionals and those affected by the planning process.

15 Seichter, "Augmented Reality Aided Design."
16 Based on the definitions of phases in "Client Note: Architect's Fees AN10.06.854."
17 From Inglobe Technologies' ARMedia, to Artefacto's Urbasee, there are numerous AR viewers on the market for full-scale design visualisation. Individual AR developers can also develop proprietary platforms that may be custom-built to suit project requirements.
18 Broschart, Zeile, and Streich, "Augmented Reality as a Communication Tool in Urban Design Processes."

USE CASES

Raseborg & *Jätkäsaari/Kämp* Tower Tours

The VTT Augmented Reality research team in Finland used MAR in 2011 to present an intended hotel complex to local authorities for planning approval. Council members assessing the new complex took a ‘virtual tour’ of the Raseborg site using their mobile devices.[19] The audience noted that use of AR *‘gave a better impression of the building volume than other methods’* and helped them *‘to understand the plans, (by) being present there.*[20]*’* A year later, a major building in Helsinki, the Kamp Tower, was also presented to city officials using MAR. These Use Cases proved that AR technology could be reliably used outdoors for full-scale design visualisation, and constitute precedents for council approval based in part on MAR visualisation.

Fig 5. *Council officers tour a proposed design in Raseborg, Southern Finland*[21]

Stadtmitte am Fluss (Germany), and the Christchurch Central Recovery Plan (New Zealand).

The CPE research team at the University of Kaiserslautern developed an 'urban walk' for the *Stadtmitte am Fluss* project in Saarbrucken. They overlaid proposed virtual designs directly onto their intended sites using MAR, and set up viewing stations where users could rate the schemes.[22]

Fig 6. *App users view the virtual design of a new pedestrian bridge on its site in Saarbruken.*

19 *Mobile AR Visualization of New Hotel Plans*.
20 *Mobile AR Visualization of Jätkäsaari/Kämp Tower Plans in Helsinki City*.
21 *Mobile AR Visualization of New Hotel Plans*.
22 Broschart, Zeile, and Streich, “Augmented Reality as a Communication Tool in Urban Design Processes,” 121.

The Human Interface Technologies Lab research team in Christchurch (HITlab NZ) took a similar approach following the Christchurch 2012 earthquake. The team developed the 'CityviewAR' app,[23] allowing users to walk around Christchurch sites and 'see' augmented models of the city's past and future buildings to scale, in real time. The app opened up direct lines of communication between residents and their city planning bodies, allowing users to comment on proposed future schemes. Both in Saarbrucken and Christchurch, use of MAR more intuitively presented future urban proposals to a large audience, and enabled a more direct conversation between the public and their urban designers.

1.2 Component Scaling & Clash Detection

Phases	*D*	*C*	*P-C*
Application	●	●	●

MAR can convey an object's true scale in its intended final location. While design professionals can interpret the scale of objects through drawing and practice, non-industry professionals often struggle with scale, grasping an object's dimensions only after it has been physically mocked up on site. MAR applications can isolate individual elements within a spatial scheme for presentation at full scale. Overlaying a virtual object at one-to-one scale on top of a physical marker can bypass the need for a tape measure, or laser pointer. By using virtual components to 'stand in' for physical objects, AR saves on the fabrication and material costs of real-world prototypes. MAR applications that scale components are useful in clash detection, to detect overlaps between proposed virtual content and real world elements. Today's commercial applications in this area are limited to mass-manufactured objects, whose modular nature provides a compelling business case for AR platforms that communicate scale.

Fig 7. A physical marker stands in for virtual furniture to test their size and placement in a room.[24]

23 "App Shows Chch Pre- and Post-Quake."
24 Siltanen and Valtion Teknillinen Tutkimuskeskus (VTT), *Theory and applications of marker-based augmented reality*, 23.

1.3 Augmenting Physical Presentation Media

Phases	D	C	P-C
Application	●	●	

MAR can augment physical models and drawings with unlimited virtual content. The most common augmentation of presentation media today is when a paper drawing – such as a 2D plan- becomes the marker for a 3D model overlay.[25] But the value-add of AR is in communicating information that other media cannot. Emerging uses for MAR include the overlay of 4D content (information with a time component) onto physical props, such as traffic flows, shadow studies, and wind flows. Overlays need not be limited to visual applications, as MAR can draw on other senses to communicate elements of a scheme, such as the acoustics within a space.

By overlaying time-sensitive virtual data onto physical drawings or models, MAR enables a new way of looking at information. Viewers can more readily appreciate the orientation of virtual content when a physical drawing or model acts as a reference point. For example, augmented content may switch between the structural, mechanical, and hydraulic systems proposed for a building, while retaining the same plan reference.

USE CASES

UCL's Augmented Reality Map

The University College London (UCL's) AR Map augments a two-dimensional map to make hidden data both visible and audible. The app draws on real-time data feeds (from live transport routes, to geo-located twitter tweets) to present the intangible components that make up this 'living' campus.[26]

Fig 8. *An AR map of UCL overlays 3D building information and 4D data.*

Christchurch City's CCDU App

The 2012 'CCDU app' by the HITlab AR team augments printed plans of Christchurch city with virtual 3D models of future buildings. Users worldwide can interact with these virtual models as though

25 As with the commercial platform developed by JB Technologies' *Smart Reality - An Augmented Reality Solution for Visualizing the Job Site*.
26 "UCL Live Campus Augmented Reality App - Created by Masters Students at CASA."

they were physical objects through the AR app. By pulling a variety of communication media into the one platform, the app simplifies access to information about the city's urban future.

Fig 9. *Christchurch City Council's Blueprint Plan is augmented with proposed block models.*

1.4 Informing the Design Process

Phases	*D*	*C*	*P-C*
Application	●	●	

MAR applications promise to impact the design process by bringing the designer into more direct contact with the building site. Future MAR applications will enable designers to not only interact with their developing design throughout the design process, but carry out design analyses while on site.

Architectural design today typically occurs outside the project site, with key design decisions made based on internalised conversations with a range of media. *Designing* involves the formation of early ideas about a project using physical and digital models, while *design review* is the process by which the end media is evaluated. Both activities occur repeatedly during the design phase of an architectural project. Typically a group activity, the *Design Review* is where design options from different designers are compared and discussed in relation to a range of issues.[27]

MAR will influence future design review processes, by expanding the media from which designers draw to make design decisions. By bringing decision makers into more direct contact with the site, MAR will enable a greater appreciation of the changing, temporal nature of a building's context. Although designers are increasingly gaining access to 3D point cloud scans of a site early in the design process, most of the information needed to understand a site's constraints and assess its merit is typically modelled from scratch by the design team. The quintessential 'black screen' of design software presumes a *tabula rasa,*[28] where all content is typically populated by the design team. Academic Jules Moloney argues that this starting point influences the design itself, by encouraging designers to consider their buildings as objects isolated from their real-world context.

Mobile AR platforms may allow building designers to gain an immediate 'reality check' of a building's surroundings early in the design process, and quickly contextualise their designs. '*AR highlights the dynamic qualities of the built environment, the fact that context changes over time.*

27 Moloney and Dave, "From Abstraction to Being There."
28 Defined by the Oxford dictionary as *'an absence of preconceived ideas or predetermined goals; a clean slate.'*

This approach to visualisation, (termed) 'temporal context', has two aspects: (1) the evaluation of designs in terms of spatial sequence and multiple viewpoints over time; (2) perceptual change over time due to the rhythms of environmental and occupancy cycles.[29]*'* Today's design visualisations typically freeze a building design within strategically selected 'hero shots' that present the building to best effect. AR's real-time nature encourages designers to consider and evaluate their designs across a range of timeframes, and from multiple viewpoints. AR use alone will not lead to 'more honest' design representations, as the viewing angle and virtual data overlay can all still be set by their users. Rather, use of AR will encourage the production of virtual designs that more closely respond to their real world context.

BIM thought-leader Dace Campbell adds that virtually any analysis a building team already does on screen—from seismic analysis, to acoustic performance, and structural modelling—can hypothetically be performed on site using MAR. *"Today's CAD and BIM tools (already perform building analyses),"* Campbell says, "*but AR will enable us to perform analysis at full scale while walking around a project site*.[30]" Should teleconferencing facilities be built into mobile AR platforms, designers will in future share in-situ AR visuals with project team members elsewhere.

USE CASES:

Vidente Research Prototype for the on-site planning of Geospatial Infrastructure

The Vidente Research team note that '(*MAR) offers immediate feedback to the user, (...) reducing errors and enabling faster and more reliable quality control of data*.[31]' In the below MAR prototype, the team considers the *'on-site planning of geospatial infrastructure,'* and places lamp posts on a site using an AR interface. The virtual lamp posts are located in real-time, and visually 'tested' in situ, with site boundaries and subsurface elements superimposed into the scene. While this simplistic Use Case does not truly call for MAR visualisation, it pre-empts what will be possible with technological development, and suitably complex design proposals.

Fig 10. *Smart Vidente prototype stills showing the interactive real-time placement of proposed virtual lamp posts on site.*

29 Moloney, "Screen Based Augmented Reality for Architecture," 3.
30 "Augmented Reality Goes Mainstream: 12 Applications for Design and Construction Firms."
31 Schall, Zollmann, and Reitmayr, "Bridging the Gap between Planning and Surveying with Augmented Reality User Interfaces."

1.5 Communicating Architectural Narrative

Phases	D	C	P-C
Application	●		●

MAR applications may communicate architectural narrative by overlaying information otherwise inaccessible to the viewer onto a building or architectural detail. In Cultural Heritage applications, MAR apps overlay virtual reconstructions of ancient splendour onto crumbling historic sites. A non-invasive technique, AR allows users to engage with historic artefacts without touching or corrupting them.[32] In 'AR sight-seeing,' virtual overlays provide glimpses into hidden spaces, granting user's 'X-ray vision'. Use of AR can bring an immediacy, interactivity, and playfulness to a narrative experience by drawing users into direct contact with a real site or artefact. There is limited scope to communicate architectural narrative in professional practice today, but opportunities abound in educational uses, and cultural events.[33]

USE CASES

The Visible City and Streetmuseum Apps

The Museum of Vancouver's *Visible City* app (2013) took users on a virtual exhibition of the city's history, tracking the rise, fall, and revival of neon in Vancouver.[34] App users could stand at predefined hotspots within the city and view historic images photo-matched to their locations. A precedent 2010 app- *'Street-museum'* by the Museum of London-[35] similarly overlaid historic photo content onto real-world sites using AR. In both cases, MAR provided immediacy and interactivity to the historic content, and significantly increased visitor numbers to the exhibits.

