A Survey of Visual, Mixed, and Augmented Reality Gaming

BRUCE H. THOMAS, University of South Australia

Visual mixed and augmented realities have historically been applied to the gaming application domain. This article provides a survey of visual mixed and augmented reality gaming in both the academic and commercial contexts. There is an exploration of both indoor and outdoor mixed and augmented reality gaming. The different games are presented via the three major display technologies: head-mounted display, handheld display, and spatial immersive display. A number of academic mixed and augmented reality research projects are described that provide an overview of the current state of the art. A set of example commercial games are also examined to provide the context for the state of the games on the market.

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1. INTRODUCTION

Mixed reality (MR) [Milgram et al. 1994] and augmented reality (AR) [Azuma et al. 2001] are well-established areas of investigation for entertainment computing, and MR/AR may one day prove to be an early "killer app" for these emerging forms of technology; MR/AR gaming may well succeed where virtual reality (VR) gaming had only a limited success. For home use, head-mounted displays (HMD) are a logical choice for VR, but the HMD issues of limited field of view, comfort, and motion sickness have made the commercial uptake poor to date. CAVE technology has been costly, plus it requires a large physical space, and as such is not a viable option for home use. However, modern, graphic-intense, first-person perspective games are now considered to be a desktop-VR setting.

This article provides a survey of the current state of the art for gaming applications in MR/AR, which will be done by exploring examples of different forms of AR gaming, where the novel aspects of each of these gaming systems will be the focus. This article provides an overview of the current state of the art for academic research into AR gaming. Due to the emerging nature this field, the literature cited here is primarily from conferences. An examination of a representative set of typical current commercial

Author's address: B. H. Thomas, School of Computer and Information Science, University of South Australia; email: bruce.thomas@unisa.edu.au.

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AR games is also provided. The article does not cover AR gaming demonstration applications that are only reported in the popular press.

For ease of reading, the term *augmented reality* will encompass both mixed and augmented realities. The differences are not important for the purposes of this article, which will explore visual-based augmented/mixed reality games only. Audio AR, such as the fine example of Dow et al.'s Exploring Spatial Narratives and Mixed Reality Experiences in Oakland Cemetery [Dow et al. 2005], is outside the scope of this article. There are also a large number of pervasive handheld games that do not have an AR interface, such as those from Blast Theory, which are excellent examples of this form of gaming [Flintham et al. 2003]; but this form is also outside the scope of this article.

The three features of AR that enable support for more novel forms of computer games, as compared to VR versions, are as follows:

(1) AR requires only a limited amount of the user's field of view to be rendered with computer-generated graphics. The vast majority of the user's view is the physical world, and only the introduced virtual game pieces require computer-generated graphics. In immersive VR, the entire visual world (i.e., the virtual world) must be rendered, causing the users to feel that they exist in a synthetic world. The use of props and CAVE display systems allows for a more natural interaction, but the user is encapsulated in a synthetic world. However, this is not to say VR games are not fun to play. Mine [2003] provides an insight into the production of extremely high-quality VR games from Disney.
(2) AR's ability to allow users to view the physical world provides a better sense of where they are and who is around them. Being able to see the physical world allows users to move freely in the combined physical and virtual worlds, with the ability to view and avoid obstacles such as chairs, trees, and other people. The ability to view other people, albeit sometimes without being able to see the other person's eyes, is a powerful visual cueing mechanism for collaborative games. For example, aiming a physical ray gun and virtually shooting at someone instead of an avatar is much more personal. Full-body cues such as waving one's hand is more naturally supported in an AR environment.
(3) Finally, the physicality of moving in open spaces is appealing to users. The ability to move around in large or small areas allows the users to understand and experience the game at a more primordial level. To physically walk over to a position is more intuitive than the use of keyboard or a mouse. To be able to pick up physical objects and employ them as input devices, as with tangible user interfaces (TUIs) [Ishii and Ullmer 1997], is powerfully engaging for a player.

1.1. Augmented Reality

Augmented reality is the registration of computer-generated graphical information over a user's view of the physical world. Supplemental information that is spatially located relative to the user can help to enhance their understanding of the world around them. AR is made up of a combination of virtual and real environments, although the exact make up may vary significantly. Milgram and Kishino used these properties to define a reality-virtuality continuum [Milgram and Kishino 1994], which can be used to compare the various forms of MR by placing them onto a spectrum. At one end of the continuum is the physical world, at the other end are the fully synthetic virtual environments (VR); AR is located somewhere in between, since it is a combination of the two. On the far left of the continuum is the physical world, with no virtual information at all. Moving to the right in the continuum is AR, where artificial objects are added to the physical world. Further to the right in the continuum (but not all the way to the right) is augmented virtuality, where physical world objects (such as a live display of

Fig. 1. The Tinmith head-mounted display.

a remote view) are added into a fully immersive virtual environment. On the far right side is a completely synthetic environment, with no information from the physical world being presented. Every type of 3D environment can be placed somewhere along this spectrum, and can be used to easily compare and contrast their properties. Mixed reality is defined as the combination of augmented and augmented virtuality.

In his outstanding survey of the discipline, Azuma defines AR systems as those that contain the following three characteristics [Azuma 1997]:

(1) it combines the real and virtual;
(2) is interactive in real-time; and
(3) is registered in 3D.

This definition does not limit AR to the use of head-mounted displays (allowing for projectors and handheld displays), but excludes noninteractive media such as movies and television shows.

To overlay 3D virtual models onto the user's view, an AR system requires some form of displayed computer-generated information to be combined with a sensor that can measure the position and orientation of the user's view. As the user moves through the physical world, the display is updated by the computer in real-time. The accuracy of the virtual objects registered to the physical world influences the realism of the fusion that the user experiences.

1.2. Structure of the Article

AR gaming currently takes on a number of different forms based on the following:

(1) whether it is played indoors or outdoors; and
(2) the type of display: head-mounted displays (HMD) [Rolland and Fuchs 2000]; handheld displays [Schmalstieg and Wagner 2007]; or projector-based displays [Raskar et al. 1999].

The Tinmith system [Piekarski and Thomas 2001] is an example of an HMD-based system, and is shown in Figure 1. It is good for mobile applications and allows for hands-free viewing. Tracking the HMD makes a very natural method for changing the user's virtual viewpoint in the game. A major drawback is that people in general do not like to wear HMDs. TU Graz's Invisible Train [Wagner et al. 2004] is a good example of handheld display technology for AR, as shown in Figure 2. The use of handhelds also allows for mobile applications, but does require the user to hold the device. The main positive for this device is that, due to the ubiquitous use of smart phones, a large section of the population has access to AR games. The projection of AR information is demonstrated via the Augmented Coliseum [Kojima et al. 2006] in Figure 3. A major benefit of projecting AR is that users in general do not touch the display itself; many of the display technologies today are not robust enough for rough gameplay. A negative is

Fig. 2. Invisible train handheld augmented reality. (With permission of Dr. Wagner, TU Graz).

that, at the moment, projectors are not bright enough to be taken outdoors in daylight, and, by and large, are fixed to a single position.

AR games based on the different form factors will be described to accentuate the properties of the different forms of gaming. There are five current form factors:

(1) indoor/HMD,
(2) indoor/handheld,
(3) indoor/projector,
(4) outdoor/HMD, and
(5) outdoor/handheld

There are currently no outdoor/projector form factor AR games, as projectors do not work well in sunlight. Although there are outdoor projector-based forms of art [Snow et al. 2011] (such as the Northern Lights presented at the 2010 Adelaide Festival of Arts),[1] there are no reported outdoor AR gaming systems. In particular, projector AR will be examined in the context of spatially immersive displays (SID). SIDs range from a single projector to a set of displays that physically surround the viewer with a panorama of imagery [Lantz 1996].

This article starts with a discussion of a number of important technologies that support the development of AR games, as a number of the games employ similar tools. The description of different AR games is structured around describing the indoor AR gaming examples first, grouped into the three different display technologies. This is followed by the outdoor AR game examples, which are grouped into two appropriate display technologies. The article finishes with a set of concluding remarks.

[1]http://www.theelectriccanvas.com.au/showcase/?id=97.

