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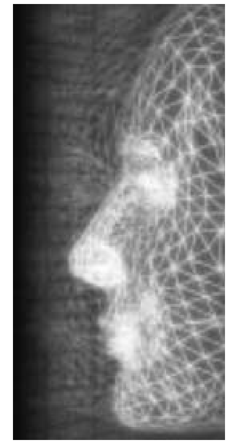
A survey of mobile and wireless technologies for augmented reality systems



By George Papagiannakis, Gurminder Singh and Nadia Magnenat-Thalmann*

Recent advances in hardware and software for mobile computing have enabled a new breed of mobile augmented reality (AR) systems and applications. A new breed of computing called 'augmented ubiquitous computing' has resulted from the convergence of wearable computing, wireless networking, and mobile AR interfaces. In this paper, we provide a survey of different mobile and wireless technologies and how they have impact AR. Our goal is to place them into different categories so that it becomes easier to understand the state of art and to help identify new directions of research. Copyright © 2008 John Wiley & Sons, Ltd.

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Introduction

For the last 40 years, interactive 3-D graphics have focused on the 'kinetic depth effect' so that the image presented by the three-dimensional display changes in exactly the same way that the image of a real object would change for similar motions of the user's head (Sutherland[1]). This basic metaphor has been the driving force behind 'virtual reality' and the immersion in virtual environments. This base idea was further enhanced to 'augment' the visual field of the user with information necessary in the performance of the current task, enabling an 'augmented reality' (AR) (Caudell and Mizell[2]). Although AR was meant to include mobility, it was not until 'The Columbia Touring Machine' by Feiner *et al*.[3] that the first outdoor mobile augmented reality system (MARS) was created. Around the same time as the development of MARS, research on wearable computers and personal imaging got started (Mann[4]). Wellner *et al*.[5] introduced the term 'computer AR' to include systems such as the augmented digital desk interface which enhances the physical world by superimposing computer generated scenes. The mixed reality–virtuality continuum has been consequently defined by Milgram and Colquhoun[6] based on the Extent of World Knowledge Continuum as depicted in the following, that is, the level that the depicted World is modeled in 3-D. Since this early work, researchers have been working to improve the methods and algorithms to allow convincing traversal of this MR continuum (Figure 1). Azuma *et al*.[7] have surveyed the MR continuum that included the notions of VR, AR, and augmented virtuality (AV).

At about the same time during the 1990s that AR research experienced the above renaissance, Weiser[8] conceptualized the idea of 'ubiquitous computing': an environment in which computing technology is embedded into all kinds of everyday physical objects, (such as appliances, doors, windows, or desks) which results in the 'computer disappearing into the background'. The opposition between the notion of virtual reality and ubiquitous, invisible computing is so strong that Weiser coined the term 'embodied virtuality' to refer to the process of drawing computers out of their electronic shells. Recently miniaturized mobile devices have extended their capabilities from simple communication devices to wearable, networked computational platforms. Mobile AR (Figure 2) can be viewed as the meeting point between AR, ubiquitous computing, and wearables.

Thus within the scope of this work, we define a mobile AR system (MARS) as the one which:

- Combines real and virtual objects in a real environment

*Correspondence to: G. Papagiannakis, MIRALab, University of Geneva, 7 Route de Drize, CH-1227, Carouge, Switzerland. E-mail: george.papagiannakis@miralab.unige.ch

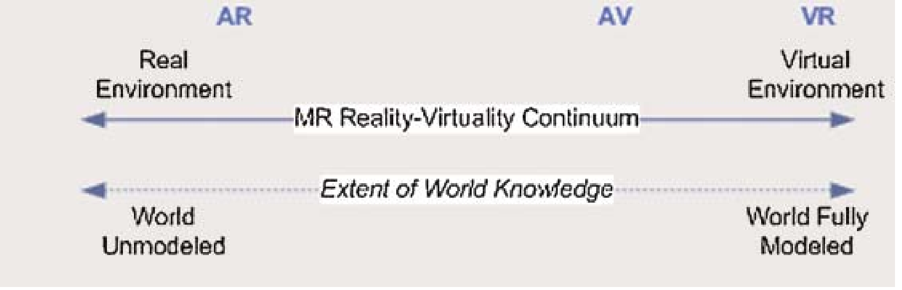

Figure 1. View of the MR continuum as originally defined by Milgram and Colquhoun.[6]

- Runs in real-time and mobile mode
- Registers(aligns) real and virtual objects with each other
- The virtual augmentation is based on dynamic, 3-D objects (e.g., interactive, deformable virtual characters)

The basic components of such a MARS include: (a) h/w computational platform, (b) display, (c) tracking, (d) tracking, (e) wireless network, (f) wearable input and interaction, and (g) software.

A successful MARS would enable the user to focus on the use of the system rather than its computing equipment. Ultimately the user should not be aware of presence computing equipment (Weiser[8]). With lightweight, wearable or mobile devices, and tracking technology embedded in the environment, it is becoming possible to achieve Weiser's vision. Recent advances in wireless technology are further supporting the creation of such environments. Since the focus of our paper is MARSs, we present the following enabling technologies:

- Mobile computational platform devices
- AR system architecture and Content
- Wireless networking

In our study, AR is treated as a user interface for both ubiquitous mobile computing as well as wearable computing since the real world is leveraged as in interface itself. An ideal MARS would include a pair of stylish sunglasses equipped with high-resolution 3-D graphics capabilities, built-in computer with wireless network support, and accurate 6 degree of freedom (DOF) tracking (Azuma *et al.*[9]). A mobile user would not need to wear or carry any further equipment in order to experience mobile AR (Hollerer[10]). All computation and sensing could be embedded in the environment itself as infrastructure. For example, cameras could cover all possible spaces, and distributed computation and displays stationed in the environment could provide AR augmentations. Already today wireless networking as well as GPS and Galileo coverage has started following this trend.

We present taxonomy of the research work that has been carried out in MARSs since the last significant survey of Sutherland[1] published in 2001. In the last few years there has been an explosive proliferation of wireless technologies, mobile devices, networking standards, and distributed computing power, allowing for new forms of such Augmented Ubiquitous Computing. The rest of this paper presents work in this area. While we try to be as complete as possible in our

Figure 2. Examples of Real, AR, and VR environments from a mobile AR system (images courtesy of Papagiannakis et al.[14]).

coverage, we have not attempted to cover all systems developed to date.

Section 'Enabling Technologies for MARSs' presents an overview of the various mobile AR enabling technologies. Since mobility is our focus, we begin by reviewing the state-of-the-art in mobile devices. There is a wide variety of hardware computing platforms used in mobile AR. We review these in Section 'Computing Hardware for Mobile AR'. The cost and effort in developing MARSs is quite high. To reduce these, a number of different software architectures and toolkits have been proposed. We provide a review of these in Section 'Software Architectures for Mobile AR'. Since mobility is a critical part of MARSs, a significant attention is devoted to wireless technologies in Section 'Wireless Networking for Mobile AR'. At the heart of AR is the registration of virtual augmentation correctly in the real world (Section 'Tracking and Registration for Mobile AR') and appropriately displaying the composition of the two worlds (Section 'Displays'). The recent advances in these mobile AR enabling technologies have allowed for a complete new breed of applications covered in Section 'Mobile AR: Applications and Challenges'. Finally in Section 'Discussion and Conclusions', we discuss and compare all recent advances in the previous domains and provide our recommendations for future research directions and synergies in the area of MARSs.