Fig 11. *Viewing the past in-situ using "The Visible City" app (Vancouver, Oct 2013). This app illustrated first-hand the difficulties of using GPS for* tracking (see 'Obstacles'). *The jumpy user experience differed from the app's slick marketing material.*

[32] "AR[t] 4," 10.
[33] Such as the Venice Biennale, where the theme of the 2014 Australian Pavilion is *'Augmented Australia'*.
34 *The Visible City*. A Similar example was the Museum of London App, developed in (2010).
35 *Streetmuseum*.

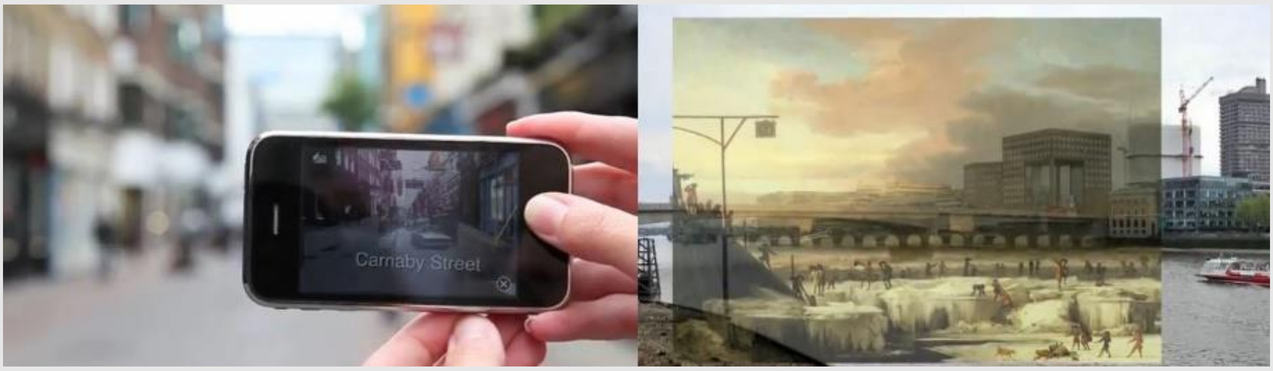

Fig 12. *The precedent "Streetmuseum" app by the Museum of London (2010).*

Discovering Van Gogh's *'The Bedroom'*

Researchers at the ARlab, Den Haag, are using MAR to reveal information about historic paintings. One MAR app allows visitors to playfully interact with selected artworks by Van Gogh, including *'The Bedroom'*. The app switches between a suite of information overlays, showing off the painting's original colours; the artist's brush-strokes; and even the back of the canvas framing. While the same information can be communicated through other media, the researchers argue that MAR makes the interaction with cultural heritage more exciting.[36] Similar applications are possible in architecture to provide background information to building details. MAR apps may for instance portray The Parthenon's original colours to tourists in real-time, or explain the many stories captured in a Gothic cathedral's stained glass windows.

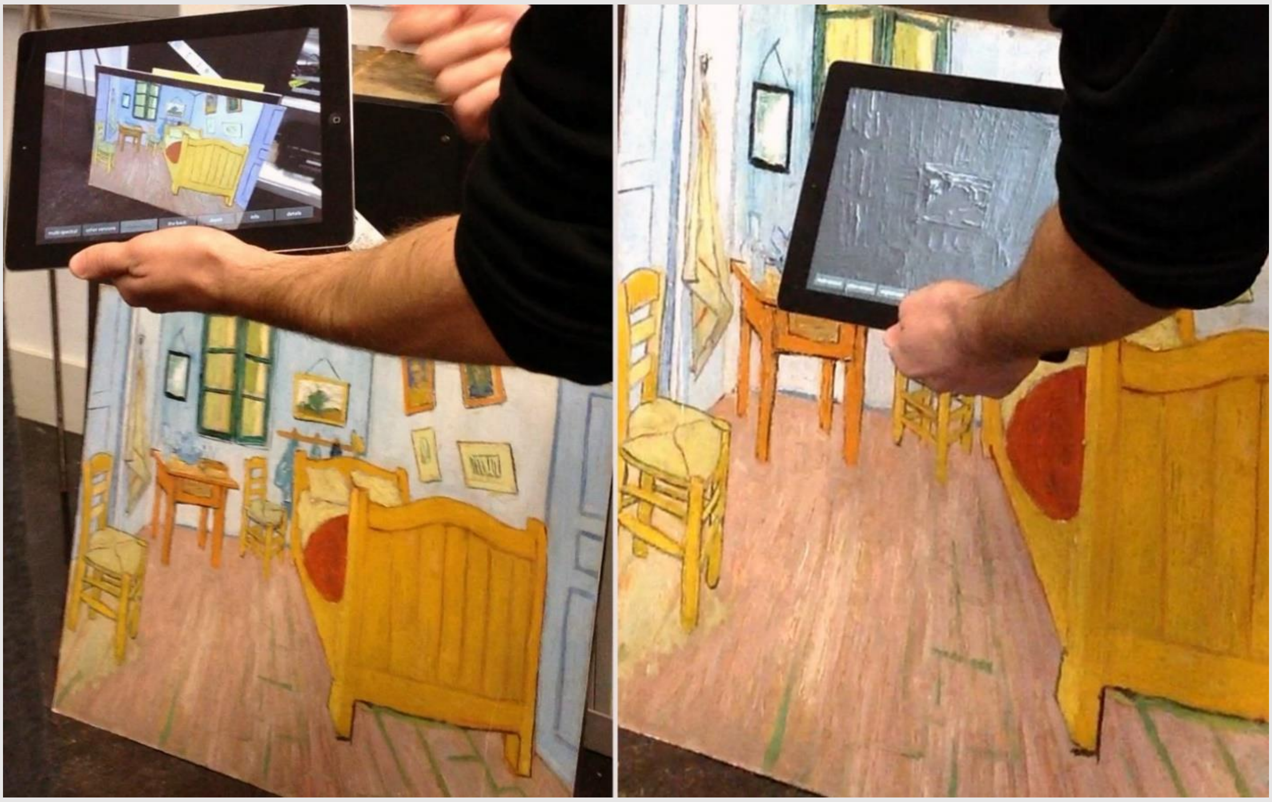

Fig 13. *An MAR app uncovers a painting's original colours (left), and paint depth (right) (Den Haag, Oct 2013).*

36 Kolstee and van Eck, "The Augmented Van Gogh's."

1.6 A New Interface between the Virtual and Real

Phases	*D*	*C*	*P-C*
Application	●		●

Today's built environment has become a canvas for digital data. Much that could once only occur in a 'bricks-and-mortar' environment has moved to virtual space, from instant mobile banking replacing banks, to digital data stores erasing library shelving. Digital technologies profoundly impact peoples' perception of their built environment, and offer new opportunities in the design of 'space' itself, be this physical or virtual.

AR will continue to alter this understanding and perception of the built environment. Architects would do well to consider the possibilities enabled by AR, and seek to involve themselves in the design of future places that straddle the digital and real. Today, multimedia developers and AR artists are merging digital and physical content to create imaginary, three-dimensional user interfaces. While the majority of AR explorations currently privilege the visual, new technologies under development will eventually enable audio AR, haptic (touch) AR, olfactory (smell) AR, and gustatory (taste) AR. Interfaces of the future will be designed to provide "*multimodal, multimedia experience(s),*[37]" with the potential to go beyond the graphical AR overlays of today. Such applications will enable new, imaginary experiences, and will require designers. Given their unique set of design skills and place-making knowledge, architects are ideally placed to explore the new junction between the virtual and real.

37 Kipper and Rampolla, *Augmented Reality*, 77.

2. Opportunities: Construction

Prior to construction starting on site, an architect and project team of consultants will have already produced coordinated developed drawings for the building works. This section assumes that the project has been developed using BIM, and that BIM data provides the virtual content overlaid onto the physical world using AR.

There are many uses for MAR during the Construction phase of a project. Architects may not be directly involved in the implementation of AR+BIM workflows on a construction site; in fact the Opportunities presented in this section would be employed by the contractor. But AR+BIM overlays on a construction site will have implications on the communication of information between the architect and the contractor. An architect administering a standard AIA contract today will typically undertake regular site visits to assess and certify progress claims from a contractor.[38] If AR+BIM is employed on site for component set-out, the information required from the architect will trend towards spatial data drawn directly from BIM. The architect's own assessment of on-site progress could also be aided using MAR.

2.1 Geo-Locating BIM Data on the Construction Site

Phases	*D*	*C*	*P-C*
Application		●	●

BIM data overlaid onto the construction site has three main uses: to visualise what is not yet built (the future); to view what is hidden (buried elements, or elements obstructed from view); and to see what cannot be seen (alignment information, easements, site boundaries, or environmental events – such as a 1-in-100-year flood level).[39] Given the data-rich nature of BIM, the permutations for visualising information in-situ are infinite.

BIM data may be geo-located directly on the construction site using MAR to communicate project information during construction.[40] Overlaying BIM data onto what is actually in place may benefit professionals undertaking site inspections, and contractors checking construction progress. AR+BIM may confirm precise installation locations for construction components; locate materials, equipment and safety zones on a project site; and locate construction and project component details for more efficient communication of this data to site workers.[41] Hazardous work areas and critical emergency information highlighted in AR view may enhance on-site safety.[42] As the Obstacles to AR use are addressed in time, new job roles will arise to validate the data being overlaid onto the project site, and ensure its accurate registration on site.

38 Royal Australian Institute of Architects and Practice Services, *You and Your Architect*.
39 Wilcox, Johnson, and Carrato, "Augmented Reality: Bringing BIM to Life."
40 One research consortium investigating the comprehensive uses for AR during construction is Fiatech, and their summary of Aspirations and Targets is reproduced in the Appendix section External References.
41 "Advancing Asset Knowledge through the Use of Augmented Reality Technologies."
42 "Augmented Reality Goes Mainstream: 12 Applications for Design and Construction Firms."

USE CASES:

Revealing Hidden Data: Visualising Subsurface Utilities

A *'new way of looking'* at digital information, MAR can increase the legibility of complex information models. The below augmented panorama visualises existing subsurface pipes.