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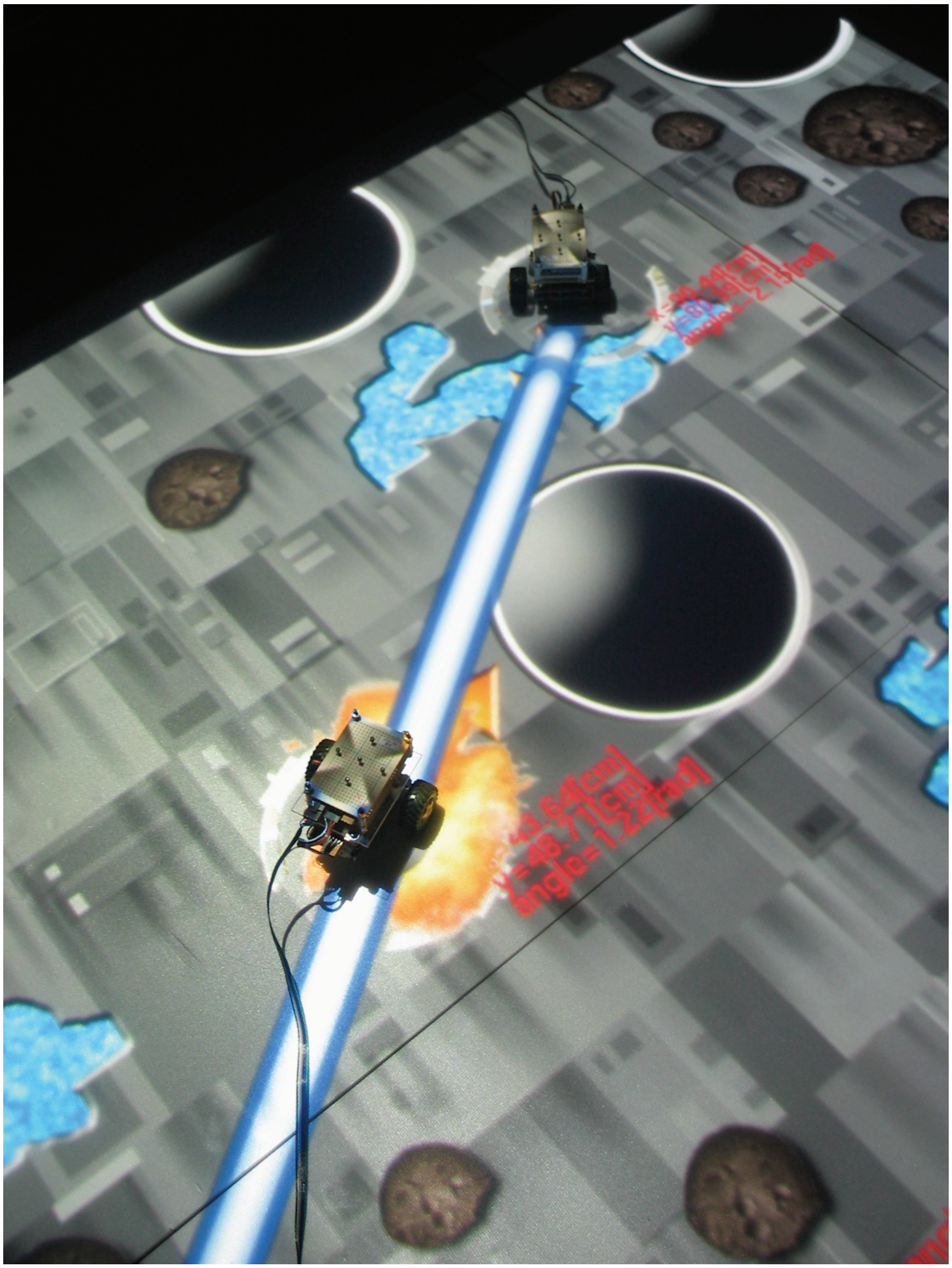

Fig. 3. Example of projector-based augmented reality. (With permission of Prof. M. Inami, Keio University).

2. TOOLS

Although this article focuses on gaming applications, a number of key supporting technologies are examined. This section will examine research concerning the following: frameworks and supporting technologies for AR gaming. In this section the term "mixed reality" is employed when the authors indicate that it is the virtual environment for their supporting technology.

2.1. Frameworks

There have been a number of hardware and/or software frameworks developed to support AR gaming. This section provides an overview of some of the more notable ones. The first is HyperReal [Romero and Correia 2003], a framework for building mixed reality and context-aware applications. Romero and Correia leverage on the fact that HyperMedia is designed for large quantities of information. The key features of their framework are the following: integration into one framework, the use of real-world entities, space/time representation, replay mechanisms, and link awareness to represent navigation information.

HYPERPRESENCE [Tavares et al. 2003] is a framework for developing mixed reality applications and games that combine both virtual and robotic elements. The main system components are support for 3D interfaces, VRML multi-user client/server architecture, and a robot server. Barakonyi et al. developed AR Puppet [Barakonyi et al. 2004]. Leveraging the property of sentient computing systems, their system can maintain a model of the physical world as observed by sensors to influence behavior. The novelty is in the ability to combine physical robots with virtual animated agents. This ability provides a rich medium for gameplay, as the virtual graphical agents are embodied in the physical world. The sensors allow for the autonomous systems to act and react in a world with humans. Leung et al. [2007] developed a generic hardware/software framework to support a wide range of multiple player games over a network. They were very interested in supporting both virtual and physical components in the gameplay. Their Tele-Table System is made of the following three layers: (1) the hardware layer; (2) the Tele-Table engine layer; and (3) the application layer. It is interesting that the project's goal is not only to support board games, but to support physical games such as air hockey.

Kuikkaniemi et al. [2006] built a mobile AR (MAR) toolkit for gaming with the Nokia MUPE open source mobile platform. They extended MUPE with four components: map interface, physical object tagger, public display, and silent communicator. Using their new toolkit they built a MAR game based on the board game, Scotland Yard18. Mupeland Yard is a two-player game, with a criminal and a detective. The criminal starts first, and the game leaves digital hints (clues) for the detectives to find. The game area is also seeded with physical, tagged artifacts. The criminal wins if it finishes the game before the detective can catch them. A detective captures the criminal when they are both physically located at a tag within a few minutes of each other. The mobile phone provides visual AR information to the users. Wagner and Schmalstieg developed Muddleware [Wagner and Schmalstieg 2007], a communication framework for MR multiuser games for handheld devices that is lightweight and highly portable. They developed the following AR game projects with the framework: Virtuoso (art history), Enigma Rally (museum), and AR Agents (storytelling).

2.2. Supporting Technologies

There have been a number of supporting technologies developed for AR gaming. The most notable is the ARToolkit [Kato and Billinghurst 1999], as this is historically the most popular AR development library. ARToolkit's public availability, ease of use, robustness, and low cost of entry, allowed for a rapid uptake of this technology. Kirner et al. 2006] investigated five case studies to examine the development of AR games with the ARToolkit. With the use of cubic markers, a 3D jigsaw puzzle was created. Investigating a two-person remote collaboration game, they developed an AR version of tic-tac-toe. Leveraging ARToolkit's ability to sense markers adjacent to each other, they developed a word game of organizing letters together. The authors also implemented a music game to explore the use of sound in AR games. Finally, a magic cubes [Zhou et al. 2005] game was constructed to help in storytelling.

DART: A toolkit for the rapid design exploration of augmented reality experiences was developed by MacIntyre et al. [2004]. It is a plug-in for Macromedia Director. This is an easy-to-use environment that enables users to quickly develop entertainment content, without worrying about the AR technology. The system supports marker-based tracking, VRPN tracking, and sensing systems. This enables users to connect 3D or 2D content to tracked objects in the user space. Camera and video support are included for both video-based and optical see-through AR.

Prince et al. [2002] developed 3-D Live, a combination of real-time volumetric rendering and ARToolkit [Kato and Billinghurst 1999]. The system is capable of capturing human actors in a green-screen room and projecting their video images onto an ARToolkit marker. The user via an HMD is able to view the actor from any angle by rotating the ARToolkit marker in front of himself or herself. The actor may be placed in a virtual room, such as a museum, a game, or a virtual stage. This technology is quite flexible for a number of real-time collaboration applications. Magic Land [Qui et al. 2005] is a combination of AR and 3D-live technology. It demonstrates original methods for users to interact with virtual objects and virtual collaborators. Inamoto and Saito [2004] provided a similar system for viewing football (soccer) matches through an HMD on a tabletop.

Finally, Dorfmüller-Ulhaas and Schmalstieg developed an optical finger-tracking system with the goal of removing annoying wires and cables during the interaction. Their technology was demonstrated in the context of an augmented reality version of chess [Dorfmuller-Ulhaas and Schmalstieg 2001].

3. ACADEMIC INDOOR AR GAMING

By and large, the development of academic AR games for the indoor home market follows the concept of users playing games in one particular location, thus enabling the leveraging of current tracking technologies. Tracking technologies are more robust and accurate indoors, as the equipment does not suffer from as many environmental concerns; and many configurations tether people to their computers. This section will examine the following three forms of indoor AR gaming display technologies: immersive head-mounted display, spatially immersive display, and handheld display. Each of these technologies will be examined in two operating modes: stationary mode with the use of some kind of tabletop and in a mobile mode.

The employment of a tabletop as an AR gaming surface provides a number of interesting user interface opportunities for HMD, handheld or tabletop-projected AR entertainment applications. The games may range from extensions to traditional noncomputer-based games, such as augmented reality Chinese checkers [Cooper et al. 2004] to new robotic interaction games such as Augmented Coliseum [Kojima et al. 2006]. There are many advantages to playing games on a computer rather than on a physical board, such as the ability to introduce animation and other multimedia presentations. The animation can do more than add excitement to the gamplay, it can also help the players learn the game and understand invalid moves.

An example of an indoor mobile AR game is MIND-WARPING [Starner et al. 2000]. This game employs an HMD and allows users to play the game by physically walking/running throughout a floor of a building (in the case of MIND-WARPING, the floor of a university building). These games tend to be more collaborative in nature. The mobile nature of the equipment allows for different styles of games that include location-based information. AR information can be attached to physical locations in the space, to tracked physical objects, and to the players of the games. This opens a new set of styles for games.

3.1. Immersive HMD

One direction for immersive HMD-based AR games is to develop AR versions of original games. I see this form factor as a new display device attached to existing gaming infrastructure (a game console or existing PC). Due to the static nature of the placement of the gaming infrastructure, the HMD and sensors would be cabled to the infrastructure. RVBorder Guards: A Multi-player Mixed Reality Entertainment [Ohshima et al. 1999] is one of the very early versions of a first-person shooter HMD. This section investigates the different AR games from the point of view of table-based immersive HMD and mobile immersive HMD.

3.1.1. Table-Based Immersive HMD. Use of the tabletop as an AR gaming surface provides a number of interesting user interface opportunities for HMD-based systems. A clear option for AR gaming is the ability to make the game more animated. For example, the game of Wizard's Chess depicted in the movie *Harry Potter and the Philosopher's Stone*[2] provides graphic animations of chess pieces fighting whenever a piece is captured. The use of AR allows for animated game pieces to interact with each other and with the players of the game. Animation could assist the following characteristics of the game: tuition on how to play the game, tactics, and current attributes for playing a piece (power level, strength, or ability).