Enabling Technologies for Mobile AR Systems

Computing Hardware for Mobile AR

Mobile Workstation and Wearable PC. A number of systems (Tamura *et al.*[11], Cheok *et al.*,[12] Piekarski *et al.*,[13] Papagiannakis *et al.*,[14] Hughes *et al.*,[15] Weiser,[8] Schmeil and Broll,[16] Wagner and Schmalstieg,[17] and Egges *et al.*[18]) have employed mobile workstations (Figure 3), often aggregated together with other mobile equipment, in the form of a backpack (weighting 1–6 Kg), so that the user can freely move in the real environment and have their hands free for input and interaction. These backpacks include amongst others, mobile workstations such as Dell™ Inspiron and Precision, Alienware™, and JVC™ sub-notebooks. Although severe ergonomic issues are apparent due to the size and weight of the backpack, it allows researchers to focus on their research without the constraints that smaller devices often present, namely in the computational power, operating system, and hardware connectivity. Almost all of the desktop computing system can be made mobile by using high-end notebook computers. However, due to the backpack setup, the use of head mounted displays (HMDs) is enforced as opposed to handheld display that other devices can offer. The next step toward this direction is the employment of ultra mobile PCs (UMPCs), discussed in Section UMPC that could provide both handheld as well as HMD capabilities.

Tablet-PC. In an attempt to use mobile powerful handheld displays for AR, tablet-PCs have been employed in a number of MARSs (Klein and Drummond,[19] Stork *et al.*,[20] Zauner *et al.*,[21] and Renevier *et al.*[22]). A tablet-PC is a notebook or slate-shaped mobile computer which allows to be operated via a fingertip or stylus thus offering a more convenient way of interaction. Special tablet-PC editions of the Microsoft Windows™ and Linux™ OS have been mostly involved in the AR systems. The use of tablet-PCs eliminates the operating system and hardware shortcomings of small-size devices and the ergonomic issues of laptops inside backpacks.

Figure 3. Example of a mobile AR system based on a laptop, backpack, and video see-through HMD (images courtesy of Papagiannakis et al.[71]).

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Figure 4. Examples of handheld mobile AR devices: UMPC, PDA, and SmartPhone (images courtesy of Wagner and Schmalstieg[17]).

UMPC. A very recent trend in MARSs is the usage of UMPCs (Figure 4). UMPCs are based on the Microsoft Origami™ specification released in 2006 and have been developed jointly by Microsoft™, Intel™, and Samsung™, among others. UMPCs are basically small mobile PCs running Microsoft Windows XP. A number of researchers have started employing them in AR simulations such as Wagner and Schmalstieg,[17] Newman *et al*.,[23] and specifically the Sony Vaio™ U70 and UX180, as well as Samsung™ Q1. Elmqvist *et al*.[24] have employed the Xybernaut™ Mobile Assistant, which, although shares some common characteristics with UMPCs, does not belong in the UMPC category.

PDA. Before the recent introduction of UMPCs or SmartPhones with CPUs of significant compute power, personal digital assistants (PDAs) were the only truly mobile alternative for AR researchers. PDAs now have enhanced color displays, wireless connectivity, web-browser, and global positioning system (GPS) system. However, a number of computational issues make their use difficult for AR due to lack of dedicated 3-D capability and floating point computational unit. Goose *et al*.,[25] Reitmayr and Drummond,[26] Wagner and Schmalstieg,[17] Barakonyi and Schmalstieg,[27] Wagner *et al*.,[28] Gausemeier *et al*.[29] have all employed them as handheld display devices for AR applications, whereas Makri *et al*.[30] and Peternier *et al*.[31] allowed for a custom-made connections with a special micro-optical display as an HMD. The majority of these applications were developed on top of the Microsoft Windows Mobile™ OS.

Smartphone. Currently mobile phones are the most widely used device. Hence, their usage in MARSs would allow extending even more their range of applications and capabilities. Smartphones are fully featured high-end mobile phones featuring PDA capabilities, so that applications for data-processing and connectivity can be installed on them. Rashid *et al*.,[32] Wagner and Schmalstieg,[17] Henrysson *et al*.,[33] Olwal[34] utilize them as final mobile AR displays. They are also often used in conjunction with a stationary server, as in the case of Rauhala *et al*.,[35] where a notebook PC was also used as an intermediate central data processing unit. As the processing capability of smartphones is improving, their application use is increasing. Jonietza[36] uses their smartphone to calculate the location of just about any object its camera is aimed at. As the smartphone changes location, it retrieves the names and geographical coordinates of nearby landmarks from an external database. The user can then download additional information about a chosen location from the Web—say, the names of businesses in the Empire State Building, the cost of visiting the building's observatories, or hours and menus for its five eateries. The most often used operating systems upon which these AR applications were build include Symbian™, Windows Mobile™, and the Linux™ OS.

Software Architectures for Mobile AR

In this section, we review the recent AR software system architectures beyond those initially introduced by Feiner *et al*.,[3] Tamura *et al*.,[11] and Billinghurst *et al*.[37] covered in the survey of Sutherland[1]. The reviewed frameworks in this section feature basic kernel, networking, display, tracking, and registration components based on hybrid methods (sensor and vision-based), allowing for the prototyping of different AR applications as a result of their toolkit, plug-in architecture. This is how most new architectures are different from old mobile AR architectures that were built as single monolithic pieces of software.

Schmalstieg *et al*.[38] introduced the 'Studierstube' collaborative AR platform, based on a heterogeneous distributed architecture. Studierstube's software development environment has been realized as a collection of C++ classes built initially on top of the open inventor (OIV) scenegraph toolkit and later on top of Coin3D. Applications are written and compiled as separate shared objects and dynamically loaded into the run-time framework. A safeguard mechanism makes sure that only one instance of each application's code is loaded into the system at any time. Besides decoupling application development from system development, dynamic loading of objects also simplifies distribution, as application components can be loaded by each host whenever needed. Studierstube is intended as an application framework that allows the use of a variety of displays with a variety of tracking devices with the concept of a distributed shared scene graph, similar to distributed shared memory. From the application programmer's perspective, multiple workstations share a common scene graph. Numerous mobile AR applications have been built based on this architecture such as Wagner *et al.*,[28] Reitmayr and Drummond,[26] and Newman *et al.*[23]

Ponder *et al.*[39] aimed to address some of the most common problems related to the development, extensions, and continuous need of integration of heterogeneous simulation technologies under single system roof. VHD++ combined both framework (complexity curbing) and component (complexity hiding)-based development methodologies. In effect large-scale architecture and code reuse is achieved adding to development efficiency and robustness of the final both AR and VR virtual character applications. The (now open-source under LGPL license) VHD++ framework provides an efficient research environment (a) offering full power to researchers and at the same time (b) allowing them to publish their research results in form of ready to use, plug-able Services (plug-ins encapsulating heterogeneous technologies) that are plugged to the generic runtime engine. Currently the list of Services that encapsulate the heterogeneous technologies emphasize on virtual character simulation such as facial and body animation, deformation, speech, cloth simulation, AR marker, and markerless tracking, scripting etc. A number of AR applications were based on this framework such as those by Papagiannakis *et al.*[14] and Egges *et al.*[18]

Building complex VR/AR applications usually is a time-consuming task, even if only a small part of the system functionality is to be evaluated. Using the MORGAN framework developed by Ohlenburg *et al.*,[40] distributed multi-user VR/AR applications can be implemented much faster. MORGAN is a component-based framework that relies on the CORBA middleware for network communication. It currently supports many devices, including mouse and keyboard as well as haptic input devices, object tracking systems, and speech recognition libraries. Thus, multimodal user interfaces can be rapidly developed and evaluated. Additionally, MORGAN provides a distributed render engine with automatic scene graph synchronization capabilities where all components are accessible from remote computers.