Fig 14. An Augmented Panorama by Bentley that locates existing sub-surface utilities [43]

Visualising the Future: The Port Botany MAR Demonstrator

Laing O'Rourke Sydney's *Engineering Excellence Group* use a similar prototype MAR app to visualise BIM data – from electrical, to sewerage and hydraulic systems - directly on the construction site. Their app allows users to place their own geo-tag observations directly on site, and feed this information back to a data store accessible to remote team members.[44]

Fig 15. Laing O'Rourke's app allows users to visualise proposed subsurface utilities.[45]

43 *Information Intelligibility*.
44 A similar ability to geo-tag virtual and real objects directly on site through an AR interface has been explored by PARWorks for **Real-time Field Reporting**, and the VTT AR Research team for **Facilities Management**.
45 Braham, *Port Botany Augmented Reality Demonstrator. Laing O'Rourke Sydney & Explore Engage.*

Visualising the Future: The Reading Station Area Redevelopment Project (RSAR)

Bechtel UK used MAR in 2012 to provide real-time access to BIM data for part of the Crossrail Project. The BIM leads chose AR to *'improve the efficiency and safety of field personnel. Having BIM data accessible for decision making at the site maximize(d) (the field presence of site hazards), which (was) the most effective way to create a safer site.*[46]*'*

Fig 16. *Bechtel's AR device view visualising a proposed platform canopy during construction.*

Viewing 'what cannot be seen': MAR for Construction Drawings

Bentley's *Applied Research* group investigates new ways to communicate complex information, and uses AR to literally bring construction drawings to the building site. Operating on the basis that unintelligibility is pervasive in the construction industry, the group works to make sense of complex information.[47] The below MAR prototype uses simple markers to call up relevant drawings on site. Construction details are overlaid in AR directly onto the real site of building, allowing viewers to 'see what cannot be seen'. This Use Case highlights the potential for AR+BIM in real-world clash detection applications, as well as in compliance checking.

Fig 17. *Bentley Applied Research Group Prototype, showing BIM data overlaid directly on site.*

46 Wilcox, Johnson, and Carrato, "Augmented Reality: Bringing BIM to Life."
47 *Information Intelligibility*.

2.2 Task Support for Construction Processes

Phases	D	C	P-C
Application		●	

MAR can provide 3-dimensionally registered instructions onto physical components to provide task support for assembly processes. Boeing spear-headed the first AR application in an industrial assembly process in the early 1990's.[48] But while the automotive, aviation and astronautics industries have explored AR extensively for task support, the construction sector has lagged behind. This is largely due to the one-off nature of most construction projects, and the multiple processes involved in procuring a building, compared with the modular nature of industrial mass-manufacturing.

Companies that employ AR for repetitive manufacturing processes do so *'to increase effectiveness (fewer errors), and efficiency (shorter time to complete the task) through the use of context-sensitive, up-to-date and media-rich information.*[49]*'* AR applications can display instructions to those assembling components using voice commands or visual display cues. MAR apps that augment a worker's view can call up assembly instructions, specifications, and relevant standards to support construction processes. AR instructions may be seen from all viewpoints, allowing workers to concentrate on the assembly task without the need to interpret written manuals.

AR for task support is ideally suited to prefabricated building construction. Prefabrication enjoys a similar procurement process to industrial manufacturing, occurring in controlled factory conditions, and away from inclement weather. But once the existing tracking challenges posed by open-air construction sites are overcome (refer Obstacles), non-specialist workers may in future be trained on complex tasks using MAR platforms directly on the job site.

USE CASES:

AR Task Support for Space Frame Assembly

Researchers at the *Computer Graphics and User Interface Lab (CGUI)* at Columbia University in 1996 developed a 3D user interface perceived through a see-through, head-worn display, to overlay graphics and sound onto a person's natural sight and hearing.[50]The prototype aided its user to assemble a complex space frame, by instructing on what part to select from a pile of parts; confirming that the correct piece was being installed; directing the installation by indicating the part's intended location; and confirming that the component had been correctly installed. Similar systems are possible for complex assembly-based construction tasks.

---

48 Indeed, a researcher at Boeing – Tom Caudell- coined the term "Augmented Reality" while working on a head-mounted digital display that helped guide users in assembling electrical wire bundles for aircrafts. Regenbrecht, Baratoff, and Wilke, "Augmented Reality Projects in the Automotive and Aerospace Industries," 1.
49 Ibid., 2.
50 Webster et al., "Augmented Reality in Architectural Construction, Inspection and Renovation."

Fig 18. An *early 3D interface using a see-through head-worn display to aid in the assembly of a space frame, by Columbia University's CGUI.*

2.3 Real-time Field Reporting

Phases	*D*	*C*	*P-C*
Application		●	●

MAR applications allow users to perform daily field reporting by accessing and creating information directly on site. MAR applications can interface with the real-world construction site and the project management system, allowing users to complete construction reports, and check site progress directly 'within the field'.

In real-time field reporting applications, MAR platforms allow users to author and retrieve location-specific data on site without the need to contact persons off-site. By pointing a mobile device to areas on the job site, an augmented overlay may visually highlight areas for review, and allow elements in the vicinity of the user to be meta-tagged with information.[51] AR applications may call up information relevant to a user's specific location on a project site. For architects working on large and complex sites, the ability to quickly locate assets via visual AR overlays onsite may enhance communication between members of a project team. Future applications may use construction workers' locations relative to certain tasks to extrapolate their on-site construction progress. Workers erecting steelwork, for example, may move across a building site over the course of the day, allowing an MAR application to log their progress on the steel frame's construction.[52] In applications that function as a 'Site-Diary' however, special care will be needed to maintain users' privacy (refer **4. Obstacles**).

51 This functionality is similar to Bentley's 'hypermodeling' feature, allowing markers floating within a virtual model to link to and call up a drawing representing that location. This improves the effectiveness of the information environment,
52 Conversation with Prof. Steven Feiner at Columbia University CGUI, New York, October...

USE CASE

MAR Real Time Field Reporting App

PAR Works' MAR app, by researchers at the University of Illinois,[53] allows users to geo-tag elements on a building site in real-time, and call up relevant specifications or information pertaining to any building component directly on site. The portable mobile display acts as an interactive 'Site Diary' for its users, and is accessible both on and off the project site. The app allows daily reporting and retrieval of information, online as well as offline.

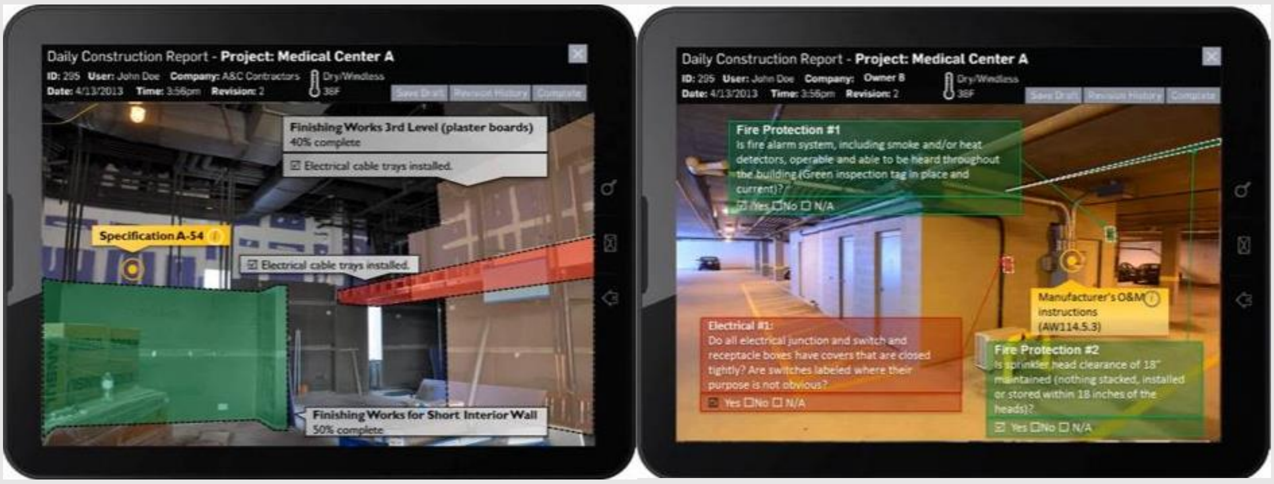

Fig 19. *Snapshots from PAR Works' MAR app, allowing site users to tag and access site information directly on the job site.*

2.4 4D Phasing of Construction Work Sites

Phases	D	C	P-C
Application		●	

Augmented Reality can extend a project's 4D scheduling and site logistics planning to the project site.[54] MAR applications may superimpose virtual objects onto paper plans to communicate the behaviour of dynamic components on site,[55] or directly overlay virtual objects on site to detect potential clashes of equipment with real-world elements.

Industrial manufacturers operating within closed, controlled environments today are pioneering the use of AR to better understand their factory processes; to maximise use of their production space; and to enable team members to understand actual production progress, as compared to planned progress. Charting the construction phasing of a project typically falls to the site contractor, who may be unable to employ AR on open-air sites until key **Technological Challenges** are resolved. Superimposing phasing information onto a construction site also presumes that this virtual data already exists, which may not always be the case (refer section ***4. Obstacles)***.

53 "Advancing Asset Knowledge through the Use of Augmented Reality Technologies."
54 "Augmented Reality Goes Mainstream: 12 Applications for Design and Construction Firms."
55 Combining the Opportunities discussed in **1.2: Component Scaling & Clash Detection**, and **1.3: Augmenting Physical Presentation Media**.

USE CASE

MAR to plan Virtual Construction Work Sites

Co-Director of the Australian Joint Research Centre for Building Information Modelling,[1] Prof. Xiangyu Wang, advocates use of AR for the planning of virtual construction worksites. He argues for an AR system that superimposes animated 3D objects onto paper plans, allowing contractors, consultants, and planners to quickly assess the movement of equipment or machinery on site; detect potential clashes; and assess the phasing of the construction site over time.

Fig 20. *Virtual construction site planning animation overlaid atop physical plan marker.*[56]

2.5 Way finding & Site Navigation

Phases	D	C	P-C
Application		●	●

Navigational apps today commonly pair Augmented Reality with Geographic Information System data (GIS), overlaying visual cues onto real city-scapes to direct users to specific sites. MAR applications can aid users to navigate real world building sites during Construction and Post-Completion.

Users within a complex building may benefit during Construction and Post Completion from platforms that target their exact location, and serve up relevant navigational content indoors. During Construction, large-scale sites are prime candidates for MAR-aided site navigation, particularly where key building elements -such as stairs- are yet to be constructed. On large-scale, complex sites, users may find it difficult to assess their whereabouts on site using plans of the proposed final building; way-finding MAR platforms may be more helpful in guiding workers to their end destinations. Such applications are contingent, however, on the resolution of technological challenges with tracking.