An interesting feature of HMD-based AR is that different kinds of information may be displayed to different users. In the case of displaying current attributes, private information about a playing piece could be displayed to the user who controls the piece. This private information could include visualization of potential placement of pieces or future actions. Szalavári et al. [1998] investigated these issues with an AR version of the classic Chinese game Mah-Jong. They employed face-mapping for quick and accurate placement of game pieces to improve the game experience. Because Mah-Jong requires both public and private information, they developed what they term a *powerful automatic privacy mechanism*. The players hold the private information on handheld PIPs (personal information panels). For this game, a PIP is a magnetic, tracked passive prop. The game is played at a table and AR displays all the game pieces. The AR for this game is the combination of virtual game pieces and the physical game space (people and table).

A tabletop AR version of the fantasy game Jumanji, set in Singapore, was developed by Zhou et al. [2004]. Instead of employing dangerous creatures, the game virtually transports the user to Singapore shopping locations. The user employs dice with MXR-Toolkit[3] fiducial markers (similar to ARToolkit markers) as the means for game control. The use of physical dice adds a nice tangible feel to the game. Minatani et al. [2007] developed an AR version of Othello with the ARToolkit as the tracking technology. What makes this a very interesting game is the fact that you play a remote user with a physical board. Your opponent and the opponent's pieces are displayed to each player as virtual objects. The authors explored the rendering space to enable users to "feel" as if the other player was sitting at the same table.

[2]Warner Brothers Motion Pictures.
[3]http://sourceforge.net/projects/mxrtoolkit/.

AR2Hockey was one of first AR games [Ohshima et al. 1998]. The game uses optical see-through HMD display technology for two players. The game is played on a standard table with landmarks. The landmarks allow for a hybrid optical tracking and the Polhemus' Fastrack. The game basically supports the traditional form of air hockey, but replaces the physical pucks with virtual ones. As an extension to this, Mueller et al. developed an AR remote version of air hockey [Mueller et al. 2006]. Two remote physical air hockey tables, one for each player, provide the playing surface for the game. There is a video conferencing display across the middle of each table providing a real-time video feed of the other player. What makes this game different is that the users play with physical pucks. Once a puck is hit across the table, it is caught with a mechanism under the video conference display. The mechanism then automatically shoots the puck back in response to the shot from the other player. The game of pool (or billiards) has been investigated by a number of researchers as an application domain for AR. Jebara et al. developed the first mobile AR pool system [Jebara et al. 1997]. This is an HMD-based AR game, for which many of the first algorithms for image processing and physics engines for pool-based games were developed. This game served as a trainer for the end user by displaying AR information on the correct cue placement. Each of these games supports a physical gaming interface, adding to the evidence that AR incorporates both the physical and virtual worlds. AR2Hockey was a very early AR game, and as such required more expensive display and tracking equipment; but the price for both these forms of hardware has fallen dramatically. The Jebara et al. pool system also required a large structure, the pool table, to play the game upon. This system also incorporates a tutoring system for the players, including suggestions for shots.

Nilson developed a tabletop HMD-based AR version of Tankwar [Nilsen 2005] with ARToolkit. The players operate on a virtual map, controlling a small army of tanks, artillery, and helicopters to capture and defend objectives on the map. The user interface is a combination of lens-based selection techniques, magic lens, speech interfaces, and transitions between ego- and exo-centric views. The AR aspect was incorporated to enhance the social aspects of the game. A number of AR card games have been developed: Billinghurst et al. created an ARToolkit memory game, where the users flip physical cards [Billinghurst et al. 2000]. When a card is flipped over, a 3D graphic is displayed. The cards interact with each other by playing an animation when there is a match between the cards. This was the first AR game developed with the ARToolkit. Diaz et al. created a variant which employed hand gestures as the means of interaction [Diaz et al. 2006]. They used special cards to enable the system to sense card flipping by embedding Hall effect switches in the cards. BattleBoard is another example of a tabletop AR card game [Andersen et al. 2004]. This is an ARToolkit fiducial marker-based AR system which attaches virtual game pieces to the markers. One player employs an HMD with a camera and the second player views the game through a monitor. Battles are fought when pieces come in close proximity to each other, and thus activate AR animations. The Billinghurst et al. card game was designed for a public demonstration at an ACM SIGGraph conference with quick gameplay. BattleBoard employs a similar technology to the Billinghurst et al. card game, but BattleBoard's design is more advanced, and is similar to a duelling card game. The Tankwar game was developed for more extended gameplay, investigating how AR could be employed for games with a more traditional time span.

Abreu and Mendes created an ARToolkit-based version of the game, Mastermind [Abreu and Mendes 2008]. The authors developed an ARToolkit marker-based version of a human verse game, in which a simple rotation made by the marker indicates that the player is done with his or her turn; colored pieces are moved via keyboard commands. Barakonyi et al. developed an HMD-based AR game, MonkeyBridge [Barakonyi et al. 2005], with the Studierstube AR platform [Schmalstieg et al. 2002].

The goal is to get the game avatar to touch a target in a virtual ocean depicted on the tabletop. Players build bridges for their virtual AR characters, which can be virtual blocks or physical tiles made of bright balsa-wood and stone cubes showing through the virtual objects. Players indirectly control the movements of the character by building blocks to walk over the ocean. (The authors were investigating the use of agents to improve the AR gameplay.) Oda et al. [2007] developed an HMD AR racing game that embeds a true computer racing game within an AR context. This game is played on a large surface, such as the floor. The innovation here is that the user steers the car with small bicycle handlebars mounted with ARTag [Fiala 2005] fiducial markers (ARTag is a similar technology to the ARToolkit). Users can define race courses and obstacles by placing markers on the game board. The AR provides the virtual game pieces and head-up display for the players. These three games all attempt to support more complex gameplay. The Mendes' game user interface is simple, but the game logic is complex. The Monkey Bridge game combines complex physical user interaction with a complex virtual game. Once again, the game leverages the natural coexistence of physical and virtual worlds within AR. Driving games are quite popular, with Oda et al. leveraging the properties of AR to bring the game from the screen into the physical room. While the form factor of bicycle handlebars might not be perfect for long-term gameplay, the robust nature of the game's interaction is supported by this device.

Fischer et al. [2006] developed an AR painting system that changes the physical and virtual objects which can be viewed in one of three types of styles: a cartoon-like style consisting of colored patches and silhouettes; a painterly style consisting of small brush strokes emulating a pointillist painting style; and a black-and-white technical illustration style. The authors have been investigating a number of non-photorealistic rendering techniques to emulate different forms of art and cartooning [Fischer et al. 2005]. Woods et al. [2004] investigated and developed a number of educational exhibits used in science centers, museums, and libraries. These exhibits were built with the ARToolkit. The Black Magic Kiosk is a major exhibit developed for the Telecom Technology Pavilion at the America's Cup in New Zealand in 2003. Woods et al. also developed the Augmented Reality Volcano Kiosk for Science Alive! in Christchurch, New Zealand and then exhibited at the Science Works in Melbourne, Australia. Their paper provides a good overview of systems for public learning; the authors are also very interested in building robust AR games that could withstand deployment in a public setting.

3.1.2. Mobile Immersive HM. By employing a wearable computer with an HMD, users are able to physically move around in indoor environments. MIND-WARPING [Starner et al. 2000] is a mobile HMD-style of game which enables users to see one another and allows them to shoot each other virtually. This makes for a virtual form of laser tag. This game requires a large instrumented space, as in MIND-WARPING, a floor of a computer science building at a university. To play this style of game in someone's home would require a game that is designed for a smaller indoor area. Gandy et al. developed an acting-based AR Karaoke game [Gandy et al. 2005] built on top of the DART AR authoring tool [MacIntyre et al. 2004]. The idea is to play a favorite scene of a movie from inside the movie. The user wears an HMD and acts out a part in a movie scene via voice and movement. The movie is shown to the user in a first-person perspective, with the user acting against a prerecorded scene from the movie. Figure 4 depicts the user's view from an HMD playing AR Karaoke with the movie *Princess Bride*. The user's friends can watch the final result of the user's actions. This concept takes the notion of the Eye-Toy® to a new level: a group game in which the players move around in front of their friends instead of in front of a camera.

Fig. 4. User's view of AR Karaoke. (With permission of M. Gandy, Georgia Institute of Technology).

The TouchSpace [Cheok et al. 2002] provides a two-player game that explores a number of different interaction paradigms, and focuses on physical groupplay. The games are played in large indoor tracked areas (employing an IS900 tracking system) with HMDs. The game is played in two stages: In the first stage, the players use handheld controls with virtual TriCoder-like devices [Wloka and Greenfield 1995] to explore and provide clues as to what is contained in a set of physical boxes on the floor. The players are guided by AR cues to physically open a box to determine if it contains treasures and, hopefully, not dangers, such as bombs. Once they find a sufficient number of treasures, the players enter a second AR stage of the game. This first entails looking for a castle by panning around the floor and viewing a portion of the AR landscape mapped onto a handheld device. Once they find the castle, the players zoom into an airplane cockpit for a fully immersive VR experience in order to battle a witch and free the princess. TouchSpace explores natural physical movement, physical props, and the transition between AR and VR. The complexity of the gameplay and rich interactions demonstrate a new level of AR gaming. This game demonstrated how detailed and engaging games can be achieved with current technologies.