Weiser[8] built a series of MARSs prototypes, starting with extensions to the 1997 'Touring Machine' from Feiner *et al.*[3] and leading up to their most recent system, MARS 2002. This featured a shared central Java and Java3D infrastructure which enables AR, VR, and desktop-based indoor/outdoor communication. Important features of this architecture are the central database and networking server for inter-process communication and the relational database backend for persistent data storage. The platform allowed for indoor/outdoor tracking, navigation, and collaboration based on hybrid User Interfaces (2-D and 3-D). As AR interfaces have to consider both virtual and physical objects and potentially a multitude of devices (input and output) visuals become easily cluttered and overwhelming. A main innovation from this system was a rule-based architecture for adaptive MARS interfaces and UI management.

Hughes *et al.*[15] utilize their own MR Software Suite (MRSS) for the development and delivery of their MR experiences. The main system consists of four sub-systems called Engines: three rendering engines for visual, audio, and special effects multimodal simulation and a fourth integration engine combining the above in interactive, nonlinear scenarios. The central networking protocols receive and integrate sensor data such as tracking, registration, and orientation with input from other sources, for example, artificial intelligence and specialized physics engines, and execute a nonlinear, interactive script. This then produces a multimodal simulation situated within real world conditions based on the rendering and display technology available. The key technologies used in this MR system are Open Scene Graph and Cal3D for graphics, Port Audio for sound, and a DMX chain for talking to special effects devices. The network protocol is built on top of TCP/IP. Authoring of stories is done in XML, which can include C or Java-style advanced scripting. The MR system can run stand-alone (one user) or in combination with multiple MR systems (each managing one or more users).

Wagner and Schmalstieg[41] recently introduced Muddleware, a communication platform for mixed-reality multiuser games that is light-weight and highly portable, as shown in several MR game projects that was employed. A hierarchical database built on XML technology allows convenient prototyping and simple, yet powerful queries. Server side-extensions address persistence and autonomous behaviors through hierarchical state machines. The core of Muddleware is a memory-mapped database that provides persistence and can be addressed associatively using XPath. Clients connect to the server by any of four APIs: Immediate C++, Shared Memory C++, Java, and Muddleware Script. All data elements are stored as nodes of a modified XML DOM. Clients store arbitrary messages as XML fragments, and use XPath to specify query or update operations. A simple benchmark by the authors showed that its XML server can easily handle thousands of complex requests per second.

An integrated and uniform approach for building mobile applications for mixed reality environments has also been presented by Piekarski and Thomas[42] as an evolution of previous AR applications. The architecture uses a data flow methodology with an object-oriented design aiming to provide a simple model for programmers to re-use as well as compose new AR applications. Using this toolkit approach, a number of kernel features such as distributed programming, persistent storage, and run time configuration are possible. The design is based on the C++ language and the capabilities of this software architecture are demonstrated by the Tinmith-Metro mobile outdoor modeling application, as well as other AR examples (AR-Quake game etc.).

Wireless Networking for Mobile AR

This section will discuss the impact of wireless networking in AR. Wireless network characteristics differ quite markedly from wired in latency, bandwidth, bandwidth fluctuations, and availability. These have direct impact on the performance and quality of user experience in AR. In addition, there are many different types of wireless networks available. These impact the types of applications that can be developed. To support a usable AR system, a wireless network should provide sufficient data rate, low latency, and support for mobility. The ability to be mobile by itself introduces several new application possibilities but when combined with the knowledge of location, the same applications can become more useful and exciting. In the following sections, we present how different types of networks support these key requirements.

Wireless WANs and 3G Networking. The wireless wide area networks (WWANs) are ideal for AR systems that need to support large-scale mobility, for example, nationwide or in a large city. Systems that provide location-based services are a very good example of such an application. The prototype system developed by Nokia in which the phone can calculate the location of just about any object its camera is aimed at (Jonietza[36]) falls in this category. As the phone changes location, it retrieves the names and geographical coordinates of nearby landmarks from an external database. The user can then download additional information about a chosen location from the Web—say, the names of businesses in the Empire State Building, the cost of visiting the building's observatories, or hours and menus for its five eateries. To be useful the system needs to support large-scale mobility.

In the WWAN category, there are several choices available from the slow speed of 9.6 kbps to high speeds of the third generation (3G) of 2 mbps. While the availability of slow speed 2G WWANs such as GSM and code division multiple access (CDMA) is widespread, due to their slow speed and high latency, they are limited in their use for AR. It is possible to use such networks to implement applications where much of the data is local and little needs to be sent over the network. This scenario is very similar to early days of networked virtual reality systems which used modem-based slow speed connectivity for sharing data such as in NetEffect (Das *et al.*[43]).

Viktorsson and Borg[44] make an interesting use of the subscriber identity module (SIM) card used in GSM phones. SIM card is typically used by the user to store his personal information such as contact information of people he knows, his preferences, and other personal information. Information about avatar characteristics for a user can also be stored in a SIM card. It can then be moved from one access terminal to another. A virtual world, which the avatar is designed to enter, can then be accessed from many different access terminals by means of inserting the SIM card and entering a personal identity number (PIN) code. Thus, besides making it possible to access a virtual world from different access terminals, this technique also makes it possible to use avatars in new applications.

Beyond 2G, we have the 2.5G and 3G WWANs which are designed to support multimedia applications by

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providing better network infrastructure. As a result, these networks should also provide better support for networked AR systems. An example of a system which runs on 3G phones and requires the high data rates of 3G networks but not necessarily their support for mobility is the virtual disco system by Artificial Life (http://www.3g.co.uk/pr/jan2005/9022.htm). The 3G virtual disco is presented to the users as a 3-D animated virtual building with several floors representing different music clubs and styles of music according to the selection and tastes of the listeners. In the intro sequence the user can select an animated 3-D character (avatar) as his or her virtual persona and visit the different music rooms in the virtual disco. Users can download or stream music in combination with high quality 3-D animation clips showing synchronized dancing avatars.

General packet radio service (GPRS) is considered as a 2.5G network and is built on top of a GSM network. The theoretical maximum data rate of a GPRS network can be as high as 171.2 kbps, but in practice, per connection, typically much lower data rate is available. Often, this is because of the limitations of the network infrastructure. In addition, the downlink and uplinks data rates are also significantly different, with uplink data rate being lower. Beyond data rates, the telecommunication operators have significant control over other quality of service (QoS) parameters, including priorities for services, transmission delay between different stations, and reliability of packet transmission. By controlling these parameters the performance of the network can be tuned for different purposes such as the number of connections the network can support, and QoS for services running on the network. As expected, the operators would optimize their network for supporting maximum connection as it results in higher revenue for the operator. This leads to not only low data rates but also high latency. Highly interactive, multi-user VR environments require that end-to-end latency remain less than 100 milliseconds (Smed *et al.*[45] and Pantel and Wolf[46]). This low level of latency is not supported by most 2.5G networks.

A few evaluation studies have been reported that measure the performance of network VR services on wireless WANs. Perovic *et al.*[47] have tested the performance of three VR systems over a GPRS network. In their GRPS network, the uplink data rate supported by the network was 44.8 kpbs while the uplink was 11.2 kpbs. Their VR applications included a multi-user community where users could see each other's avatars, a conversational virtual character and a 3-D multi-user game. As expected, with low data rates and high latency, they found the GPRS network to be insufficient for supporting the networked VR applications.

Goseta *et al.*[48] have done an experimental performance evaluation of networked VR systems in universal mobile telecommunication system (UMTS) network. UMTS is considered a 3G network. The UMTS core network is based on GPRS network toology but differs in its air interface transmission. The air interface access method for UMTS is based on wide-band CDMA whereas GPRS is based on time division multiple access (TDMA) and frequency division multiple access (FDMA). The theoretical maximum data rate in a UMTS network is 2 mbps. However, due to the current mobile phone limitations, data rates higher than 384 kbps cannot be supported. For a large number of interactive, multi-user VR environments, this data rate works well, but high latency (round trip time 300–580 milliseconds) in UMTS networks cause problems in implementing real-time services in VR environments. A number of location-based mobile games have been developed over the last few years which either use GPS or triangulation techniques based on cell-towers for location and a WWAN for networking.