56 *insideAR 2012*.

USE CASE

Indoor Way-finding MAR app

Copenhagen Airport (CPH) in 2011 became the world's first airport to use MAR to aid passengers to navigate its interiors. While GPS positioning is typically used for external geo-location based apps- such as Wikitude's World Browser, pictured below- GPS cannot be reliably used indoors. The CPH app makes use of the airport's existing Wi-Fi infrastructure for tracking.[57] While the majority of navigational apps with AR today are visual, future augmented navigation cues may encompass other senses.[58]

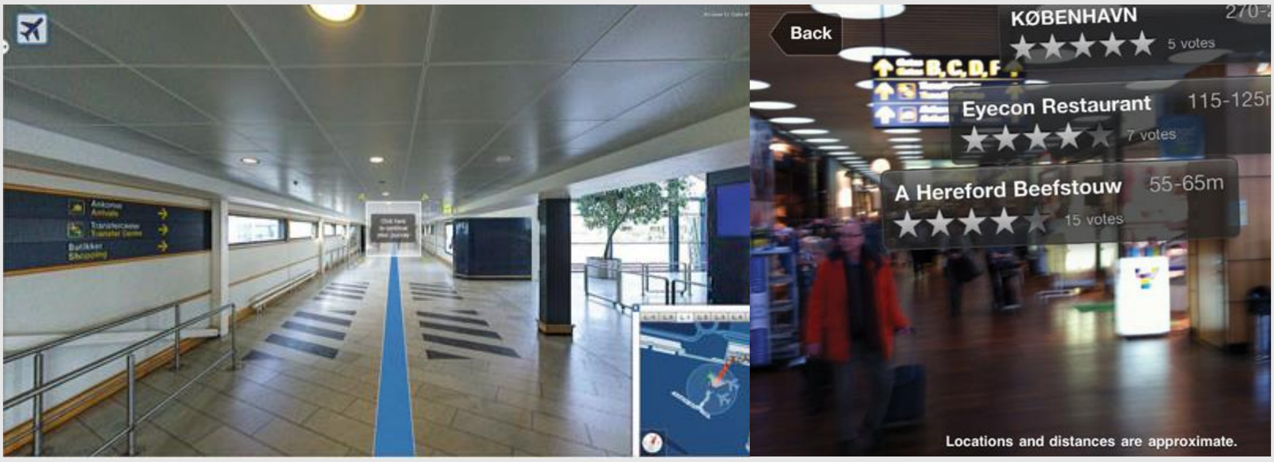

Fig 21. *Copenhagen Airport's MAR app helps passengers navigate its complex interior.*[59]

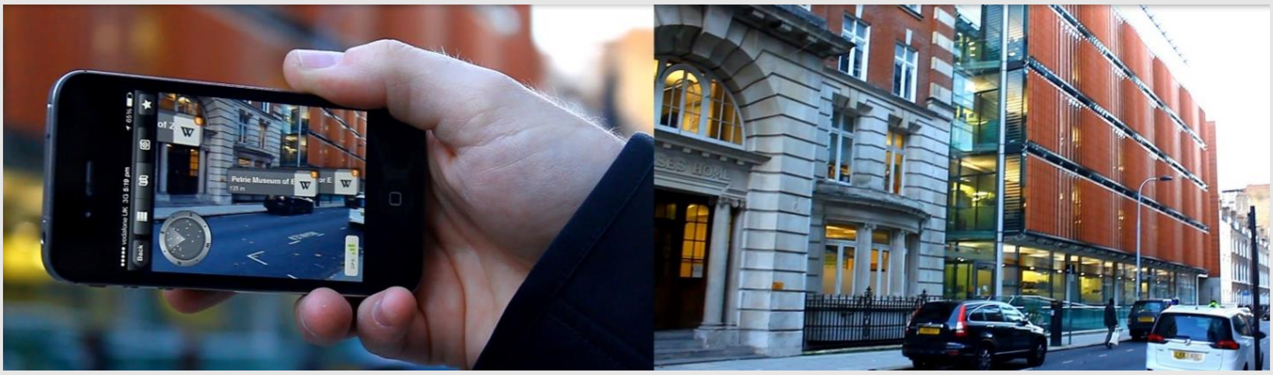

Fig 22. *The general-purpose Wikitude World browser overlays information regarding the immediate environment -including directions- in AR view. (London, Oct 2013).*

57 "Copenhagen Airport Unveils First 360 Degree Wayfinding App."
58 As with 'HeareApp', an app that augments audio information with the real world ambient noise to create accessible paths for visually impaired users. Source: *HeareApp English Introduction to Accessible Augmented Reality Audio Navigation*.
59 "SITA and Copenhagen Airport Launch the World's First Indoor Augmented Reality Application | SITA.aero."

3. Opportunities: Post-Completion

Mobile AR will impact the testing, assessment, inspection and review of a building's performance during Post-Completion.[60] This section focuses on two opportunities relevant to architects: the potential for MAR applications that train users in maintenance and repair tasks; and MAR platforms that aid Facilities Management.

Post-Completion[61] seeks to maintain a building's performance throughout its useful life, allowing for *'the continued adjustment, optimization and modification of building systems to meet specified requirements.[62]'* Architects typically have limited ongoing involvement in the Post-Completion phase of a building's life. Key tasks performed during this phase are the seasonal testing of equipment, elements, and assemblies by subcontractors; the inspection and review of building components before the end of the Defects Liability Period by architects; the completion of final commissioning reports for building components and systems by commissioning agents; and follow-up checks by architects to ensure client/end-user satisfaction.

3.1 Training for Maintenance and Repair

Phases	*D*	*C*	*P-C*
Application			●

AR visual and auditory overlays may assist users to carry out complex repair and maintenance tasks on building systems. By directly overlaying real-time computer graphics onto actual equipment, persons with little or no prior training may be guided through maintenance or repair tasks on complex machinery and equipment.

MAR training apps enable off-site collaborators to monitor and assist in building component repairs, by providing live communication links to the user on-site. Integrating such a 'real-world knowledge base[63]' with detailed 3D models can allow MAR applications to train building operators independent of a user's geographic location. Buildings with highly specialised component parts and/or numerous modular elements are ideal candidates for MAR apps that aid in maintenance or repair tasks; this is especially true where the cost of developing a custom app is offset by savings in the on-going future training of building operators. While no working MAR applications exist today for the construction industry, proof-of-concept prototypes have been developed in the aviation and aeronautics industries.

60 An overarching summary by Fiatech of their 'AR Aspirations and Targets' during Post-Completion is reproduced in the Appendix section External References.
61The Post-Completion phase of architectural practice is also variously referred to as 'Post Practical Completion,' 'Use and Aftercare', 'Operations', 'Post-Construction,' or 'Facilities Management.' "RIBA Plan of Work 2013 Overview."
62 "The Building Commissioning Guide."
63 "Wiki:armar - CGUI."

USE CASES

Columbia University's "ARMAR" Research Project

Researchers at Columbia University's *Computer Graphics User Interfaces Lab* are developing experimental AR systems to aid maintenance under the direction of Prof. Steven Feiner. The *Augmented Reality for Maintenance and Repair* (ARMAR) research project uses AR overlays to increase the accuracy, productivity, and safety of maintenance personnel undertaking highly specialist tasks.[64] The project encompasses research threads ranging from a complete AR job aid, to specific interaction techniques. The below AR user interface guides persons with little prior knowledge of their task through the assembly of an aircraft engine combustion chamber. The complexity of such a task far exceeds that typically required for building maintenance, and demonstrates AR's potential in the maintenance and repair of specialist building equipment.

Fig 23. *AR guides a non-specialist worker through the assembly of an aircraft engine combustion chamber.*

3.2 MAR for Facilities Management

Phases	*D*	*C*	*P-C*
Application			●

Combining a building's Facilities Management System (FMS) with BIM allows building users to monitor and plan for ongoing maintenance requirements. Provided that the BIM model is continually updated to accurately represent what is on site, MAR applications may draw from BIM and FMS content, to help users locate building systems without destructive demolition or further survey work.[65]

AR in Facilities Management may be used to identify assets, and call up relevant information about a component in-situ by way of computer vision and object recognition systems. An AR platform may also allow users to directly comment on building elements as metadata overlays, and feed this commentary directly into the Building Information Model.

64 Ibid.
65 "Augmented Reality Goes Mainstream: 12 Applications for Design and Construction Firms."

Future trends, such as Internet of Things (IoT), will open up further possibilities for AR in Facilities Management. IoT denotes the idea that every object in the future will have an online presence, allowing a variety of information to be collected by sensors linked to the internet. As the Internet of Things and Augmented Reality continue to develop, *'AR will (probably) become one of the predominate interfaces for the IoT in much the same way that the graphical user interface (....) became the interface for the Internet.*[66]*'*

USE CASES

MAR for Building Maintenance Prototype

The VTT AR Research team have developed a prototype app to locate hidden project components for facilities management; to call up operation and maintenance information in context; and to track the completion of maintenance activities by feeding this information back to the Building Information Model. The MAR system allows users to browse maintenance targets in AR view and quickly identify areas of concern. The app is linked to BIM, and allows user feedback through the one platform.

Fig 24. *An app guides a user to a maintenance target in real-time by highlighting the element in AR view.*[67]

The Building Technology Showcase (BTS)

The *Fraunhofer Centre for Sustainable Energy Systems* in North Boston uses AR to display information and data about its building technologies. The first floor building lobby acts as a mini museum, showcasing the products and technologies used throughout the building. AR overlays educate visitors on the hidden Building Management System, and its associated technologies.[68] The MAR app allows users to 'see' different building systems at work, and be 'immersed' in physically inaccessible spaces. A unique feature of this system is that the AR visuals are based on live and historic data, and may be manipulated by app users to accurately explain how these systems function. By allowing users to 'peel back' the walls around them in AR, data drawn from building technologies comes more immediate and engaging.

[66] "Pedagogy Meets Big Data and BIM - Big Data, Sensing and Augmented Reality."
67 *Mobile Augmented Reality for Building Maintenance*.
68 *Augmented Reality for Building Technology*.