Govil et al. [2000] developed an AR video-based HMD golf simulator. They set out to improve traditional VR golf simulators in cost and provide "a higher fidelity *feel* of the game." They employed an easy to implement ARToolkit such as the fiducial marker that tracks the HMD relative to the ground where the ball is. This leveraged the fact that the user was looking at the ball when it was hit. The camera also tracked the velocity vector to determine the direction and speed of a physical ball after it was hit by a physical golf club. Matysczok et al. developed the HMD-based AR-Bowling game [Matysczok et al. 2004]. The idea is to place a bowling lane in any room the player desires. The physical world is observable, but an AR overlay of a bowling lane is presented to the user. The basic interaction is the user's view, down the bowling alley, which is tracked with ARToolkit markers that are placed on a wall. The user's hand is tracked with a Polhemus tracker and the action of letting go of the bowling ball is determined with a set of pinch gloves from Virtual Technologies. Hand gestures determine the speed and spin of the ball leaving the user's hand. There is a physics engine that simulates the correct path for the ball and the force on the pins. Both the AR golf and bowling games leveraged a large user action (i.e., a golf swing and a bowling action). The haptics of bowling are much more difficult to replicate. For safety reasons, the user is unable to hold a real bowling ball and play the game in the home. On the other hand, the technology that enables players to strike physical golf balls indoors is a well-understood.

BLADESHIPS [Takemura and Haraguchi 2003] is an AR interaction /attraction system. The key to this system is the user's interactions via hand motions in a multi-user application. This is an HMD-based game that has "belt-like" ship entities. The user must hit virtual and physical objects in the room-sized play space. The tracking of this game is supported by a Polhemus Fastrak 6DOF system. The ships may be longer than the shape of the game area, forcing the ships to fold, similarly to the game of Snakes. Each of the physical objects in the room is scanned as a 3D model in the game and tracked using computer vision. The large playing space is a novel aspect of this game. This is a clear example of employing an existing game design, *Snakes*, onto a new platform, AR.

Santiago et al. [2003] and Romero et al. [2004] developed a game to solve mysteries, which is similar to TouchSpace, in that a number of augmented physical items are collected together in a room. In the game, the players attempt to solve the mystery of finding Edward Hopper's Diary. The players are given clues via HMD AR. The more clues and puzzles the user solves, the more experience is gained by the player, which then enables the player to move up levels in the game. They use virtual spaces such as the virtual Nighthawks dinner, inspired by Edward Hopper's famous painting of the same name. This AR game was developed within the HyperReal framework [Romero and Correia 2003]. Unlike many other AR games, this is a team-based game played against the computer, thus supporting a more collaborative approach to player interaction. The games were limited to a single room with only two paintings; it is unclear how this game will scale up to a larger collection of paintings.

The Butterfly Effect [Norton and MacIntyre 2005] has the stated goal to "*explore the design of an interesting AR game that leverages the structure of the physical world during game play without requiring the computer to have a detailed model of the world*". The game is for children to collect butterflies with a "tornado stick," a tube about 25cm long with two buttons attached to the middle. The children wear an HMD, connected to an Intersense IS1200 VizTracker, and the AR context is displayed in a cylinder configuration around the player. The butterflies have no concept of the actual physical environment, thus (at times) making them difficult to catch. The tornado stick has two modes, catching and tornado. Pressing the catching button while the stick is in contact with the butterfly will capture it. The tornado mode activates a tornado that blows the butterflies around at a 90-degree angle to the stick, with the hope that they will be easier to catch. This game is novel, as it is targeted at young children. The age group for most of the games in this article range from young adults to older ones, with the Butterfly Effect being one of the exceptions.

A drama-based game, Façade, was extended into an HMD AR version, AR Façade [Dow et al. 2007a, 2006, 2007b]. This game is a major break from traditional AR gaming ideas developed previously. This is a complex, real-life, role-playing game; very much like interactive theatre. Originally, the game was played on a traditional workstation; AR Façade is played on a HMD with a mobile backpack system, with gestures and voice as the main forms of interaction. The authors constructed virtual and physical representations of many of the game objects, such as walls and furniture, in an apartment. Objects that were manipulated by both the virtual characters and the physical players were presented as AR objects to the game player in the HMD. Due to the large area the game is played in a large area with an IS1200 tracking system. A Wizard of Oz method was employed to support user interactions to make for more robust gesture and speech processing systems during user studies. The authors found this form of interaction engaging for the user, but more research is required [Mehta et al. 2007].

3.2. Spatially Immersive Display

I envision that home entertainment centers enhanced with spatially immersive displays will be an appealing form of AR. Wrapping the game's visual and sound space around the user in a semi-immersive fashion would draw the user further into the game. Removing the need for wearing an HMD makes this form of AR games an attractive option for the user. There is only a "table-based" mode for SID, where a table could be any flat surface, such as the floor, wall, or any flat surface.

Chen et al. [2009] investigated the dynamics of social interaction and communicative behaviors. They performed a user study that was undertaken with a collaborative multi-user tabletop game called "Comino". Comino is a collaborative puzzle-based tabletop game for up to four players who have to use both real and digital domino tiles. The authors identified three main themes: the use of space, reduced nonverbal cues, and knowledge transfer. [Leitner et al. 2008] developed the IncreTable game which allows users to play with real and digital domino tiles, physical robots, and virtual cars. The robots employ the same technology as AR Coliseum. IncreTable was inspired by The Incredible Machine by Sierra, and, like the Comino game, it centers on the manipulation and activation of physical and virtual dominos.

Colvin et al. implemented an early third-person AR fantasy-based game built on top of an ARToolkit supported by six-sided dice [Colvin et al. 2003]. The game setup is a camera pointing down on the tabletop game space and a projector in displaying on the wall behind the game space. The supported game is an AR Wizard Duel, in which two powerful wizards fight each other. The wizards have the ability to summon creatures out of spell cubes to assault one another. The game supports three types of game entities: goblins, cannons, and dragons. A creature can defeat anything at a lower level than itself. Each monster is encoded on two different faces of each of the wizard's dice. The wizards maintain combat readiness in anticipation of the other wizard suffering three defeats. This game is more complex than that of Zhou et al. [2004] and uses projector technology; projector technology is less intrusive for face-to-face game situations. Katayose and Imanishi [2005] developed an AR-enhanced dueling and trading card game. The characters' battles are shown as AR 3D graphical animations. A barcode reader is used to identify the trading cards. Lam et al. [2006] developed a more advanced version of a dueling trading card game. This game had better game logic and better graphical characters. Card detection was also done via computer vision. Both of these games employed different display technologies than BattleBoard [Andersen et al. 2004]. Dueling trading card games lend themselves naturally to AR, as AR allows the animated fantastic characters to battle each other when cards are placed in play.

Augmented Reality Chinese Checkers is played as a tangible AR game with projector-based AR. The users manipulate ARToolkit cardboard fiducial markers to control the playing space and pieces. Chinese checkers is ideal for a tabletop-based AR game because it can be played by up to six players and has relatively simple rules for a board game. AR provides extra functionality to an existing board game. For example, saved games can be started without resetting the board. When the players are ready to start the game, the game board reappears as it was. Augmented Reality Chinese Checkers can also provide animation and other multimedia presentations to enhance the player's experience. Such enhancements cannot be produced with a traditional physical board. This game is novel in that it extends an existing board game, and this aspect has not been widely examined to date.

Extending the interaction to include tangible or physical playing pieces allows for a more natural interaction. Chekhlov et al. [2007] developed Ninja on a Plane, which is a SID-based AR game. The idea is that computer vision (SLAM) technologies are used to understand planer surfaces. The user guides the AR ninja down a set of obstacles which the user constructs with physical blocks. There is a maximum vertical and horizontal leap the ninja can achieve safely. This paper explores how to develop ARToolkit-like games without the traditional black and white square markers. By using SLAM's natural tracking feature, the user can utilize any planar object with enough identifiable visual features. While the game has a simple game design, the tangible nature of the physical interaction is engaging.

Cavazza et al. [2003] have investigated the use of AR to provide a *magic mirror* interface to their interactive story-telling system. The user's image is captured in real time via a video camera and superimposed on the game displayed to the user on a virtual stage. The authors employed Unreal Engine[4] to support the AR technology. This form of AR is similar to post-production for special effects for a movie. The users are able to interact with the game through gesture and speech. The game is based on the James Bond series of films and books. The same team has been investigating AI-based interactive storytelling by superimposing the player on the game [Charles et al. 2004]. The three most important components of acting in their AR game are stated as follows: "*User's attitude through the recognition of his gestures. Spoken utterances while conversing with the virtual actors.* and *Physical interaction from the user onto objects or characters of the virtual stage.*" The novelty in this game is that it brings nonlinear virtual story-telling into a familiar physical environment. Users sit across a physical deck and interact with the "bad guy" while playing the part of James Bond. This game provides a similar experience to the AR Façade game.

CoGAME [Hosoi et al. 2007] explores the use of lightweight handheld projectors to illuminate the floor as a game space. The users interact with the game via "manipulation-by-projection". The projectors display AR roads for the physical robots to move on. Two players in a turn-taking mode add sections to the virtual road to direct the robot to specified destinations. The authors developed a custom client-server architecture to support their computer vision technology. CoGAME explored innovative techniques of employing a projector as an input device. This game is similar to Augmented Coliseum, in that the user controls physical robots, but in this case the user employs handheld projectors as the interaction device. This is a very promising avenue of investigation for novel game interaction.