WLANs. Wireless local area networks (WLANs), as the name suggests, are wireless networks implemented in a local area such as a home or an office building. WLANs typically will support much higher data rates (between 11 and 54 mbps) and lower latency than WWANs but their support for mobility is limited than in WWANs. Currently, WLANs can be built using any of the IEEE 802.11a/b/g/n standards compliant equipment.

Human Pacman (Cheok *et al.*[12,49]) is an interactive role-playing, physical fantasy game integrated with human-social and mobile-gaming that emphasizes on collaboration and competition between players. By setting the game in a wide outdoor area, natural human-physical movements become an integral part of the game. In Human Pacman, Pacmen and Ghosts are human players in the real world who experience mixed reality visualization from wearable computers. Virtual cookies and actual physical objects are incorporated to provide novel experiences of seamless transitions between real and virtual worlds and tangible human computer interface, respectively. Human Pacman uses WLAN technology to enable mobility in small-scale environments.

While the transmission range of one WLAN base station or access point is typically 100 m, a number of access points can be used to provide coverage in much

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larger areas. Using the approach, currently there are efforts underway to provide WLAN coverage in entire cities. In this scenario, WLANs can be seen to be competing with 3G networks which are designed to provide WWAN capability (Ferguson[50]). As the two wireless networking technologies begin to co-exist, it is useful to allow the VR environment to operate on whichever connection is connection is available at the time of operation and to be able to operate on cheaper connections. In the current state of the art, WLANs are significantly cheaper in cost than WWANs.

McCaffery and Finney[51] have developed a wireless overlay network concept which allows the application to select the most appropriate of a number of different network technologies as the mobile device moves around in the environment. The migration between different networks happens transparently to the application. To test their overlay network, they have developed a Compaq iPAQ-based first person shooter game called Real Tournament (Mitchell *et al*.[52]). For this game, their overlay network works on top of IEEE 802.11b and GPRS.

WLAN capability in game machines has become very popular. As a result, many of the new game machines now come with built-in support for WLANs or provide attachments for WLANs. Wi-Fi Max for Sony PSP is a good example of such an attachment. By plugging-in Wi-Fi Max into an Internet-enabled PC, one can create a wireless access point. Five PSP machines can wirelessly connect to this access point and play games with one another as well as with other Internet PSP players. Similarly Microsoft Xbox 360 can be made WLAN ready by installing a Wi-Fi adapter card in it.

WPANs. The wireless personal area networks (WPANs) are short-range (typically a few meters), high-bandwidth wireless networks used for applications such as printing, file transfer, and remote control. Often WPANs are implemented using Bluetooth or infrared communication technologies. In VR, WPANs have been extensively used in combination with PDAs to interact with 3-D VR environments. To control 3-D environments, users often need to provide inputs through buttons, sliders, and menus. Such input can be provided through a handheld device which can communicate with the VR environment through WPANs.

Watsen *et al*.[53] have investigated the contention between 2-D and 3-D interaction metaphors and involved the use of a 3Com PalmPilot handheld computer as an interaction device to the VE, allowing the use of 2-D widgets in a 3-D context. Tweek (Hartling *et al*.[54]) presents users with an extensible 2-D Java graphical userinterface (GUI) that communicates with VR applications. Using Tweek, developers can create a GUI that provides capabilities for interacting with a VE. Tweek has been used in VR Juggler (Bierbaum[55]), an open source virtual reality development tool. More recently, use of handheld devices and WPANs has been extended to interaction with real-world scenarios. For example, Ubibus (2004)[56] is designed to help blind or visually impaired people to take public transport. The application allows the user to request in advance the bus of his choice to stop, and to be notified when the right bus has arrived. The user may use either a PDA (equipped with a WLAN interface) or a Bluetooth mobile phone. The system is designed to be integrated discretely in the bus service via ubiquitous computing principles. It tries to minimize both the amount of required changes in the service operation, and explicit interactions with the mobile device. This is done by augmenting real-life interactions with data processing, through a programming paradigm called spatial programming.

Tracking and Registration for Mobile AR

AR requires very accurate position and orientation tracking in order to align, or register, virtual information with the physical objects that are to be annotated. Without this, it is rather difficult to trick the human senses into believing that computer-generated virtual objects co-exist in the same physical space as the real-world objects. There are several possibilities for classifying tracking methods. First, technological characteristics can be used to differentiate between the approaches. Another criterion is the applicability in different environments like indoor or outdoor, or the granularity of the determination of the position or the inclusion of the position together with the orientation within the physical space can be administered.

This section outlines the tracking strategies used in recent MARSs. A wide range of both visual and non-visual tracking technologies, such as magnetic and ultrasound, have been applied to AR as already described in recent surveys from Sutherland,[1] Azuma *et al*.[9] and Weiser[8]. More specifically, Piekarski and Thomas[42] provide an extensive comparison of recent tracking methods and sensors, categorized based on their (a) accuracy, (b) resolution, (c) delay, (d) update

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Technology	Range (m)	Setup (hour)	Resolution (mm)	Time (seconds) (in which useful tracking occurs, i.e., before drift)	Environment
Magnetic	1	1	1	∞	In/Out
Ultrasound	10	1	10	∞	In
Inertial	1	0	1	10	In/Out
Accelerometer	1000	0	100	1000	In/Out
UWB	100	10	500	∞	In
Optical: outside-in	10	10	10	∞	In
Optical: marker-based	10	0	10	∞	In/Out
Optical: markerless	50	0–1	10	∞	In/Out
Hybrid	10	10	1	∞	In
GPS	∞	0	1000	∞	Out
Wi-Fi	100	10	1000	∞	In/Out

Table 1. Comparison of tracking technologies (adapted from DiVerdi and Höllerer[58])

rate, (e) infrastructure and operating range, (f) cost, (g) degrees of freedom, and (h) portability and electrical power consumption. However, the low cost of video cameras and the increasing availability of video capture capabilities in off-the-shelf PCs has inspired substantial research into the use of video cameras as means for tracking the position and orientation of a user (Klein[57]). A recent comparison from DiVerdi and Höllerer[58] has been adapted for our survey and presented in Table 1.

Tracking With GPS, GSM, UMTS. Probably, the most predominant system for outdoors tracking is the GPS (Intermedia[59]). GPS is a time measurement-based system and can be applied in almost all open space environments except narrow streets or covered sight to the sky due to trees or other obstacles to receive the signals from at least four satellites. The accuracy of the localization can vary between 3 and 10 m depending on the satellite connection and the continuity of the navigation of the receiver. The accuracy can be increased by so called differential GPS (D-GPS) by terrestrial stations to an accuracy of 2–5 m. GPS receivers are becoming less and less expensive as they are introduced in mass-market devices such as PDAs and mobile phones. Schmeil and Broll[16] employed standard GPS for outdoors location tracking and a 3-DOF orientation tracker mounted on the HMD for orientation tracking and registration of a virtual guide on the real outdoors environment. Azuma *et al.*[60] presented a method to enhance the position tracking accuracy of GPS, for more accurate and believable registration for MARSs. They propose a new hybrid tracking system of improved accuracy for military operations, where an AR helmet has three rate gyroscopes, two tilt sensors, a GPS sensor, and an infrared camera that occasionally observes small numbers of mobile infrared beacons added to the environment which help to significantly correct the sensor errors.