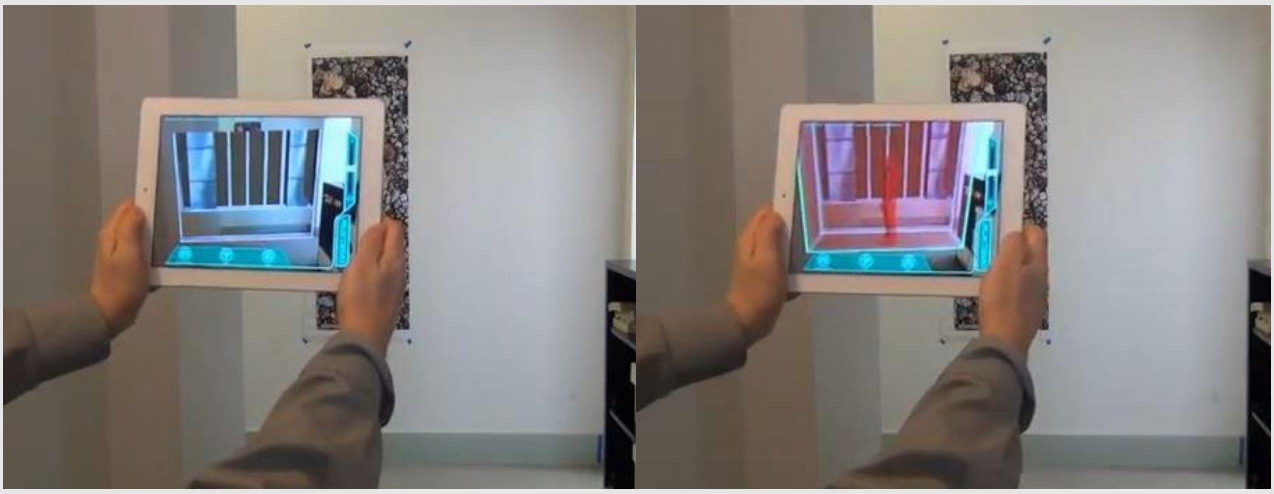

Fig 25. *The BTS' MAR demo explains the building's hidden systems and technologies, allowing app users to view real-time data drawn directly from the building systems.*

4. Obstacles

MAR's opportunities are numerous, but existing challenges prevent it from reaching a wider audience in the AEC industries. The Use Cases discussed in this paper are early prototypes, with shortcomings that currently prevent their adoption into practicing architects' workflows.

The Obstacles hindering MAR's progress are treated here within three key categories: Technological Challenges, Human Factors and Financial Constraints. As key technology enablers emerge to address these issues, the technological challenges facing MAR will be resolved in time. A greater challenge for the risk-averse construction industry will be to overcome the Human Factors and Financial Constraints impeding MAR's uptake once the Technological Challenges have been addressed.

4.1 Technological Challenges

MAR Displays
MAR displays must suit their professional application and setting. Most MAR platforms today use screen-based displays (including tablets and mobile phones). Yet screen-based displays pose problems when used outdoors in sunny conditions. Glossy screens reflect back ambient light, and are better suited to indoor environments with low level illumination. High ambient illumination outdoors makes displays appear dim, drawing greater power on the device to increase screen brightness. A device's short battery life, coupled with the quality and size of its graphic display, may pose further problems in applications calling for high accuracy, longevity, and visual realism.

While screen-based displays are often adequate for *Design* or *Post-Completion* activities, the Construction phase typically requires users to keep their hands free for other activities. Head Mounted Displays (HMDs) theoretically lend themselves to site applications, but today's HMD prototypes are not fit for on-site use. Often weighty, bulky and '*typically tethered by video cabling,*[69]' contemporary HMDs have restricted movement and usability. The proximity of the augmented overlay to a user's eye may cause eye fatigue in continuous-use applications.[70] The low perceptual quality of graphical presentation through head-worn AR displays can adversely affect the user experience.[71] And while HMDs can approximate natural fields of view, any increase in field of view typically increases the size of the glasses. Future HMDs for professional uses must then address multiple issues: user health and safety, particularly where peripheral vision is lost; the social impacts of their use on site when the size of glasses is increased; and the device's capacity to provide high quality, graphical presentations with the desired level of visual realism.

69 Dunston and Shin, "Key Areas and Issues for Augmented Reality Applications on Construction Sites."
70 Ibid., 165.
71 Huang, Alem, and Livingston, Human Factors in Augmented Reality Environments, 34.

INFO BOX

Head Mounted Displays (HMDs)

Head Mounted Displays for AR applications are either Optical see-through, or Video see-through. *Optical See-through* displays allow users to perceive the real world directly with their eyes, and display the virtual AR overlays directly atop a user's own view. *Video See-through* displays capture the real world by camera, and mix in virtual images with video images of the real world, often with a slight time delay between the real world event and the processed AR image. Video See-through displays are more commonly encountered in today's AR applications using HMDs.

Where HMDs have a camera and computational unit built in, they may be referred to as 'wearable computers'. Yet not all wearable computers offer true augmented reality. The Google Glass is often referred to in the media as 'AR glasses,' but does not provide true AR. The Glass' display is placed in a small screen in the corner of a user's eye, and the user has to specifically look at the display by looking up. This dissociates the virtual content seen through the Glass' display from a user's surroundings.

Fig 26. *Early prototype HMD's (left), and the Google Glass (right). Photos taken at DPI Holdings Den Haag & the Human Interface Technology Lab, Christchurch.*

Tracking

Augmented Reality requires accurate registration between the real world and the virtual augmented data. Computer-generated objects must remain locked to the 3D locations and orientations of real objects. This alignment is dependent on *tracking* the real-world 'viewing pose' accurately (refer **Components of a Simple Augmented Reality System**). *Tracking* is the act of continuously identifying the position and orientation of an observer's viewpoint with respect to a 3-dimensional reference system.[72] It is beyond this paper's scope to discuss the tracking techniques available today (particularly given the speed with which this technology is changing), but the major tracking types are listed for reference purposes in the **Glossary**.

72 For a summary of the types of tracking systems available, refer to the **Appendix**. Perey and Terenzi, "Augmented Reality-Assisted 3D Visualisation for Urban Professional Users," 15.

In Construction and Post-Completion, MAR tracking systems are required to cover a large range on site while maintaining high accuracy, often to within a few millimetres. On building sites with multiple storeys, tracking must work in the 'z' axis, and identify the relative level (i.e.: positional height) of a user, while relating this to the appropriate virtual model location. Today's tracking systems do not satisfy the complex demands of chaotic construction sites, nor achieve the high accuracy required for precision applications.

The majority of outdoor Use Cases presented in this paper rely on GPS for tracking. Yet GPS only works to within 5-30m accuracy; suffers from fluctuations in signal due to weather changes or signal blocking by neighbouring structures; and struggles to get a satellite fix indoors. Other positioning systems may soon deliver the level of accuracy required in precision applications. Differential GPS (dGPS), for instance, is superior for outdoor applications, and can achieve a precision of 5 to 10cm.[73] Cell phone and WiFi antennas may also be used for positioning, but with precision ranging between 5m to 100m.[74]

As GPS typically does not work indoors, indoor tracking today is often achieved using computer vision techniques. The use of physical markers can be combined with visual clues derived from the 3D structure of a building for object recognition. But markers can slowly deform with time; may be obscured by building works; are sensitive to changes in ambient light; and have limited tracking range. Future tracking systems likely to meet the exacting requirements of construction applications will be hybrid systems that combine inertial and optical technologies.[75] The advancement of tracking technology relies on industrial and academic progress in hardware development, and will be a key enabler of AR across architectural phases. Meanwhile, stable AR with high accuracy tracking is best achieved in consultation with an AR professional with the necessary expertise.

Lack of Industry Standards & Data Preparation

Today's lack of industry standard processes for the development of AR apps is fuelling the development of custom apps that 'lock' users into one-off platforms. AR applications are costly to produce and maintain within such knowledge silos, where information cannot readily be extracted or reformatted for different media.

One grassroots organisation working to advance open and interoperable AR is the *AR Standards Community* that monitors progress across a wide range of Standards Developing Organisations (SDOs), and provides inputs to those interested in open and interoperable AR.[76] As the community chair, Christine Perey, notes however, *'until such a time that AR-ready enterprise content management systems (CMS) and Geographic Information Systems (GIS) are available from enterprise solution vendors, content creators and curators must check file format compatibility.*[77] The onus today is on the user of a specific software package to find out whether a plug-in exists to present its virtual content in AR view.

Preparing virtual data for AR use is also problematic. Architectural practices produce content in a variety of 3D file formats (driven by their practice' software provider, staff skillset and workflows), but most AR platforms do not support native 3D file formats. BIM data must be compressed or modified

[73] Perey and Terenzi, "Augmented Reality-Assisted 3D Visualisation for Urban Professional Users."
[74] Ibid.
75 Wang, "Using Augmented Reality to Plan Virtual Construction Worksite," 5.
76 "AR Standards | for Open and Interoperable Augmented Reality Experiences."
[77] Perey and Terenzi, "Augmented Reality-Assisted 3D Visualisation for Urban Professional Users," 10.

to allow mobile hardware to process it for quick, real-time visualisation (similar to the optimisation required for 3D animations and renders). The 'CityViewAR' app by the HITlab, for instance, requires dedicated 3D modellers to pare down existing BIM data of Christchurch city, as only small file sizes with reduced polygons can be processed by today's mobile devices. Similarly, Artefacto's 'UrbaSEE' AR platform requires 3D model uploads to be below a maximum file size. Such restrictions on file sizes result in a loss of visualisation detail when virtual data is viewed in AR.

The development of lossless, interchangeable file formats common to key building software packages will be pivotal to AR gaining ground in the AEC industries. Augmented Reality will be a more accessible and useful proposition for architects when virtual content can be used 'as-is' across media platforms. Unfortunately, there are hardware implications for this holy-grail of interoperability: today's mobile devices are limited by their processing power and speed. Producing realistic AR scenes with real-world occlusion, lighting, and shadows using large file sizes is beyond the technological limits of the majority of portable hardware devices currently on the market.

Producing virtual content in itself is challenging, particularly given the uneven use of Building Information Modelling (BIM) in Australian architectural industry. AR applications that 'see through walls' or 'view subsurface elements' assume a virtual content store for the hidden objects in the area inspected. Yet such an integrated 3D database to support information extraction by AEC industry consultants does not exist. At best, virtual assets would exist in a project's Building Information Model. But where BIM is not integrated into office workflows, much information is still represented in 2D.

Consultants using AR will therefore ideally have BIM workflows already in place. They will also need to establish standard processes for the transfer and coordination of virtual data, particularly where the storage and transmission of this content is difficult due to large file sizes. Those producing virtual content for viewing in AR will need to be vigilant in their modelling, and allow for the upkeep of this data. Crucially, the liability of each virtual data provider will need to be defined at the outset of any project where AR is relied upon for decision-making. Future AR+BIM workflows will necessitate new roles for providers of virtual content for AR: both to warrant the registration of the virtual content on a real site, and to validate the data itself.