Larsen et al. [2005] developed an automatic pool trainer, that focuses on computer-aided learning. They initially used a large wall-mounted display and a laser projection to display augmentation on the table. However, they found this limiting and replaced both of these with a single ceiling-mounted data projector. They also employed computer vision to determine the placement of the balls and a simple gestue menu system for the user. The system has the player place the balls in predefined locations and instructs the player on the best shot via visual AR graphics on the table. The Microsoft English speech-recognition engine was included as part of the user interface of the system.[5] The user of data projectors removed the requirement of an HMD for this implementation of a pool trainer, as this is more a natural method for the game. All the required information can be registered and projected onto the table itself, thus leveraging the natural physical shape of the pool table itself.

Read-It [Sluis et al. 2004] is an AR multimodal, tangible and collaborative tabletop system to help children learn to read. The research makes two contributions. First, the research showed that a combination of AR and tangible interaction helps children aged 5 to 7 learn to read. Second, the Read-It system was developed to allow noncomputer scientists to develop learning aids for children. The authors developed an AR-enhanced memory card game. Flipping the cards triggers the system to project AR content on the cards in order to find matches for them. Hatton et al. [2008] explored game-based

[4]http://www.unreal.com/.
[5]http://www.microsoft.com/en-us/tellme/.

learning with a projector-based AR system that projects onto the floor. The users work in pairs to explore the potential metaphors from pairing media with text objects. The AR objects float across the floor and the students pick them up and place them in a bucket. These actions serve as motivation for discussing the possible metaphors between students and teachers. These examples leverage the educational aspects of AR gaming, in that additional information may be displayed in the physical world. These forms of games allow for natural learning environments and cater for additional physical objects in the environment, such as classroom artifacts. As projectors are more common in teaching environments, these forms of games can have a substantial impact on education.

Physically active games, by their very nature, are well suited to SID environments. The users are not encumbered by technology to support the presentation of the AR information. PingPongPlus is designed to be an "athletic-tangible interface based around Ping Pong (table tennis)" [Wisneski et al. 1998]. Microphones are attached to the table to determine the location of the impact of the ball onto the table. A projector provides AR presentations on the table surface. One effect is a water ripple emanating from where the ball strikes the table. The painting and spot mode leaves virtual dots on the table. The thunderstorm mode promotes collaboration, as the longer the rally continues, the bigger the build-up of the sound of the thunderstorm and visual effects. The Pac-Man® mode combines the Pac-Man game with ping pong.

CamBall is a straightforward version of AR table tennis developed by Woodward et al. [2004] to support remote gaming. The game may be played in a one- or two-player mode in front of a SID screen. Each player holds a physical table-tennis paddle with a green square for 5DOF tracking. This is sufficient to determine whether the user has hit the virtual ball. The user's view includes a video of the other player and a virtual table. The game is simplified so as not to include aspects such as air resistance and friction. Mueller and Gibbs developed a table tennis game for three [Mueller and Gibbs 2007a, 2007b]. They are interested in *exertion interfaces,* which deliberately require intense physical effort from the user. The game is built as a video conference between the players. Each of the users plays a solo game of table tennis by hitting a ball against a white wall. The video conferencing is hidden behind a set of virtual white blocks on the wall, against which the user hits the ball. As the user hits the ball against the wall, the blocks start to crack. Only when the players crack open all the virtual blocks that prevented them from seeing each other, does a clear video image display each of the players. The goal is to crack open all the virtual blocks covering the back wall. The CamBall game was a simple extension to the game of table tennis. While the users could play remotely, there was no real use made of AR to extend the gameplay. PingPongPlus attempted to improve on the game of table tennis by added visual effects and additional game design features. Mueller and Gibbs combined two different games to provide an engaging collaboration mechanism. The latter two games really attempted to improve upon the existing game of table tennis with novel features that could only be support via AR technology.

Mueller and Agamanolis extended the concept of exertion interfaces with their *Sports Over a Distance* [Mueller and Agamanolis 2005; Mueller et al. 2003]. Like Mueller and Gibbs' table tennis game, Mueller and Agamanolis developed a soccer-like game called Breakout for Two. The game consists of two remote players, each with a large screen displaying the other player and a "breakout" board. Computer vision techniques are used to determine where the kicked ball hits the wall and with how much force. The user strikes one of eight virtual blocks to try and complete the classic game of breakout. The game combines an AR breakout game with the very physical game of soccer, in a similar fashion to the *Table Tennis for Three* game. This game is novel in that it encourages vigorous physical activity. The by-product of playing the game is more akin to playing

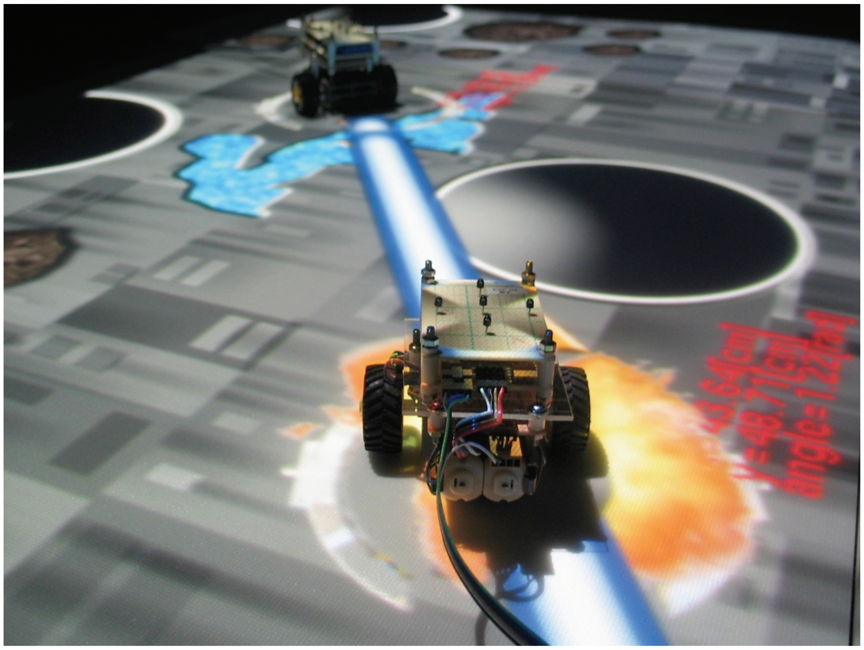

Fig. 5. Augmented Coliseum. (With permission of Prof. M. Inami, Keio University).

physical sports than playing a console game. The AR technology supports the notion of people moving physically in a large indoor environment. This is a very positive direction for AR gaming technology. In the same vein, an "artificial reality" martial arts game, Kick Ass Kung-Fu, was developed to allow users to punch, kick, and perform acrobatic moves [Hamalainen et al. 2005]. The authors employed computer vision to embed the user in the AR game, and investigated amplified movements and dynamic slow-motion visualizations to alter the aesthetic of kung-fu movies into a real-time individual experience. The game was evaluated with 46 participants, who were all martial arts practitioners. While the participants enjoyed the game, there were some difficulties with the system in understanding some movements, such as a sideways dodge.

The system "through the looking glass" is self-described as "*You can play against your own reflection.*" [Kakehi and Naemura 2005] The system has a horizontal Lumisight table and vertical mirror. Lumisight technology allows for two different images to be displayed to the users on either side of a table. In this case the mirror reflects one of the views back to the user. The visual effect is a horizontal display surface twice the depth of the physical one, with the user's reflection of the other side. The user is able to play AR air hockey with himself or herself. This game provides a single user mode that is not found in the other AR hockey games.

Augmented Coliseum [Kojima, et al. 2006] is a special-purpose game developed for tabletop AR. It employs small active robots as game pieces. The robots are physically driven around on the tabletop by remote control. The tabletop display (front- or rear-projected) provides the virtual playing space. The AR information indicates virtual barriers, explosions, and gunfire. The game provides a nice blend of virtual and physical interactions, as the robots react to both physical and virtual stimulus. Figure 5 is a photograph of the game in action, with two physical robots playing on a front-projected virtual battleground.

SCORPIODROME also supports a mixture of physical and virtual elements of gameplay [Metaxas et al. 2005]. The physical aspects are based on remotely controlled robots, that is Scorpio bug creatures, as the robotic mechanisms. The robots are controlled by standard two-handed game controllers, and are tracked with an IS600 tracking system. A top-down data projector provides the AR elements for the game. This game provides a rich array of game elements: checkpoints, treasure (diamonds), weapons (bombs and missiles), shields, plasma storms, and sculls. The game design for SCORPIODROME was not as fully developed as the design for the Augmented Coliseum game, and as such is a simpler game.

The pOwerball game [Brederode et al. 2005] is a tangible tabletop game using projector-based AR. The goal of the game is to free a set of captive creatures. Physical game pieces, that is, trampolines, accelerators, and reflectors can be placed and manipulated on the table. These physical pieces control an AR ball that allows them to free the AR creature. The goal can only be accomplished through collaboration among the players. AR paints the game on the table and the physical objects, thus providing engaging and complex game spaces. The overall goal of the design is to foster social interactions between children with and without physical or learning disabilities. The game provides a nice blend of entertainment and education. The system was developed with Macromedia Flash MX.

3.3. Handheld AR

An exciting direction for AR gaming is the use of handheld display devices. They are very portable, and the pervasive nature of mobile phones makes it easy to deploy games in the community. The nature of the handheld devices combines the output (display on the device) and the input (buttons on the device) into one single entity. The computational/graphical power of the mobile phone and its integrated camera allows many computer vision-tracking solutions to be used on mobile phones. The vast majority of the games presented in this section are table-based, with one application at the end of the section focused on mobile-based systems. Personal digital assistant (PDA) devices provided the first handheld platforms for AR gaming. Tablet computer form factors are also being used for AR applications–for example the Apple iPad[6] and the Samsung Galaxy Tab.[7] These tablets have the same sensors (camera, compass, tilt, GPS, and such) as the smartphones, but the tablets have larger displays.