Another upcoming solution is locating users by triangulating signals of their GSM mobile phones. However, the accuracy of this localization method is quite crude and subject to huge variations. In particular in rural areas with wide phone ID cells the accuracy is not acceptable. With the advent of the 3G mobile standard UMTS, the accuracy of localization will improve significantly.

Outside-in and Inside-out Tracking. Tracking a user with an external camera is an example of outside-in tracking, where the imaging sensor is mounted outside the space tracked. Outside-in tracking can be used to produce very accurate position results—especially when multiple cameras observe the tracked object. In inside-out systems, the imaging sensor is itself head-mounted and any rotation of the user's head causes substantial changes in the observed image. Klein,[57] Weiser[8] and Sutherland[1] provide a comprehensive overview of latest inside-out as well as outside-in tracking methods, not limited only to MARSs.

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Visual Marker-Based Tracking. A still common approach for more demanding AR applications is to make use of fiducials: easily recognizable landmarks such as concentric circles placed in known positions around the environment. Such fiducials may be passive (e.g., a printed marker) or active (e.g., a light-emitting diode); both types of fiducial have been used in AR applications. While many passive fiducial-based tracking implementations for AR exist, none can match the ubiquity of the freely available ARToolkit system. Tamura *et al.*,[11] Billinghurst *et al.*,[37] Wagner and Schmalstieg,[17] Newman *et al.*,[23] Henrysson *et al.*,[33] Cheok *et al.*,[12] Barakonyi and Schmalstieg,[27] and Goose *et al.*[25] have employed various versions of ARToolkit in the range of mobile devices that are covered in Section 'Computing Hardware for Mobile AR'. Makri *et al.*[30] have employed their own visual marker-based tracking methods on MARSs.

Visual Markerless Tracking. A number of recent visual tracking algorithms as described by Klein[57] can provide realistic real-time camera tracking based on different approaches (natural feature detection, edge detection, planar methods etc.) but require large amounts of processing power posing difficulties on the additional AR rendering tasks.

Stork *et al.*[20] employed a planar surface tracking algorithm, where 3-D planes of building facades are used to recover the camera pose, by tracking natural features extracted from them. Vacchetti *et al.*[61] employ another markerless tracking algorithm suitable for mobile AR, where it starts from 2-D matching of interest points, and then it exploits them to infer the 3-D position of the points on the object surface. Once the 3-D points on the object are tracked it is possible to retrieve the camera displacement in the object coordinate system using robust estimation.

In Papagiannakis *et al.*,[14] a robust markerless real-time visual tracking method was introduced based on the Boujou system from 2D3™ which can recover from complete occlusion or extreme motion blur within one frame. At a first pre-processing stage of the scene-to-be-tracked, a model of the scene which consists of 3-D coordinates together with invariant descriptors for the feature appearances is automatically created based on Structure-from-Motion techniques. During real-time operation, this database is traversed and compared against the real-time detected scene features, providing the estimated camera matrix.

Klein and Drummond[19] employed an edge-based tracking system mounted on a tablet-PC for visual inside-out tracking. The tracking system employed relies on the availability of a 3-D model of the scene to be tracked. This 3-D model should describe all salient edges and any occluding faces. Using a predicted estimate of the camera pose, an estimate of the tablet camera's view of the model can be recovered at each frame.

Sensor-Based Tracking. Infrared LEDs can output light across a very narrowly tuned wave-band, and if this band is matched at the sensor with a suitable filter, ambient lighting can be virtually eliminated. This means the only thing visible to the imaging sensor is the fiducials, and this vastly reduces the difficulty and computational requirements for tracking. For this reason, LEDs have long been used in commercially available tracking systems and real tracking applications; Olwal[34] employed IR-LEDs for robust tracking of mobile phones, based on the vision of spatially aware handheld interaction devices. Based on outside-in tracking methods they allowed for the augmentation of a real map with digital content in a focus + context fashion.

Radio frequency identification (RFID) tags have also been recently used in MARSs. RFIDs consist of a simple microchip and antenna which interact with radio waves from a receiver to transfer the information held on the microchip. RFID tags are classified as either active or passive, with active tags having their own transmitter and associated power supply, while passive tags reflect energy sent from the receiver. Active RFID tags can be read from a range of 20 to 100 m where passive RFID tags range from a few centimeters to around 5 m (depending on the operating frequency range). Rashid *et al.*[32] employed mobile phones that incorporate RFID readers for creating games in which players interact with real physical objects, in real locations.

A recent promising technology for wide-area indoor tracking is the commercially available Ultra-Wide-Band (UWB) local positioning system by Ubisense™ (Steggles and Gschwind[62]). Based on network of small-size sensors and tags this system allows for estimating the 3-D position of a tag within 15 cm accuracy of tens of meters distance of a tag from a sensor.

Wireless-LAN Tracking. Due to the fact that networked mobile AR users are enabled with wireless radio communication network interfaces (such as Wi-Fi), protocols that provide location estimation based on the received signal strength indication (RSSI) of wireless access points have been recently becoming increasingly accurate, sophisticated, and hence, popular. The main benefit of RSSI measurement-based systems is that they

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do not require any additional sensor/actuator infrastructure but use already available communication parameters and downloadable wireless maps for the position determination. Their shortcoming for mobile AR is precision and often multiple access points as well as tedious training offline phases for the construction of the wireless map. Peternier *et al*.[31] employed a Wi-Fi-localization-based method for a PDA-based Mixed-Reality system for visualizing virtual character 3-D content. Liu *et al*.[63] describe a Wi-Fi-localization algorithm based on a single access-point infrastructure as navigational aid.

Hybrid Tracking Systems. The use of inertial sensors such as rate gyroscopes and accelerometers is wide-spread in virtual and AR applications. Visual tracking systems perform best with low frequency motion and are prone to failure, especially given rapid camera movements, such as may occur with a head-mounted camera. Inertial sensors measure pose derivatives and are better suited for measuring high-frequency, rapid motion than slow movement where noise and bias drift outweigh. The complementary nature of visual and inertial sensors has led to the development of a number of hybrid tracking systems. Their ultimate goal is 'anywhere augmentation' as specified in DiVerdi and Höllerer,[58] where their hybrid tracking system for mobile AR consists of a camera facing the ground and orientation tracker inspired by the workings of an optical mouse, providing very accurate tracking resolution both indoors/outdoors in the expense of specific h/w setup. In order to tackle efficiently the mobility and robustness of an indoor mobile AR-system, an aggregation of tracking sensors/methods such as UWB position and accelerometer orientation sensors together with fiducial markers was exhibited by Newman *et al*.[23]

Displays

There are many approaches to displaying information to a mobile person and a variety of different types of displays can be employed for this purpose, such as, personal handheld, wrist-worn, or head-worn displays; screens and directed loudspeakers embedded in the environment; and, image projection on arbitrary surfaces; to name but a few. Several of these display possibilities may also be used in combination. AR displays utilized in recent MARSs can be fundamentally split into two categories: optical see-through displays with which the user views the real world directly (such as Micro-Vision Nomad, TekGear Icuiti, or EyeTop), and video see-through displays with which the user observes the real world in a video image as acquired from a mounted camera (such as Trivisio AR-Vision and i-glasses PC). There are various issues associated with both types of displays as recently reviewed by Piekarski and Thomas[42] such as (a) technological: latency, resolution-distortion, field of view, and cost, as well as (b) perceptual: depth of field, qualitative, and finally, (c) human factors: social acceptance and safety. One of the current trends for mobile AR is the fusion of different display technologies with wearable computing (Weiser[8],). Head-worn displays provide one of the most immediate means of accessing graphical information since the viewer does not need to divert his or her eyes away from their object of focus in the real world and if they are worn as part of a wearable system (i.e., not as part of a helmet) can even assume social acceptance beyond the AR prototype stage. The immediacy and privacy of a personal head-worn display is complemented well by the high text readability of handheld displays in collaboration with wall-sized displays. The attractiveness of mobile AR relies on further progress in this area, as for example, the new dedicated for AR OLED-based HMDs that appear in Stork *et al*.[20]) as well as Makri *et al*.[30] by Trivisio™.