4.2 Human Factors

Resistance to Change

Key to integrating MAR systems into architectural offices will be adequate staff training, and specialist assistance in the implementation of new workflows. MAR's introduction to architectural industry will echo that of BIM: *'One of the greater industry challenges will relate to training, particularly in relation to teamwork and collaborative approaches to design and construction, and the next generation of collaborative designers and contractors will need to embrace new working methods and leave behind some old assumptions and role stereotypes*.[78]'

Asking people to step out of their comfort zones and use new technologies will meet with initial resistance. MAR applications must be simple enough for users to learn and use independently, without the continued reliance on experts. Where known workflows are being replaced, users must

78 Sinclair, "BIM Overlay to the RIBA Outline Plan of Work," 7.

see clear benefit from the use of MAR. Future industry investment in MAR training will flow from a convincing business case, championing AR's use. New workflows that integrate MAR will likely engender new roles, as with the 'Model Manager' role introduced by the development of BIM.

Hype and Disillusionment

Today's early adopters of MAR risk disillusionment when early prototypes are not stable enough for commercial application- particularly given the exaggeration of AR's abilities in news media.[79] To separate the hype surrounding a technology from reality, ICT research and consulting company Gartner defines *Hype Cycles* for emerging technologies. In July 2013, Gartner placed AR on a downward trajectory towards the *'Trough of Disillusionment'* after reaching the *'Peak of Inflated Expectations'* in 2011.[80]

Professionals trialling AR for the first time in 2014 will be frustrated by existing technological challenges. Rather than await the development of new methodologies and products, some may write AR off entirely, and continue with 'tried and true' workflows. Yet those who persist and work through MAR's hurdles will likely reap benefits in 5-10 years' time, when the technology reaches its predicted 'Plateau of Productivity'.

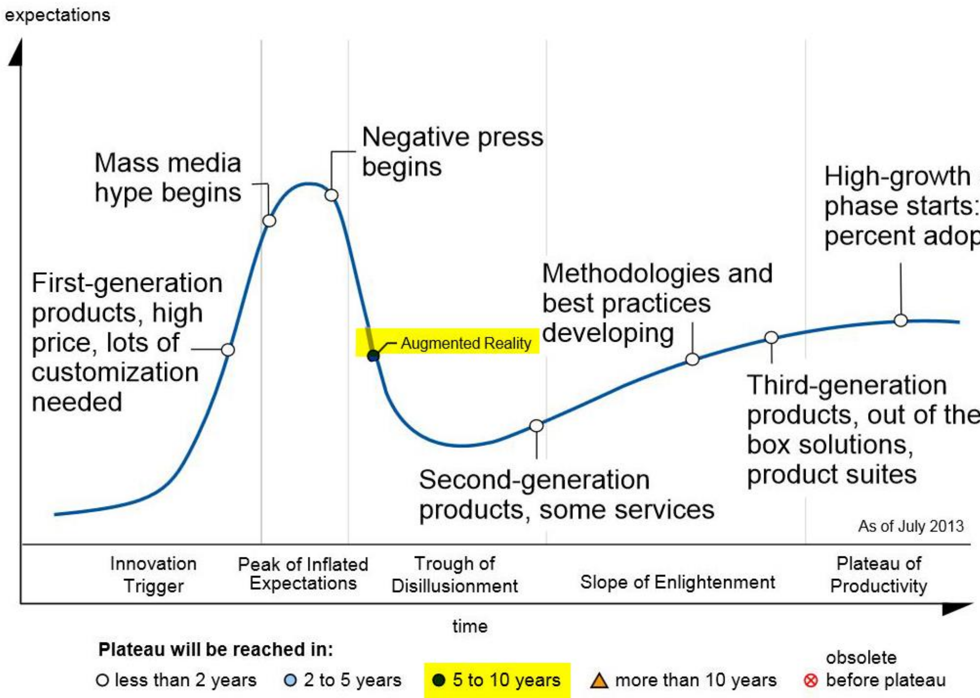

Fig 27. *Gartner's July 2013 Hype Cycle for Emerging Technologies[81] with overlay of AR by author.*

Privacy and Surveillance

The camera is an integral component within a simple MAR system, but poses a privacy challenge by recording persons in its vicinity. Where MAR applications inadvertently record a user's progress (such as in training applications, or real-time field reporting on a construction site) users may feel they are under surveillance, resulting in stress or altered behaviour. Emerging wearable computers

---

79 One commentator terms AR's exaggerated abilities in the media 'Hollywood AR': glamorous on the outside, but skint on content.
80 While Gartner treats AR as one entity, in reality there is great variation among the different AR applications, of which MAR is a subset. Some of these applications are today still in their early stages, while others are ready for adoption.
81 Le Hong and Fenn, "Emerging Technologies Hype Cycle for 2013: Redefining the Relationship."

in particular are sparking new legislation and policies that aim to maintain citizens' privacy rights. Privacy concerns are the subject of ongoing conversation for the Augmented Reality industry.

User Safety

Safety is a key priority on Australian building sites. The need for construction professionals to abide by Occupational Health and Safety laws currently precludes use of distracting devices, such as display screens or wearable devices that obstruct vision. In the context of a chaotic construction site, all AR hardware will need to comply with rigorous safety standards, such as the ability to be dropped without shattering ('ruggedness'). Even during the early Design stage, use of some equipment may pose health hazards. Optical see-through HMD's, for instance, may cause eye-strain with prolonged use, and may prove unacceptable to some organisations.

Where AR applications seek to improve the safety of workers on a complex building site (for instance, by highlighting site hazards and safe work zones in AR view), they must not inadvertently encourage user complacency. Should users rely on MAR overlays to alert them of dangers, they may reduce their overall attention to site hazards. Policies for the safe use of AR devices on site will be required in the future, to mitigate any safety risks posed by the introduction of MAR hardware into working environments.

4.3 Financial Constraints

Architectural firms seeking to develop and integrate MAR applications into their workflows will need to invest time and money for research and development. Introducing AR into an architectural office will have associated costs, including the purchase of new hardware; staff training on the safe and accurate use of new technology; licensing and/or development costs for AR platforms; and operational expenses associated with running the technology. The costs to implement MAR will depend on its intended use, and the technological barriers to be overcome to achieve a stable user experience. A proprietary platform using off-the-shelf hardware and GPS for sketch design visualisation will, for example, cost substantially less to implement and produce than a custom app that requires high accuracy to visualise BIM data during construction.

Investments in AR workflows by professional practices will ideally be made based on the calculation of a Return of Investment (ROI) on the capital.[82] An ROI calculation must estimate the actual benefits of AR use, in terms of lowering the cost of doing business by improving overall efficiency. Yet the benefits of using AR are difficult for an architectural practice to quantitatively measure. Perey and Terenzi propose an approach that isolates specific use cases, and measures the impact of AR on a group of users: for example, architectural staff using a prototype app can estimate the time saved through use of AR. Unfortunately, Australian architectural practices today have finite financial resources, and few have the motivation required for such a study. Developing a rigorous business case based on ROI calculations for the use of AR in architectural practice would be an ideal subject for future research.

[82] Perey and Terenzi, "Augmented Reality-Assisted 3D Visualisation for Urban Professional Users."

Conclusion

Augmented Reality's possibilities for architecture are endless, and the Use Cases presented in this paper are only the beginning. Future technological developments will enable greater opportunities for MAR in AEC applications. But there are key challenges ahead for this burgeoning field that encompass technological challenges, human factors, and financial constraints.

The paper has identified high level MAR applications across Design, Construction, and Post-Completion that promise a more intuitive interaction with virtual data. During the Design phase, MAR may augment a real site with an intended design at full-scale. AR used for design visualisation may allow project members to interact with virtual spatial data and convey the intended appearance, scale, and features of a proposed design in its final context. MAR may aid in component scaling and clash detection, allowing physical markers to 'stand in' for virtual scaled objects; and may augment physical presentation media to communicate 4D content. MAR may inform the design process itself enabling designers to more fully appreciate a project's context; and may communicate architectural narrative.

During Construction, MAR may overlay BIM data directly on an intended site to confirm installation locations for construction components; locate materials, equipment and safety zones; and locate construction and project component details for increased efficiency. MAR may assist construction workers to carry out complex tasks by providing 3-dimensionally registered instructions directly onto physical components for assembly. Applications that function as a 'site diary' may allow users to perform daily field reporting directly on the job site, accessing and authoring virtual geo-tagged content directly in the field. By taking 4D scheduling and site logistics planning to the project site, MAR may communicate site logistics and phasing. Paired with GIS, MAR may also aid in the navigation of building sites.

In Post-Completion, visual and auditory AR overlays may assist with complex maintenance and repair tasks on building systems. Combining a building's Facilities Management System (FMS) with BIM data may allow future MAR apps to facilitate ongoing maintenance requirements.

But MAR applications must surmount technological, social, and financial challenges before they are adopted into the workflow of practising architects. Future displays will need to address the unique safety requirements and outdoor conditions of construction applications. Tracking systems will need to satisfy the complex demands of construction uses, and achieve high accuracy. Industry standards will need to facilitate data transfer between project members, and provide greater interoperability between different media. Specialists will be required to assist in implementing MAR workflows and to provide staff training. New protocols will need to address privacy and safety concerns; and significant financial investments will need to be made by organisations keen to implement MAR in their project workflows.

The road ahead is long, and the technology reliant on many players for its development. But with persistence and time, MAR will trickle into architectural practice, softening the boundaries between the virtual and the real.

Appendix

Glossary of Literary Terms

Affordance
In the fields of design and human-computer interaction, an affordance refers to *"the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used*[83]*."*

Augmented Reality (AR)
Any system '*that enhances or augments the surroundings of the user with virtual information that is registered in 3D space and seems to co-exist with the real world*[84].'

AR research combines the fields of computer graphics (photorealistic rendering and interactive animations) and computer vision (marker and feature detection and tracking, motion detection and tracking, image analysis, gesture recognition and the construction of controlled environments containing a number of different sensors)[85].