Wagner et al. [2004] developed one of the first handheld AR games, called The Invisible Train. They developed this with the ARToolkit and a custom framework, that operates with the Compaq iPAQ 3970 PDAs (400 MHz XScale). A physical wooden train track is placed on a table with optical tracking markers for registration. Virtual trains move along the physical tracks. The interaction with the game environment is done by indicating and changing the track switches and junctions. These changes manipulate the paths of their virtual trains. The goal of the game is to stop the trains from hitting each other. The novelty of this system is the early porting of ARToolkit to a PDA and the combined physical and virtual setting. There really is no extended gameplay, but the game is very engaging for short periods of time.

Reimann developed Kick-Real [Reimann 2005], an easy to use soccer game for mobile phones. The system is based on tracking the user's foot via computer vision, in order to kick virtual balls into goals. This is a simple game designed for quick gameplay for a short period of time. Paelke et al. developed an earlier version of the game, known as *AR-Soccer* [Paelke et al. 2004]. They evaluated the original game with 30 users, finding that: "*Most test users pointed out that the more [sic] physical interaction of*

[6]http://www.apple.com/ipad/.
[7]http://www.samsung.com/us/mobile/galaxy-tab.

standing and kicking (compared to just sitting and pressing buttons) caused a lot of fun and made the game much more exciting". A simple mobile phone version of tennis, called AR Tennis, was also developed [Henrysson et al. 2006]. In this game, players sit opposite each other with an ARToolkit-marked table between them. The game is shown on the mobile phone; tilting is the main interaction method. There the authors were exploring the concept of two-player AR games for mobile phones. This was also a simple game designed for short gameplay. For mobile phone games, short gameplay is very appropriate, since ad hoc gameplay to fill short periods of time is a key niche market for mobile phone games.

Wagner and Barakonyi developed an easy-to-use AR application to teach people Japanese *Kanji* symbols [Wagner and Barakonyi 2003]. This system is based on a Kanji training system developed by Barakonyi. The input and display device for this system is a PDA. Users are given an icon that represents the word they are searching for in a group of ARToolkit cards with Kanji symbols. This is a turn-based game. Once the card is flipped over, the system can determine if the correct symbol was chosen. Correct moves score points, and AR virtual objects are displayed to show the meaning of the Kanji symbols. The novelty of the system is in the optimization of software libraries on the PDA device. This game has a similar interface to the AR memory card games.

Mulloni et al. developed a competitive team-based handheld AR game, called Cows vs. Aliens [Mulloni et al. 2008]. The layout of the physical space has ARToolkit-like fiducial markers placed on the walls of the rooms. Players walk to the markers and interact with virtual content at that location using a Gizmondo game console. The idea is to save the cows by bringing them to your team's stable. Virtual arrows depict where the cows can move to (the other fiducial markers). Players can order cows to move or aliens to kill the cows. Players can only see the virtual game pieces when viewing a marker, but they can observe the physical movements of the other players. This makes for an interesting set of game conditions, since the players must understand both the physical and virtual worlds to win the game. This game is novel in that players have virtual strategies (such as hoarding resources) and physical strategies (such as physically blocking other players). The software for the handheld devices was developed with a Studierstube ES framework, and the tracking of the devices was done with Studierstube Tracking.

4. ACADEMIC OUTDOOR AR GAMING

The following two forms of outdoor AR gaming are examined next: head-down gaming with a handheld display and head-up gaming with an HMD. Due to their outdoor setting, these games are mobile applications, and since the games are played outdoors and are mobile, some form of compact portable computer is required. Both of these forms of gaming require tracking for location via systems such as GPS and robust orientation sensing. Most of them have been developed for play while walking, but Brunnberg developed a simple AR game for passenger in a car [Brunnberg 2002; Brunnberg and Ollila 2002].

4.1. Outdoor Head-Down Gaming: Handheld Displays

Outdoor head-down gaming presents visual information through a handheld device that augments the world in an indirect manner. Traditionally, a map format was used to place the user within the virtual environment. The display device is independently tracked by position and orientation from the player's body. This decoupling enables novel interactions, such that, for example, players can "shoot around the corner".

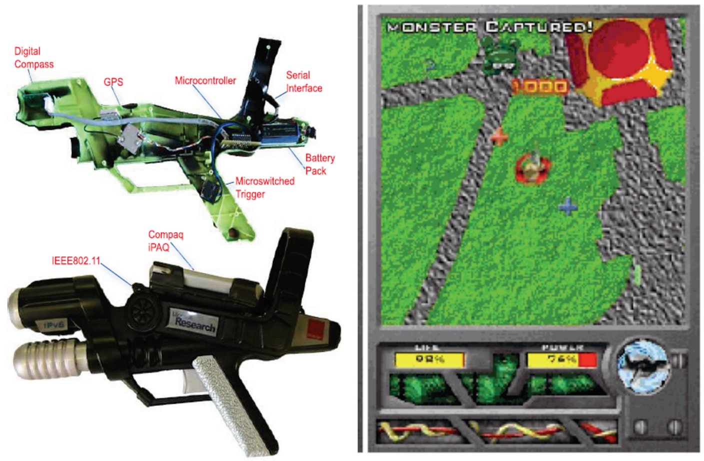

Fig. 6. (Right): The Real Tournament handset includes inbuilt GPS, electronic trigger, and digital compass connected to a Compaq iPAQ and teammates connectd via IEEE802.11 or GPRS. (Left): Screenshots as seen by a Real Tournament player. (With permission of Joe Finney, Lancaster University).

Players have the following two modes of operation: (1) operations performed while walking with the screen, head down; or (2) walking about looking at the physical world. The speed at which the players can move is dictated by the mode they are operating in. Players are able to move only slowly while looking at the screen, but to move swiftly, the player has to be able to look up and pay attention to the physical world. Location-based mobile phone games are an impoverished version of this form of gaming. The Blast Theory team has taken the concept of pervasive gaming and have come really close to the concept of AR [Benford et al. 2005].

The outdoor handheld adaptation of Real Tournament [McCaffery and Finney 2004; Mitchell et al. 2003] is a fine illustration of the AR game concept. The players grasp a gun-like device and move by walking and turning unencumbered. The players' movements in both translation and orientation are simultaneously linked to the physical and virtual worlds. The Real Tournament handset includes an inbuilt GPS, an electronic trigger, and a digital compass. All of these components are connected to a Compaq iPAQ and the teammates are connected via IEEE802.11 or GPRS; see Figure 6. The gun-like interface supplies a superior affordance for first-person-shooter-style games. The nature of the technology allowed for game designs over very large physical areas; and this is a unique nature of heads-down gaming. Large game spaces can be mapped onto large physical spaces. Tasks like registering to physical objects, such as buildings, are not required.

Reimann and Paelke expanded an outdoor AR adaptation of their game, *Forgotten Island,* with their game engine MobEE [Reimann and Paelke 2005]. The outdoor adaptation employs GPS for course tracking and ARToolkit markers for registering the game entities onto physical objects. The game genre is mixed, with elements of fighting and puzzle solving. The players are directed to places in a large identified region, such as a campus. The game was implemented on an HP iPaq Pocket PC PDA, including a plug-in FlyCam. As a different form of gaming, Burigat and Chittaro developed LAMP3D, a location-aware tourist application which can display 3D VRML graphical objects on PDA [Burigat and Chittaro 2005]. The additional infrastructure for placing markers in the physical world makes this game more difficult to scale up to larger areas.

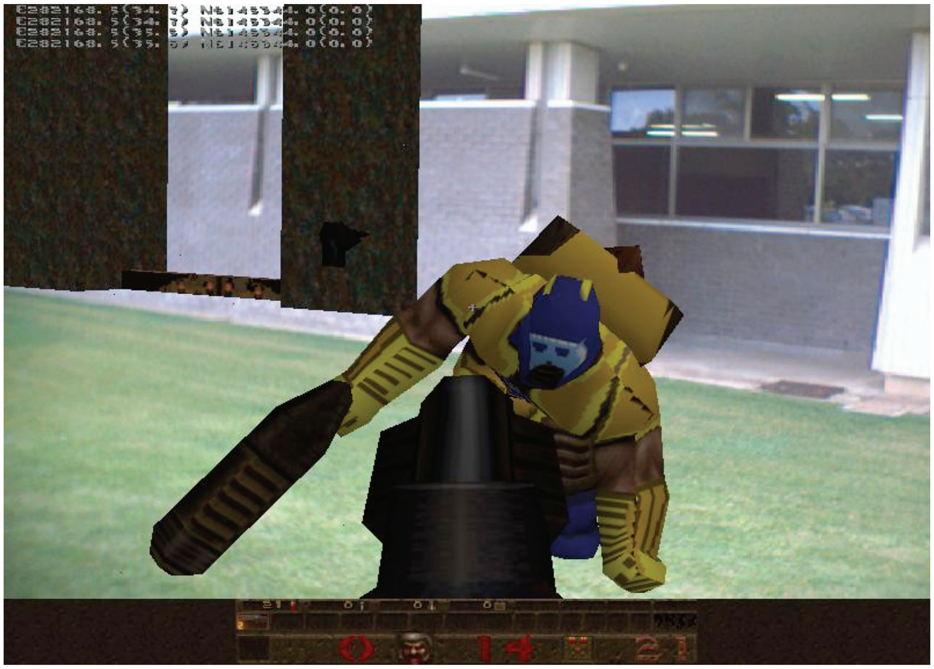

Fig. 7. Screenshot of the user's view of ARQuake.