Wearable Input and Interaction Technologies

Piekarski and Thomas[42] define a wearable computer to be a self powered computing device that can be worn on the body without requiring the hands to carry it, and can be used while performing other tasks. It should thus be worn like a piece of clothing, as unobtrusive as possible. Key factors amongst others are comfort, weight, size, mobility, and esthetics. How to interact with wearable computers effectively and efficiently is an area of active research. Mobile interfaces should try to minimize the burden of encumbering interface devices. The ultimate goal is to have a free-to-walk, eyes-free, and hands-free interface with miniature computing devices worn as part of the clothing. This ideal wearable MARS cannot be reached yet with current mobile computing and interface technology. Weiser,[8] Piekarski and Thomas,[42] Kölsch *et al*.,[64] and Revenier *et al*.[22] provide overviews of recent approaches on multimodal input and interaction technologies for wearables which extends the scope of the current survey. Readers are encouraged to refer to these works for further details.

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Some devices already nicely meet the size and ergonomic constraints of mobility: auditory interfaces, for example, can already be realized in an inconspicuous manner, with small wireless hands-free earphones and microphones are barely noticeable. AR characters are envisaged to assume new roles as central interfaces on such wearable systems, based on natural language-based communication and interaction patterns similar to the ones observed between real humans.

Furthermore, recent clothes manufacturers have gradually started creating clothes with special focus on allowing the efficient incorporation, carriage and operation of mobile devices such as iPods, PDAs, or SmartPhones such as the jackets from Zegna™ (i-jacket) or Scottvest™ (v3 jacket). As a wearable computer is a very personal device, it should be worn like a piece of clothing, as unobtrusive as possible so that a user could interact with this computer based upon context. Mann[4] in his early vision of wearable computing presents the miniaturization of hardware components and their fusion with clothing, as the main factor allowing individuals to freely move about and interact supported by their personal domain. In the forthcoming mobile AR networked media environments, overcoming information overload and access complexity via natural conversation with wearable, incorporated in everyday clothes companions can play decisive roles as new personalized information interfaces.

Mobile AR: Applications and Challenges

This section presents the recent advances as well as new additions to the applications areas where MARSs are used. This is not an extensive chronological list as we mainly aim to complement the most recent surveys from Azum a *et al.*[7,9] studying the convergence of the AR, ubiquitous, and wearable computing. The main mobile AR applications studies that this survey covers are:

- Virtual character-based applications for AR
- Cultural heritage
- Edutainment and games
- Navigation and path-finding
- Collaborative assembly and design
- Industrial maintenance and inspection

The above constitute research directions that are already identified and aimed to drive further the area of augmented ubiquitous computing. In this manner, augmented ubiquitous computers will help overcome the problem of information overload. There is more information available at our fingertips during a walk in the woods than in any computer system, yet people find a walk among trees relaxing and computers frustrating (Weiser[8]). Machines that fit the human environment, instead of forcing humans to enter theirs, will make using a computer as refreshing as taking a walk in the woods.

Virtual Characters in AR

Virtual Characters have already been synthesized with real actors in common non-real-time mixed reality worlds, as illustrated successfully by a number of cinematographic storytelling examples. One of the earliest research-based examples was and the virtual 'Marilyn Monroe' as appearing in the research film 'Marilyn by the lake' by MIRALab, University of Geneva as well as Balcisoy *et al.*[65] However, these 'compositing' examples involve non-real-time (offline) pre-rendered simulations of virtual characters and mostly are rendered and post-processed frame by frame in an ad-hoc manner by specialized digital artists or compositors as they are termed in the industrial domain of special effects (SFX). The active SFX sector with applications in film, television, and entertainment industry has exemplified such compositing effects in a constantly growing list of projects.

In this survey, we study the recent surge of employing virtual characters in MARSs (Figure 5). A first such real-time example in a mobile setup employed virtual creatures in collaborative AR games (Hughes *et al.*[15]) as

Figure 5. Real-time virtual characters in AR (images courtesy of Papagiannakis et al.[71] (left) and Wagner et al.[28] (right)).

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well as a conversational and rigid-body animated characters, during a construction session (Tamura *et al.*,[11] Cheok *et al.*[12]). In cultural heritage sites, a recent breed of MARSs allows for witnessing ancient virtual humans with body animation, deformation, and speech, re-enacting specific context-related scenarios (Papagiannakis *et al.*[14]) as well as allowing visitors to interact and further enquire on their storytelling experience (Egges *et al.*[18]). An important aspect of such AR examples is that these virtual characters are staged in scenario-based 'life-size' scaling, position orientation as a result of markerless AR tracking and registration. Further recent examples of marker-based tracking such as ARToolkit, various researchers employed dynamic content on top of such markers, such as 3-D storytelling book content (Billinghurst *et al.*[37]) and other interactive characters reacting to user's actions (Barakonyi and Schmalstieg,[27] Wagner *et al.*[28]). Very recent examples include also the use of virtual characters as outdoor navigation guides (Schmeil and Broll[16]).

Cultural Heritage

MARSs are increasingly being tested in rich content environments, as they can enable visualization of 'unseen' valuable and complex 3-D content as well as provide added edutainment-value in today cultural heritage sites. The shift that the cultural heritage sector is currently facing in its traditional economic paradigm combined with the increasing digitization efforts allow for AR interfaces to be used as ideal and novel showcases of both tangible (objects, static edifices) and intangible (ceremonies, customs, myths) cultural artifacts. In particular, mobile AR guides were employed in the site of ancient Olympia, Greece in order to visualize the non-existing ancient temple edifices (Vlahakis *et al.*[66]), and in Pompeii, Italy to visualize ancient Roman characters reenacting stories based on the site frescoes (Papagiannakis *et al.*[14]). Illustrate examples of a MARS in ancient Pompeii.

Navigation and Path Finding

MARSs have also been widely employed for mobile navigation assistance. Such systems typically involve a hardware device as described in Section 'Computing Hardware for Mobile AR' and based on an AR platform similar to those as described in Section 'Software Architectures for Mobile AR', they allow for multimodal navigation AR aid while traversing physical buildings or outdoor locations. As shown in different approaches are followed based primarily on whether indoors or outdoors AR navigation is needed. Weiser,[8] Elmqvist *et al.*,[24] Olwal,[34] and Newman *et al.*[23] work indoors while Bell *et al.*,[67] Reitmayr and Drummond[26] and Azuma and Leonard[60] are employed outdoors. Absolute tracking and registration remains still an open issue and recently it has mostly been tackled by no single method, but mostly with an aggregation of tracking and localization methods, mostly based on handheld AR. A truly wearable, HMD-based mobile AR navigation aid for both indoors and outdoors with rich 3-D content remains still an open issue and a very active field of multi-discipline research.

Edutainment and Games

Magerkurth *et al.*[68] present an overview of pervasive gaming containing a section on AR Games (Figure 6). Recently AR multi-user games appeared based on generic AR frameworks (Wagner and Schmalstieg[41]). Traditional 2-D games also find their application in mobile AR, based on the well-known 'Pac-Man' gaming genre (Cheok *et al.*,[12] Rashid *et al.*,[32] and Klein and Drummond[19]). Mobile phones have also been used as kineasthetic AR interfaces in an AR tennis game (Henrysson *et al.*[33]). Based on the 'Shoot'em up' computer gaming genre, several AR games have been realized using MARSs, such as those described in Hughes *et al.*[15] and Piekarski and Thomas[42]. The main unsolved research issues include multiple, interactive virtual characters in AR, common-vision collaborative games as well as convincing illumination registration and real-time rendering.