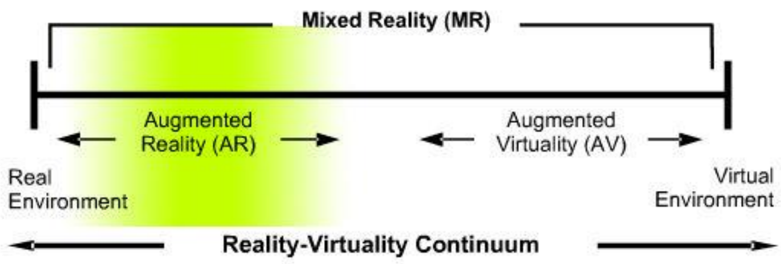

Fig 28. *Order of reality concepts ranging from reality to virtuality*[86]

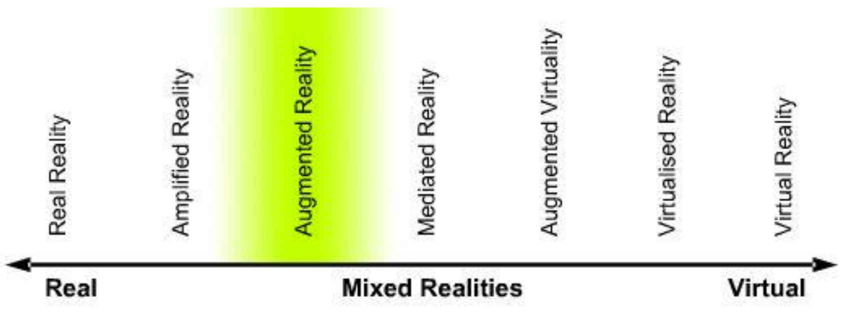

Fig 29. *Order of reality concepts ranging from reality (left) to virtuality (right)*[87].

Building Information Modelling (BIM)
Defined by the Construction Project Information Committee (CPIC) as: '*...digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for*

83 "Affordances — SSRC."
84 Azuma (1997)
85 Siltanen and Valtion Teknillinen Tutkimuskeskus (VTT), *Theory and applications of marker-based augmented reality*, 18.
86 Image adapted from Wang and Schnabel, *Mixed Reality in Architecture, Design and Construction*.
87 Ibid.

information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition[88].'

The Internet of Things (IoT)

Refers to a world where sensors and actuators are embedded into physical objects, and linked through wireless and wired networks that all live and interact with one another. IoT allows objects- be they physical or virtual- to be searched, tracked and interacted with.

Mobile Augmented Reality (MAR)

The meaning of Mobile Augmented Reality (MAR) is indicated by the key word: mobile. This paper uses the definition of Mobile AR provided by Hollerer & Feiner (2004): *"Mobile AR applies (the concept of AR) in truly mobile settings; that is, away from the carefully conditioned environments of research laboratories and special-purpose work areas*[89]*."*

A summary of the components required for MARS are:

- A computational platform
- Displays
- Registration
- Wearable input and interaction technologies
- Wireless networking
- Data storage and access technology

Note that *Mobile AR* and *Mobile Phone AR* do not share the same meaning. Mobile AR encompasses a range of displays, including head-worn equipment, displays integrated into the physical world, and includes mobile hand-held devices. There are key differences in the AR experience and functionality between different displays, for instance between a mobile phone and HMD - 1) The display is handheld rather than head worn, 2) The phone affords a much greater peripheral view, and 3) With a phone, the display and input device are connected.[90]

Obstacle

A thing that blocks one's way or prevents or hinders progress[91].

Opportunity

A time or set of circumstances that makes it possible to do something[92].

Real-time

The precise time in which an event or process occurs.

Tracking

The act of continuously identifying the position and orientation of an observer's viewpoint with respect to a given 3D reference system over time[93].

---

88 Sinclair, "BIM Overlay to the RIBA Outline Plan of Work."
89 Höllerer and Feiner, "Mobile Augmented Reality."
90 Billinghurst and Henrysson, "Mobile Architectural Augmented Reality."
91 "Obstacle: Definition of Obstacle in Oxford Dictionary (British & World English)."
92 "Opportunity: Definition of Opportunity in Oxford Dictionary (British & World English)."
93 Perey and Terenzi, "Augmented Reality-Assisted 3D Visualisation for Urban Professional Users."

Active Tracking	Require calibrated sensors and signal sources whose readings are received from an external beacon/receiver system that must be supplied with power. (i.e.: GPS).
Passive Tracking	Relies on inertial sensors, and does not require the use of power to emit or receive a signal. (i.e.: accelerometer, gyroscope).
Optical Tracking	Relies on computer vision, and encompasses marker-based and Natural Feature Tracking (NFT) approaches.
Hybrid tracking	Combines inertial (Passive) and computer-vision (Optical) tracking techniques.

Virtual Reality (VR)
An immersive environment simulated wholly by the computer[94].

94 Siltanen and Valtion Teknillinen Tutkimuskeskus (VTT), *Theory and applications of marker-based augmented reality*, 20.

External References

Fiatech's *list of AR's Aspirations and Targets to resolve the following construction issues*[95] *during CONSTRUCTION*	Mentioned in:
• *Confirmation of Installation Locations*	2.1 – Geo-locating BIM on the Construction Site.
• *Ensuring Usage of Correct Drawings*	2.3- Real-time Field Reporting
• *Locating Construction and Project Component Details*	2.1 – Geo-locating BIM on the Construction Site.
• *Locating Construction Materials and Equipment*	2.1 – Geo-locating BIM on the Construction Site.
• *Locating Installation Instructions and Guidance Notes*	Task Support
• *Schedule Compliance*	2.3- Real-time Field Reporting
• *Identifying Existing Utility Locations*	2.1 – Geo-locating BIM on the Construction Site.
• *Identifying Safety Zones*	2.1 – Geo-locating BIM on the Construction Site.
• *Dealing with Interface and Clashing Issues*	1.2 – Component Scaling and Clash Detection
• *Address Public Inquiries and Planning*	1.1 – Full-Scale Design Visualisation In Situ
• *Address Local Residents/ Private Property Concerns*	1.1 – Full-Scale Design Visualisation In Situ

Fiatech's *list of AR's Aspirations and Targets to resolve the following construction issues*[96] *during POST-COMPLETION*	
• *confirming the availability of asset data;*	
• *locating hidden project components;*	
• *identifying project component sequencing*	
• *integrating operational and maintenance manuals;*	
• *accessing order requests; and*	
• *tracking the completion of maintenance activities*	

95 "Advancing Asset Knowledge through the Use of Augmented Reality Technologies," 10–11.
96 Ibid.

Components of a Simple Augmented Reality System

The components for a simple AR system consist of a **camera**, a **computational unit**, and a **display**. The camera captures an image, and then the system overlays virtual objects on top of the image, and displays the result as a combination of both real world objects, and virtual components.

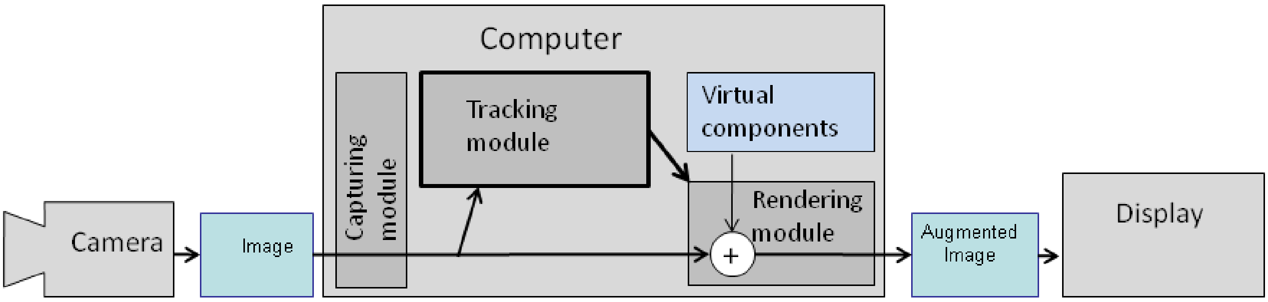

Fig 30. *Flowchart for a simple AR system setup*[97]

The **Tracking Model** calculates the relative pose of the camera in real-time. The **'pose'** refers to the camera's six degrees of freedom (6DOF) position, or location and orientation of an object in space (three degrees of freedom for position, and three for orientation[98]). The simplest way to calculate the pose is to use physical markers, though more sophisticated methods for tracking exist today.

The **Tracking module** allows an AR system to enhance the real scene with virtual information. The **Rendering module** draws a virtual image on top of a camera image.

With simple AR, the system needs to 'mimic' the real camera, to get the optical characteristics of the virtual camera to match the real camera, and produce a convincing final overlay.

This process of matching the virtual camera to the system's 'real' camera is known as '**camera calibration'**[99].

97 Siltanen and Valtion Teknillinen Tutkimuskeskus (VTT), *Theory and applications of marker-based augmented reality*.
98 Neumann and You, "Natural Feature Tracking for Augmented Reality," 53.
99 Siltanen and Valtion Teknillinen Tutkimuskeskus (VTT), *Theory and applications of marker-based augmented reality*, 23.

Acknowledgements

This paper began as a personal interest project, and developed across many evenings and week-ends in parallel to my full-time role as an architect. The “AR trail” took me on a study tour across North America, Europe, and Oceania, to the labs of leading universities, AR developers and researchers, and digital technology leaders in the construction sector.

A big THANK YOU to **NAWIC** and **Architectus** for making my study tour possible; to Ewen Wright, for his immense contribution; and to everyone who so generously took the time to meet with me, and/or provided Use Cases, feedback, and suggestions on research avenues.

Rodd Perey, Principal at Architectus Sydney (Research Mentor)
Christine Perey, Founder, PEREY Research & Consulting
Prof. Steven Feiner, Director Computer Graphics & User Interfaces Lab, Columbia University
Prof. Mark Billinghurst, Director, HITlab NZ
Damon Hernandez, Director of Tech Tools, Idea Builder
Dulcidio Coelho, THINKlab Technical Director, University of Salford
Dr. Yolande Kolstee, Researcher & Head, AR Lab
Wim van Eck, AR Researcher, AR Lab
Victoria Rowley, Danika Berlin and Lucy Swank, METAIO
Dr. Rowan Braham, Innovation Engineer, Laing O'Rourke
Paul Devitt, BIM Leader, Laing O'Rourke (UK)
Rob Snyder, Researcher, Bentley Systems
Paul Kouppas, Director, Explore Engage
Stuart Bull, Former Director, BIM Consulting
Ryan Hanlen, Former Senior Consultant, BIM Consulting
Stephen Poelsma, DPI Holding
Lucie Le Boisselier, Artefacto
Prof. Charles Woodward, VTT Technical Research Centre
Dr. Reihard Konig, Professor Future Cities Lab, ETH
Lukas Treyer, Ph.D Candidate, Future Cities Lab, ETH
Tom Lleyden, Head of Technology, HASSELL
Prof. Tom Kvan, Dean of the Faculty of Architecture, Melbourne University
Prof. Jane Burry, Director SIAL, RMIT

Bibliography

"Advancing Asset Knowledge through the Use of Augmented Reality Technologies." Accessed December 1, 2013. http://fiatech.org/webinars/archived-webinars/2013-webinars/mediaitem/6152-advancing-asset-knowledge-through-the-use-of-augmented-reality-technologies.