4.2. Outdoor Head-Up Gaming: Head-Mounted Display

ARQuake is the first reported example of an outdoor head-up game is [Piekarski and Thomas 2002; Thomas et al. 2000; Thomas et al. 2002], an outdoor AR version of the game Quake[8]. Figure 7 depicts the user's view from the HMD of the ARQuake game.

ARQuake is a first-person perspective application with the following attributes: (1) The application is situated in the physical world. (2) The point of view, which the application, shown to the user, is completely determined by the position and orientation of the user's head. (3) Relevant information is displayed as AR information via an HMD. (4) The user is mobile and able to walk through the information space. (5) The user interface requires only a simple handheld single- button device.

In the ARQuake application, the physical world is modeled as a Quake 3D graphical model. The AR entities (monsters, weapons, and objects of interest) are displayed in a spatial context with the physical world. The Quake model of the physical world (walls, ceilings, and floors) is not shown to the user: the HMD allows the user to see the actual walls, ceilings, and floors, which ARQuake requires for internal models only. Coincidence of the physical and virtual structures is critical to the game. The AR application models the existing physical outdoor structures as clear objects, and so exclusion of their rendered image from the display becomes, in effect, one of the rendering techniques. As with Quake, a user looks in a particular direction to aim his or her weapon. This form of interaction is a particularly intuitive feature for systems employing HMDs for first-person shooter games.

Human Pacman [Cheok et al. 2003, 2004; Magerkurth et al. 2005] also explores the notion of wide-area outdoor gaming, based on Pacman, the classic arcade game from Atari. The human Pacman players wear outdoor AR systems to walk around in

[8]http://www.idsoftware.com/.

a physical game space, avoiding the game's enemy entities, ghosts, and picking up plain and magic cookies. The ghosts are played by actual people, also equipped with wearable outdoor AR systems, making this a competition-based game, with one team of two Pacman players plus two helpers, and the other team of two ghosts and two helpers. The goal of the Pacman players is to physically pick up as many instrumented game pieces, plain cookies, as possible. There are also AR cookies to pick up, and the game's paths are presented as AR information. The goal of the ghost players is to *catch* the Pacman players by physically tapping them on the shoulder. Each helper is assigned to one player, and provides overall situational awareness to that player through a VR interface to the game world. The helpers communicate through voice-over IP. In addition, the game has AR magic cookies that allow the Pacman to capture the ghosts. While this is a very entertaining game, it requires a large amount of physical infrastructure in an outdoor setting. This gaming concept would be more appropriate in a theme park, which could support such an infrastructure.

Broll et al. [2006] developed three outdoor AR gaming systems with their mobile AR hardware and software (MORGAN) technologies. All the games provide a first-person-perspective AR view of the game entities. Broll et al.'s first game NetAttach is an indoor and outdoor scavenger hunt-style game. The players must destroy a central database. This is done by collecting items outdoors in order to decipher passwords and thus gain entrance to the database. The indoor player provides information to the outdoor player with a voice connection, and the indoor player is allowed to view a map which has additional information. The outdoor users employed GPS for location information, but wore ARToolkit markers on their chests for greater position accuracy. Broll et al.'s second game, Epidemic Menace, is a cross-media game, consisting of competing teams of two players. The media includes both live AR graphics and predefined production-quality media. TimeWarp is the final game developed, where the central story is about Heinzelman and involves characters that time travel. This game is designed to cover the city center of Cologne in AR graphics. ARCHEOGUIDE is an early example of 3D HMD AR information in a wearable form [Gleue and Dahne 2001; Vlahakis et al. 2001, 2002]. This project explored the visualization of ancient Olympia, Greece. ARCHEOGUIDE is an early example of the use of outdoor augmented reality, and one for the first outdoor 3D tourist applications. This form of presentation to users of particular sites is now more possible with the advent of high-end smart phones and easy access application sourcing (the Apple app store, for example).

Avery et al. [2005] developed AR Moon Lander, a game that puts the user in control of a moon-lander module. The player must manoeuvre a moon lander to touch down safely onto the landing pad. The game is based on the 1979 arcade game, Lunar Lander. The game was developed for low-cost computing hardware: HMD that do not have stereoscopic displays, consumer grade GPS, and low-end orientation sensors. This makes it very difficult to judge depth, and very hard to determine if the lander is directly over the landing pad along the Z axis (perpendicular to the screen). During game- play, the user can move around to the side of the lander, where left/right movements relate to forward/back movements from the original location. The lander lands on a virtual overlay of a moonscape. By centering the game on an object that floats in space, the user cannot see how accurately it is aligned with the physical ground. There is no tight registration of any virtual object to the physical world, so drift does not become a problem. The objective is to land the lander on the landing pad, but the landing pad is also virtual, so any drift affects both virtual objects equally.

5. ACADEMIC MIXED MODES OF AR GAMING

A number of games have combined different display technologies into a single gaming experience. This includes the concept of *through walls,* which is defined as follows: some users are interacting with an application indoors while other users are interacting with the same application in real-time outdoors [Thomas and Piekarski 2009].

The Citywide project investigated a number of "through the walls" games [Izadi et al. 2002]. The first demonstration was a game called The Haunted Campus. In this game, the outdoor users would physically explore a university campus looking for hidden virtual information. They employed a PDA to visualize the virtual avatars. The indoor users provided the "smarts" for the system and intervene during the game. The second demonstration was called "Unearthing Virtual History". This application has sonic interface to represent hidden artifacts. The authors employed two complementary software platforms, MASSIVE-3 for building collaborative virtual environments, and EQUIP for fine-grained data sharing.

Herbst et al. have explored experiences in the spatial and the temporal dimensions with a pervasive outdoor AR game for exploring history in an old part of Cologne [Herbst et al. 2008]. They employed a novel concept of presenting AR historical information in different time periods. They explored the use of both HMD and handheld display technologies (a Dell Aximx51v operating a Windows Mobile 2005). The handheld device not only supplied information, but also provided the user interface to the system. The authors noted that care must be taken in the complexity and content presented on the handheld device. Hall et al. [2001] explored the concept of allowing the visitor to a museum to become a virtual archaeologist. Employing the MORGAN AR technologies, they were able to provide an engaging experience to enhance the users' social experience and education concerning antique artifacts and their associated history. They employed indoor VR, indoor AR, and outdoor AR visualizations. A wide array of display technologies were employed, including HMDs, handheld devices, and notebook computers.

Sandor and Klinker developed a rapid prototyping software infrastructure for AR [Sandor and Klinker 2005]. This easy-to-use infrastructure was employed for a number of industrial applications. The authors built an AR game, SHEEP [MacWilliams et al. 2003], that exploits TUIs. The game entails herding and attracting the virtual sheep. A large part of the gameplay was based on the ability to interact in a full 3D manner in a large room. The game supports a variety of display technologies: HMD's, handhelds, and notebook computers. The game supports both physical objects, to be manipulated, and virtual ones. The goal is to herd sheep into your corral, while not letting others steal your sheep. This game has a similar blend of physical and virtual skills as the Cows vs. Aliens game.

The Augurscope project [Holger et al. 2002] is unique, as it employs a large tripod-mounted display (approximately the size of a studio TV camera and tripod), that has GPS tracking and 2DOF tracking of the display. Users are able to wheel the Augurscope around outdoors to provide an immersive AR experience. The authors built an historical application for virtually recreating Nottingham's medieval castle, which has been removed and replaced by a ducal palace. There is a recreation of the castle, which includes multi-media content with virtual actors. This project investigated a new form of display technology to enable the user to experience history with a different AR experience. The Augurscope project technology was developed with a more complex array of sensors and display technologies than the ARCHEOGUIDE, and was designed to provide a more immersive feel. ARCHEOGUIDE employed a more mobile set of technologies, and made a system that makes walking through ancient buildings easier.

6. COMMERCIAL AUGMENTED REALITY GAMING SYSTEMS

Commercial AR games can currently be found on major gaming platforms, including consoles and handheld devices. This section will provide a number of examples of AR games found on these different platforms. The console-based AR games are all indoor games, and the handheld games range from indoor to outdoor, allowing for both locations.

6.1. Console-Based Games

Console-based games all employ the video-based see-through technique to support the AR presentation. The AR game is viewed on the display device of the games' console, typically a television. Due to the cost of launching a console-based game, the number of AR games is quite limited as compared to the AR games on handheld devices. However, the quality of the games found on consoles is of a very high standard. The two AR example games described use different tracking technologies. The Eye of Judgement AR game uses fiducial marker-based tracking, and Start the Party! employs a custom six degree of freedom tracking system.

The Eye of Judgement game[9] for the Sony PS3 is a third-person AR game which incorporates a digital video camera to capture the game board, and displays the AR version of the game on a television. This form of gaming requires the users to focus on both the physical game board for a part of the game and the AR version displayed on a monitor. Playing cards are placed on the game board to put them into play. Once on the game board, they act as fiducial markers to track augmented reality monsters and game pieces displayed on top of them. The games engine drives the 3D graphics of the cards once they are in play. This game was one of first commercial AR games on the market to make use of fiducial markers.

Start the Party![10] on the Sony PS3 employs the Playstation Move handheld six degree of freedom input device and the Playstation Eye camera system. The Playstation Eye is a follow on from the Sony EyeToy, which was the first commercial AR game in 2003. The EyeToy used a mirror metaphor to place the player in the game, where the player views himself or herself in a mirror image enhanced with augmented reality graphics over the video image. Sony enhanced this experience with the new Playstation Move input device. The Move provides a six degree of freedom physical input device in the user's hand(s). This allows for a more complex gaming experience than before. Start the Party! employs the same mirror image AR technique, but the interaction is much more expressive than vision tracking the user's hands in the EyeToy. The Move device is overlaid with other 3D graphical objects, such as large pins, paintbrushes, and swords.