Collaborative Assembly and Construction

One of the main features of mobile collaborative AR is that the augmentation of the real world is adapted according to multiple-user location and knowledge. Renevier *et al.*[22] exhibited such a MARS for both archaeological field work as well as asynchronous collaborative game. Furthermore, the industrial CAD design field has also recently benefited from MARSs (Stork *et al.*[20]) allowing multiple users to reviews complex 3-D CAD architectural or automotive industry models. Finally in the filed of on-site collaborative AR and construction, Piekarski and Thomas[42] employed

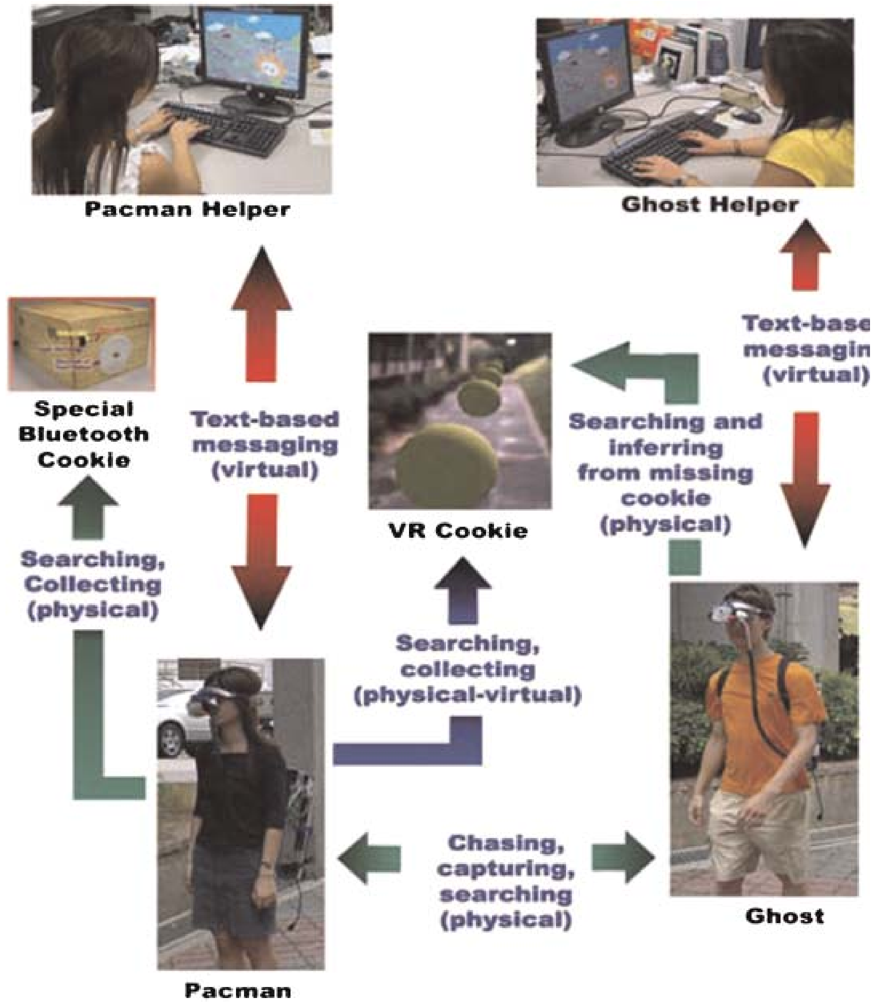

Figure 6. Mobile AR games (images courtesy of Cheok et al.[12]).

their generic AR software framework for novel 3-D construction on real sites.

Maintenance and Inspection

On of the early mobile systems employed on industrial maintenance or inspection for service personnel as well as consumers were introduced by Gausemeier *et al*.[29] It involved a PDA-based handheld AR solution where the inside-out visual tracking was distributed on a stationary network server and the final augmentation transmitted to the mobile device. In the same domain the approach from Vacchetti *et al*.[61] allowed for interactive virtual humans augmenting the real scene in order to provide new training capabilities for professionals, beyond the traditional video material approach, however based on a mobile workstation so that tracking, registration, and simulation are performed in real-time on-site. On-site mobile AR augmentation for industry professionals was also implemented on PDA based on mobile inside-out visual tracking as handheld as well as HMD AR by Goose *et al*.,[25] Makri *et al*.[30] Recently a handheld AR interface to a sensor network has been proposed by Rauhala *et al*.[35] based on SmartPhones for on-site humidity inspection.

Discussion and Conclusions

The following Table 3 exhibits complete AR Systems as employed in different application areas.

In this table the abbreviations shown in Table 2 were used.

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Abbreviation	Meaning	Abbreviation	Meaning	Abbreviation	Meaning
I/O	Indoors/outdoors	IO	Inside-out	OI	Outside-in
mb	Marker-based	Ml	Marker-less	UWB	Ultra-wideband
3Ddyn	Dynamic (animated) 3-D	3Ddyn*	Advanced dynamic, deformable 3-D	3Dstat	Static 3-D
IR	Infrared sensor	Inert	Inertial sensor	PAN	Personal area network

Table 2. Abbreviations
The "*" is only to denote the difference between "3Ddyn" and "3Ddyn*". Exact differences explained in the 'meaning column'.

From the above comparison it is clear that there is no single ideal MARS approach but rather different AR systems according to location (indoors or outdoors), type of display (handheld or HMD), content augmentation (static 3-D, virtual characters) as dictated by each application domain.

Of course still important challenges lie in all three areas such as highlighted by the reviewed literature:

- Limited computational resources: While mobile devices are transforming from simple communication or dedicated multimedia devices to more powerful computational platforms, there will still be need for more computing power. More powerful processor chips are available but their high power consumption and high heat generation present challenges for their use in mobile platforms.
- Size, weight: Wearable AR systems should not be a burden but as unobtrusive as possible.
- Battery life: An important factor of the sustainability of the above AR applications. Except the smart phone category, most other devices suffer significantly from this aspect, limiting the AR application to few hours. Components that have large electrical energy requirements need more batteries, which add to both weight and size. The power consumption of devices is directly proportional to clock speed and heat dissipation.
- Ruggedness: All above mentioned MARSs are early prototypes and depending on the display setup (handheld or HMD), device materials, cables, connectors, and cases normally used indoors may be unsuitable outdoors. Sensitive electronic equipment needs to be protected from the environment or it will be damaged easily.
- Tracking and Registration: These are the basic components of a MARS as specified before. The current trend shows that a combination of tracking modalities is employed for best results, such as, vision or sensor-based. This helps avoid the problems of a single tracking approach. Since different methods are employed for indoors or outdoors tracking, the target of supporting unprepared environments is still elusive.
- 3-D graphics and real-time performance: One of he limiting factors for rich mobile content was the absence of dedicated 3-D processing units in mobile devices. Nowadays more such as functionality is incorporated into such devices as well as the emergence of new powerful small-factor PCs (such as UMPC) allows for new possibilities in more compelling AR content and applications.
- Social acceptance and mobility: The miniaturization of devices as well as their aggregation into wearable systems will contribute to gathering social acceptance momentum. The current AR prototypes are quite bulky or intrusive. Another important factor is the evolution of mobile phones where very soon GPS, graphics acceleration, and other sensors would allow them to be fully transformed into first class mobile AR computational systems. Thus, mobility is tightly intertwined with social acceptance of future MARSs.
- Networked Media: With the increasing expansion in bandwidth new breed of audiovisual networked media applications are envisaged and MARSs can profit significantly. However, issues such as content adaptation (Singh[69]) and sharing, user modeling, and personalized interfaces will also need to be addressed for compelling AR applications.