"Affordances — SSRC." Accessed March 29, 2013. http://mediaresearchhub.ssrc.org/icdc-content-folder/affordances/.

"App Shows Chch Pre- and Post-Quake." Accessed December 1, 2013. http://www.3news.co.nz/App-shows-Chch-pre--and-post-quake/tabid/309/articleID/289706/Default.aspx.

"AR Standards | for Open and Interoperable Augmented Reality Experiences." Accessed January 29, 2014. http://www.perey.com/ARStandards/.

"AR[t] 4." Issuu. Accessed February 22, 2014. http://issuu.com/arlab/docs/art4_issuu.

Augmented Reality - the 8th Mass Medium: Tomi Ahonen at TEDxMongKok, 2012. http://www.youtube.com/watch?v=EvyfHuKZGXU&feature=youtube_gdata_player.

Augmented Reality for Building Technology: Final, 2013. http://www.youtube.com/watch?v=bXqe2zSepQ4&feature=youtube_gdata_player.

"Augmented Reality Goes Mainstream: 12 Applications for Design and Construction Firms." Accessed September 10, 2013. http://www.bdcnetwork.com/augmented-reality-goes-mainstream-12-applications-design-and-construction-firms.

Azuma, Ronald T. "A Survey of Augmented Reality." Presence: Teleoperators and Virtual Environments 6, no. 4 (1997): 355–385.

Billinghurst, Mark, and Anders Henrysson. "Mobile Architectural Augmented Reality." Mixed Reality In Architecture, Design And Construction (2009): 93–104.

Braham, Rowan. Port Botany Augmented Reality Demonstrator. Laing O'Rourke Sydney & Explore Engage. Accessed February 3, 2014. http://vimeopro.com/user24482771/enexg/video/84820957.

Broschart, Daniel, Peter Zeile, and Bernd Streich. "Augmented Reality as a Communication Tool in Urban Design Processes." Accessed December 1, 2013. http://programm.corp.at/cdrom2013/papers2013/CORP2013_29.pdf.

"Client Note: Architect's Fees AN10.06.854." The Royal Australian Institute of Architects Practice Services, April 1999.

"Constructech Magazine | Augmented Reality in Construction." Accessed January 19, 2014. http://www.constructech.com/news/articles/article.aspx?article_id=9231.

"Copenhagen Airport Unveils First 360 Degree Wayfinding App." Future Travel Experience. Accessed January 19, 2014. http://www.futuretravelexperience.com/2013/04/copenhagen-airport-unveils-first-360-degree-wayfinding-app/.

Dunston, Phillip S, and Do Hyoung Shin. "Key Areas and Issues for Augmented Reality Applications on Construction Sites." In Mixed Reality in Architecture, Design and Construction, 156–170. Springer, 2009.

HeareApp English Introduction to Accessible Augmented Reality Audio Navigation, 2013. http://www.youtube.com/watch?v=WADdBJe32Ik&feature=youtube_gdata_player.

Höllerer, Tobias, and Steve Feiner. "Mobile Augmented Reality." Telegeoinformatics: Location-Based Computing and Services. Taylor and Francis Books Ltd., London, UK (2004). http://web.cs.wpi.edu/~gogo/courses/cs525H_2010f/papers/Hollerer_AR_2004.pdf.

Huang, Weidong, Leila Alem, and Mark Livingston. Human Factors in Augmented Reality Environments. London: Springer, 2013.

Information Intelligibility, 2013. http://www.youtube.com/watch?v=kQPxPF-If5I&feature=youtube_gdata_player.

insideAR 2012: Augmented Reality for Construction Planning Demo, 2012. http://www.youtube.com/watch?v=KYvJ9mI3cI4&feature=youtube_gdata_player.

Kipper, Greg, and Joseph Rampolla. Augmented Reality: An Emerging Technologies Guide to AR. 1st ed. Syngress, 2012.

Kolstee, Yolande, and Wim van Eck. "The Augmented Van Gogh's: Augmented Reality Experiences for Museum Visitors." In Proceedings of the 2011 IEEE International Symposium on Mixed and Augmented Reality–Arts, Media, and Humanities, 49–52. ISMAR-AMH '11. Washington, DC, USA: IEEE Computer Society, 2011. doi:10.1109/ISMAR-AMH.2011.6093656.

Le Hong, Hung, and Jackie Fenn. "Emerging Technologies Hype Cycle for 2013: Redefining the Relationship," August 21, 2013. www.gartner.com.

Mobile AR Visualization of Jätkäsaari/Kämp Tower Plans in Helsinki City, 2012. http://www.youtube.com/watch?v=c1DUkVhqVsM&feature=youtube_gdata_player.

Mobile AR Visualization of New Hotel Plans, 2011. http://www.youtube.com/watch?v=wvSPzG7AqLY&feature=youtube_gdata_player.

Mobile Augmented Reality for Building Maintenance, 2013. http://www.youtube.com/watch?v=uYFtYbqvoq0&feature=youtube_gdata_player.

Moloney, Jules. "Screen Based Augmented Reality for Architecture." 577–584, 2007. http://preserved.caadria.org/man/caadria2007_577.content.pdf.

Moloney, Jules, and Bharat Dave. "From Abstraction to Being There: Mixed Reality at the Early Stages of Design." International Journal of Architectural Computing 9, no. 1 (2011): 1–16.

Neumann, Ulrich, and Suya You. "Natural Feature Tracking for Augmented Reality." Multimedia, IEEE Transactions on 1, no. 1 (1999): 53–64.

"Obstacle: Definition of Obstacle in Oxford Dictionary (British & World English)." Accessed January 30, 2014. http://www.oxforddictionaries.com/definition/english/obstacle?q=obstacle.

"Opportunity: Definition of Opportunity in Oxford Dictionary (British & World English)." Accessed January 30, 2014. http://www.oxforddictionaries.com/definition/english/opportunity.

"Pedagogy Meets Big Data and BIM - Big Data, Sensing and Augmented Reality: Paper and Key Note Presentation." Digital Urban. Accessed September 11, 2013. http://www.digitalurban.org/2013/09/pedagogy-meets-big-data-and-bim-big-data-sensing-and-augmented-reality-paper-and-key-note-presentation.html.

Perey, Christine, and Graziano Terenzi. "Augmented Reality-Assisted 3D Visualisation for Urban Professional Users," 2013.

Regenbrecht, Holger, Gregory Baratoff, and Wilhelm Wilke. "Augmented Reality Projects in the Automotive and Aerospace Industries." IEEE Computer Graphics and Applications 25, no. 6 (December 2005): 48–56.

"RIBA Plan of Work 2013 Overview," n.d.

Royal Australian Institute of Architects, and Practice Services. You and Your Architect: Building Projects. Melbourne: RAIA Practice Services, 1994.

Schall, Gerhard, Stefanie Zollmann, and Gerhard Reitmayr. "Bridging the Gap between Planning and Surveying with Augmented Reality User Interfaces," 2011.

Seichter, Hartmut. "Augmented Reality Aided Design." The University of Hong Kong, 2007.

Siltanen, Sanni, and Valtion Teknillinen Tutkimuskeskus (VTT). Theory and applications of marker-based augmented reality, 2012.

Sinclair, Dale, ed. “BIM Overlay to the RIBA Outline Plan of Work.” RIBA Publishing, May 2012.

“SITA and Copenhagen Airport Launch the World’s First Indoor Augmented Reality Application | SITA.aero.” Accessed January 18, 2014. http://www.sita.aero/content/sita-and-copenhagen-airport-launch-world-s-first-indoor-augmented-reality-application.

Smart Reality - An Augmented Reality Solution for Visualizing the Job Site, 2013. http://www.youtube.com/watch?v=Ha7WpBdJSbo&feature=youtube_gdata_player.

Strange, Adario. “Apple Granted Patent for Head-Mounted Computing Device | News & Opinion | PCMag.com,” July 5, 2012. http://www.pcmag.com/article2/0,2817,2406706,00.asp.

Streetmuseum, 2010. http://www.youtube.com/watch?v=qSfATEZiUYo&feature=youtube_gdata_player.

“The Building Commissioning Guide.” http://www.wbdg.org/ccb/GSAMAN/buildingcommissioningguide.pdf, April 2005. http://www.wbdg.org/ccb/GSAMAN/buildingcommissioningguide.pdf.

The New IKEA Catalog App: Create Your Space, 2013. http://www.youtube.com/watch?v=uaxtLru4-Vw&feature=youtube_gdata_player.

The Visible City: Virtual Exhibition & Mobile App, 2013. http://www.youtube.com/watch?v=HyYgSBd_n5g&feature=youtube_gdata_player.

UAR Underground, 2012. http://www.youtube.com/watch?v=uqYAzkIhORE&feature=youtube_gdata_player.

“UCL Live Campus Augmented Reality App - Created by Masters Students at CASA.” Digital Urban. Accessed September 11, 2013. http://www.digitalurban.org/2013/06/ucl-live-augmented-reality-app-created-by-masters-students-at-casa.html.

Wang, Xiangyu. “Using Augmented Reality to Plan Virtual Construction Worksite.” International Journal of Advanced Robotic Systems 4, no. 4 (2007): 501–512.

Wang, Xiangyu, and Marc Aurel Schnabel. Mixed Reality in Architecture, Design and Construction. [Netherlands]: Springer, 2009.

Webster, Anthony, Steven Feiner, Blair MacIntyre, William Massie, and Theodore Krueger. “Augmented Reality in Architectural Construction, Inspection and Renovation.” In Proc. ASCE Third Congress on Computing in Civil Engineering, 913–919, 1996. http://www.columbia.edu/cu/gsapp/BT/RESEARCH/PAPERS/ar-asce.html.

“Wiki:armar - CGUI.” Accessed January 12, 2014. http://graphics.cs.columbia.edu/wiki/doku.php?id=wiki:armar.

Wilcox, David, Marvin Johnson, and Peter Carrato. “Augmented Reality: Bringing BIM to Life.” Journal of Building Information Modeling no. Fall 2012 (2012): 18–19.

You Will Want Google Goggles - MIT Technology Review. Accessed February 28, 2013. http://www.technologyreview.com/review/428212/you-will-want-google-goggles/.