6.2. Handheld-Based Devices

The use of handheld devices has proved to be the largest area of growth in commercial AR gaming. While there are a vast number of handheld devices that support AR gaming, Table I depicts a representative sample of the current state of popular platforms that support commercial AR game titles. These devices all employ video-based see-through display technology to support the AR process. The major difference is in the sensing technologies each of the devices contain. The different sensors allow for the support of the various tracking and registration techniques. The AR.Drone GAMES are unusual AR games for the iPhone and iPad, in that they allow the user to experience, via an AR telepresence, flying a drone hover craft.[11]

All of these devices support fiducial marker-based tracking for a set of AR game titles. The HTC Magic (and many other Android-based phones), and the iPhone 4 (and iPhone 3GS) all support tilt sensor games and GPS with orientation sensor games.

[9]http://www.eyeofjudgment.com/.
[10]http://us.playstation.com/games-and-media/games/start-the-party-ps3.html.
[11]http://ardrone.parrot.com/parrot-ar-drone/uk/ar-games.

Table I. Commercial Handheld Display Devices that Support AR Games

Device	Camera	GPS	Compass	3-Axis accelerometer	3-Axis Gyro
PSP[14]	Add-on	Add-on	No	No	No
Nintendo DSi[15]	Built-in	DS Add-on only	No	No	No
HTC Magic[16]	Built-in	Built-in	Built-in	Built-in	No
iPhone 4[17]	Built-in	Built-in	Built-in	Built-in	Built-in

6.2.1. Fiducial Marker-Based Tracking. EyePet[12] is a PSP AR virtual pet game that uses fiducial markers for registration and tracking. This game allows users to move their virtual pets around the house or even outdoors. The standard virtual pet gaming features include washing, feeding, and changing the appearance of the pet. There is an interesting health- checking feature where the user can perform an X-Ray-like operation on the virtual pet. There is also a PS3-based version of EyePet that incorporates the Move input device.

The inviZimals: Shadow Zone PSP AR game[13] allows users to collect and battle animals in the game. The game employs fiducial markers, which can be moved around the house, for registration and tracking. The game has a background story to explain why these animals are invisible, except when viewed through the PSP device, and gives a more compelling reason for the use of augmented reality. When the markers are placed close together, the animals interact with each other.

Drift[18] is a simple car-racing game based around a fiducial marker placed on a table. The user controls the game through the iPhone touch screen. This game is designed to be played anywhere the small fiducial marker can be placed, and is designed for a quick gaming experience. A number of inexpensive phone-based games have been developed for short gameplay.

6.2.2. Tilt Sensor-Based Tracking. Fairy Trails[19] is an iPhone platform game, which provides a quick gaming experience involving rendering augmented reality “fairies” on top of the player’s current location. The player taps on each fairy to collect it. The player looks for the fairies by physically rotating his or her body and tilting the camera. There are quite a few AR games based solely on this form of interaction. The games can easily be played anywhere, and do not require the user to walk physically. However, no interaction with the physical world is supported by this game.

Arcade Reality[20] is an AR first-person perspective shooter game. The iPhone and Palm Treo are the currently supported hardware platforms. In the game, the user aims the cross-hairs in the middle of the screen at the virtual aliens and asteroids and then shoot them. Standard additions of better weapons, shields, and health can be obtained during the game. It also does not have any interaction with the physical world.

6.2.3. GPS with Orientation Sensor-Based Tracking. SpekTrek[21] was developed for both Android-based phones and the iPhone. This is an augmented reality ghost-hunting game that works in a head-down map mode and in a heads-up AR mode. The map

[12]http://www.eyepet.com/.
[13]http://www.invizimals.com/.
[14]http://www.playstation.com/.
[15]http://www.nintendo.com/.
[16]http://www.htc.com/.
[17]http://www.apple.com/.
[18]http://www.slapdowngames.net/.
[19]http://freeverse.com/.
[20]http://www.toyspring.com/.
[21]http://spectrekking.com/.

Table II. Augmented Reality Gaming Taxonomy

	Indoor	Outdoor
HMD	☑	☑
Handheld	☑	☑
SID	☑	☒

mode allows the user to navigate to the location of a ghost or game piece. The user physically walks around in order to investigate the virtual world. The heads-up AR mode provides a first-person perspective AR view of the game and physical world. This mode allows the user to capture ghosts and pick up game items. What makes this phone-based game unique is that it is designed for a longer game-playing experience: 15 minutes to over 45 minutes.

7. DISCUSSION

This survey provides an overview of the current state of the art for gaming applications in mixed and augmented reality. The survey provides an exploration of research examples of different forms of AR gaming. The focus is on the novel aspects of each of these gaming systems. This article does not focus on AR gaming reported in the popular press. Clearly, there are a number of excellent AR gaming experiences, such as AR Zombie,[22] that demonstrate novel aspects of AR gaming, but the focus of this survey is on results reported by the academy and commercial AR games. Overall, AR is a growing method for presenting a gaming experience for users.

A simple taxonomy was used to partition the different AR form factors, Table II outlines this taxonomy (at the time of this publication there are no outdoor SID games). The descriptions of the different AR games were placed in this taxonomy. A number of reported AR games were of mixed mode across a number of the cells of the taxonomy.

Overall, there has been a large academic research effort on HMDs for AR gaming. This is due in part to the length of time researchers have been experimenting with this form of display technology, and not a real indication of the current focus of AR gaming. The number of commercial AR games with handheld display technologies indicates this form of platform will be at the forefront of research and deployment of AR gaming in the near future. SID technology will also be an active area of investigation for AR gaming. In particular, for SID displays, I see group-based SID games that allow people to act silly in front of their friends and family as a major new development. Informal evaluations regarding the use of AR for game playing indicates that people enjoy this environment [Thomas and Piekarski 2002]. There are a number of issues and possible areas of investigation to produce better AR gaming technology, such as safety, modeling tools, and the standard set of outdoor AR problems.

Museums are a sound place to embed AR activities because they provide a stable infrastructure. Regular placement of AR in museums should be seen in the near- to-medium-term future. The main goal of museums is to provide additional information about the artifacts on display, in other words to augment the artifacts. Stapleton et al. [2005] provide an excellent example of this with Sea Creature Journey. They enhance a static display of fossils with AR to form an "Experiential Learning Landscape". The use of AR engages museum patrons, particularly the children, thus providing a better learning experience.

The extension of spatial immersive displays to spatial augmented reality (SAR) [Bimber and Raskar 2005] is an exciting new direction for AR gaming. The Virtual

[22]http://www.augmentedenvironments.org/lab/research/handheld-ar/arhrrrr/.

Showcase [Bimber et al. 2003] is a novel spatial augmented reality display targeted at museums. The Virtual Showcase is in the form factor of a traditional museum showcase. The system applies half-silvered mirror beam splitters, which permits stereoscopic 3D overlays together with physical artifacts. The system permits up to four head-tracked people at one time. Data projectors dynamically illuminate the physical subject matter on a per-pixel basis, allowing for sensible occlusion effects involving real and virtual objects. The system also supports a wide range of storytelling components to provide a full museum experience.

SAR visualizations may help present information in an educational setting, whether in a school or museum. Initial investigations into improving museums with projector-based augmented reality has shown that they really benefited from this technology [Bimber et al. 2005]. SAR [Raskar et al. 2001] projects digital information directly onto a physical object, which enables picking up physical objects and manipulating them. This is inherently engaging to the public. SAR allows users to physically pick up surrogates of heritage artifacts for examination. This form of technology can also be employed to annotate existing heritage artifacts by adding extra information.

In hindsight, my experience with AR gaming [Avery et al. 2006, 2005; Cooper et al. 2004; Heinrich et al. 2008; Piekarski and Thomas 2002, 2003; Porter et al. 2009; Thomas et al. 2000; Thomas et al. 2002; Thomas et al. 2002; Thomas and Sandor 2009] has allowed me a broad understanding of the field.

Finally, I would like to address two questions: Overall, augmented reality gaming is an exciting research domain; and this article provides a mapping of academic research achievements to date. The current commercial AR games depict an emerging growth area, which has only just begun to develop.

(1) *What has my experience with this technology been in comparison with what has been reported in the literature?*

My experience with the limitations of current technology is similar to problems reported in the literature. The availability of affordable sensors with the required precision and accuracy has been and still is a real issue. There is no sense in developing gaming technology that is way beyond the price of current consumer-grade technology. I found that the collaboration between technologists and game design/artists creates successful games. As with any electronic gaming, this process is a fusion of the power of modern computing technological advances and creative graphics, storytelling, gameplay, and design. Technology is never going to outperform good gameplay. New technology will enable game designers to develop different and innovative gaming styles.

(2) *If I were to embark on this technology today, what mistakes would I avoid and what directions would I go in?*

First of all do not fight the technology. We had a saying during the development of the a_rage system, “Embrace the cheapness!” The idea is to leverage the sensor noise and error. Our system displayed virtual objects “swimming” around on the screen; so we made flying aliens float in the sky. We focused the gameplay on the screen graphics and not on a fine registration of the physical world. The GPS allowed users to step into large areas and the user would shoot virtual objects but not physical ones. As I previously stated, gameplay is the most important feature. If I were to make a game to sell, I would not develop one on a futuristic platform, but rely on a stable platform such as the new smart phones. For more academic gaming research, I would focus on new methods for interacting with the games. The question I would ask is *What is the next Kinect?*

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