The recent advances in mobile augmented ubiquitous interfaces are envisaged to be built to emulate and extend basic biological principles and communication patterns. Multimodal interfaces which enable multisensory perception through fusion of different information sources using embedded computing capacity are the ultimate goal. Such radical research in new fusion patterns between AR, wearables, and ubiquitous

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computer animation & virtual worlds

Application domain of mobile AR systems	Method	Computing devices					Indoor/outdoor, wireless networking			Tracking and registration						Displays	AR Content
		MPC	TPC	UMPC	PDA	Phone	I/O	WLAN/ gprs	PAN	Gps	IO	OI	Sensors	UWB	WLAN	HMD/ handheld	3Ddyn/ 3Dstat/2-D
Virtual character based	Billinghurst *et al.*[37]	×					I		×		mb					Handheld	3Ddyn
	Tamura *et al.*[11]	×					I		×		mb					HMD	3Ddyn
	Cheok *et al.*[12]	×					O	×			mb					HMD	3Ddyn
	Papagiannakis *et al.*[72]	×					I,O		×		ml					HMD	3Ddyn*
	Hughes *et al.*[15]	×					I	×			mb					HMD	3Ddyn
	Barakonyi *et al.*[27]	×			×		I	×			mb	×		×		Handheld	3Ddyn
	Peternier *et al.*[31]				×		I,O	×							×	HMD	3Ddyn
	Wagner *et al.*[28]	×			×		I,O	×			mb	×				Handheld	3Ddyn
	Schmeil and Broll[16]	×					O		×	×						HMD	3Ddyn*
	Egges *et al.*[18]	×					I,O		×		ml					HMD	3Ddyn*
Navigation and path finding	Bell *et al.*[67]	×					O		×	×						HMD	2-D
	Hollerer[10]	×					O		×	×			×			HMD	2-D, 3Dstat
	Olwal[34]					×	O	×				×	IR			Handheld	2-D
	Reitmayr and Drummond[26]				×		O	×		×			×			Handheld	2-D
	Azuma and Leonard[60]	×					O	×		×			×			Handheld	2-D, 3Dstat
	Elmqvist *et al.*[24]			×			O	×							×	HMD	2-D
	Newman *et al.*[23]			×			O	×			×		Inert	×		Handheld	3Dstat
Edutainment and games	Klein and Drummond[19]		×				I		×		×		×			Handheld	3Ddyn
	Henrysson *et al.*[33]					×	I		×		mb					Handheld	3Ddyn
	Rashid *et al.*[32]					×	I	Gprs					RFid			Handheld	2-D
	Piekarski and Thomas[42]	×					I,O	×			mb					HMD	3Ddyn*
Cultural heritage	Vlahakis *et al.*[66]	×					O	×		×	×		×			HMD	2-D, 3Dstat
	Papagiannakis *et al.*[14]	×					I,O		×		ml					HMD	3Ddyn*
Collaborative assembly	Renevier *et al.*[22]		×				I		×	×			×			HMD	3Dstat
	Stork *et al.*[20]		×				I				ml		×			HMD	3Dstat
Maintenance and inspection	Gausemeier *et al.*[29]				×		I	×			ml					Handheld	2-D/3Dstat

Vacchetti *et al.*[61]	×			–		×	ml	HMD	2-D, 3Ddyn*
Goose *et al.*[25]		×		–	×		mb	Handheld	2-D/3Dstat
Rauhala *et al.*[35]	×		×	–		zigBee, bluetooth	mb	Handheld	2-D/3Dstat
Makri *et al.*[30]		×		–	×		Both	Both	2-D/3Dstat

Table 3. Mobile AR systems comparison
The "*" is only to denote the difference between "3Ddyn" and "3Ddyn*". Exact differences explained in the 'meaning column'.

computing can lead to new ways of unsupervised audiovisual common-cause techniques for perception of coverage, context awareness, and improved and augmented visual performance in a variety of tasks and take advantage of such new 'cyborgian' interfaces (Clynes[70]). The cyborgian mode of interaction manifestates itself when a human and other external process interact in a manner that does not require conscious thought or effort. A person riding a bicycle is one cyborgian example, since after time the rider operates the machine (bicycle) without conscious thought or effort, and, in some sense, the machine becomes an extension of the wearer's own body. Sometime soon we should find such compelling examples involving mobile augmented ubiquitous interfaces.

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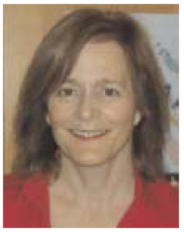
Authors' biographies:

George Papagiannakis is a computer scientist and senior researcher at MIRALab, University of Geneva. He obtained his Ph.D. in Computer Science at the University of Geneva in 2006, his M.Sc. (Hons.) in Advanced Computing at the University of Bristol and his B.Eng. (Hons.) in Computer Systems Engineering at the University of Manchester Institute of Science and Technology (UMIST). His research interests are mostly confined in the areas of mixed reality, illumination models, real-time rendering, virtual cultural heritage, and programmable graphics. He has actively been involved and significantly contributed to the CAHRISMA, LIFEPLUS, STAR, ENACTIVE, JUST and ERATO FP5, and FP6 European projects. Currently he is participating in the INTERMEDIA, INDIGO, and EPOCH FP6 EU projects. He is a member of ACM and IEEE.

Gurminder Singh is a Professor of Computer Science and Director of the Center for the Study of Mobile Devices and Communications at the Naval Postgraduate School (NPS), CA. His primary area of focus is wireless technology and applications. He is currently involved in research in Wireless Sensor Networks and Mobile Devices. Prior to NPS, he was the President and CEO of NewsTakes, Inc., a company specializing in repurposing of multimedia content for delivery to wireless networks and devices. Dr Singh has published extensively and edited special issues of the Communications of ACM, ACM Transactions on CHI, IEEE Multimedia, and ACM Multimedia Systems etc. He founded the ACM Virtual Reality Software and Technology Conference in 1994 and co-chaired VRST 2005. Dr Singh received his Ph.D. in Computing Science from the University of Alberta, Canada.



Nadia Magnenat-Thalmann has pioneered research into virtual humans over the last 25 years. She obtained several Bachelor's and Master's degrees in various disciplines (Psychology, Biology, and Chemistry) and a Ph.D. in Quantum Physics from the University of Geneva. From 1977 to 1989, she was a Professor at the University of Montreal and led the research lab MIRALab in Canada. She moved to the University of Geneva in 1989, where she founded the Swiss MIRALab, an internationally interdisciplinary lab composed of about 30 researchers. She is author and co-author of a very high number of research papers and books in the field of modeling virtual humans, interacting with them and in augmented life. She has received several scientific and artistic awards for her work, mainly on the Virtual Marylin and the film RENDEZ-VOUS A MONTREAL, but more recently, in 1997, she has been elected to the Swiss Academy of Technical Sciences and has been nominated as a Swiss personality who has contributed to the advance of science in the 150 years history CD-ROM produced by the Swiss Confederation Parliament. She has directed and produced several films and real-time mixed reality shows, among the latest are the UTOPIANS (2001), THE AUGMENTED LIFE IN POMPEII (2004), and REAL-TIME TERRA-COTTA SOLDIERS (2006). She is editor-in-chief of the Visual Computer Journal published by Springer Verlag and co-editor-in-chief of the *Computer Animation & Virtual Worlds* journal published by John Wiley.

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