

Outdoor Augmented Reality Gaming on Five Dollars a Day

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Abstract

The latest hardware available for creating playable augmented reality games is too expensive to be used in consumer-level products at the current time. Low-end hardware exists that is much cheaper, but the performance of these hardware components seems to be inadequate for use in AR games in their current state. This paper discusses the hardware options available for a consumer-level AR gaming system, as well as the rationale behind selecting an appropriate sensor technology, head mounted displays, power sources, and controllers. We also outline the limitations presented by these hardware components and how they affect the possible game play. This paper presents a novel set of game design techniques and software solutions to overcome many of the hardware's limitations, and allows for games to be created that do not require more expensive high-end hardware platforms.

Keywords: augmented reality, gaming, and game design.

1 Introduction

The Wearable Computer Laboratory of the University of South Australia has been investigating mobile Augmented Reality (AR) for a number of years (Piekarski 2004, Piekarski 2003). A major application of the science and technology of this research is in the field of AR gaming (Cooper 2004). Although we have demonstrated AR technologies for outdoor games, the hardware platforms are primarily designed for use in our research into user interfaces and 3D modelling. Our research AR hardware platform requires state of the art display and tracking technology, and is shown in Figure 3. The cost and form factor of this technology is not appropriate for a gaming platform which is affordable for use by the general public.

This paper presents our design and implementation solutions for the production of consumer level hardware and software suitable for outdoor AR gaming. The title of our paper is worded in a similar spirit to VR on Five Dollars a Day (Pausch 1991). Key to making games playable is proper game design which exploits the strengths of the low cost hardware while minimising any limitations present. Figure 1 shows a photo of our Moon

Lander game in operation outdoors, taken through an optical see-through head mounted display. The virtual objects in the game are superimposed over the user's view of the physical world.

In this paper, we firstly discuss the general concept of AR with a set of example AR applications. With an overview of AR gaming, we discuss a set of core technologies (display, tracking, and power) in terms of their limitations and purely technological solutions. Using these limitations and technological solutions, we have developed a set of game design concepts to produce playable games which are immune to any limitations present. Our outdoor AR game Moon Lander is presented as an example of our technology and new game design techniques. We finish the paper with some concluding remarks.

2 Background

Our AR gaming technologies draw from a vast array of previous investigations in the fields of augmented reality and wearable computing. This section provides a brief introduction to augmented reality, and a number of indoor and outdoor AR gaming systems are presented. We try to draw from the game play of these systems to build better outdoor AR games.

2.1 Augmented Reality

Augmented reality is the overlaying of registered computer generated images over the user's view of the physical world (Azuma 1997). When accurately positioned and orientated relative to the user's view, these generated images give the appearance of virtual objects situated in the physical world. These images are displayed to the user via a head-mounted display (HMD). We are



Figure 1. Photo of our Moon Lander AR game

currently mainly interested in optical see-through HMD technology, which allows for the computer generated images to be projected on top of the physical world using some form of optical combiner. Figure 2 depicts how computer generated images are optically combined with the user's vision of the physical world.

Augmented reality has a wide variety of uses, ranging from simple navigation systems which display compasses and other cues to the user (Suomela 2000, Thomas 1998), to supporting complex 3D modelling applications controlled by the body (Piekarski 2003). The ability to still see the physical world assists in many complex tasks, such as aircraft manufacture (Curtis 1998), maintenance and construction (Feiner 1993), and medicine (State 1996).

Mobile AR as used in an outdoor environment allows a user to be untethered to any particular physical location and enables them to freely explore large environments. The first example of this form of mobile augmented reality was the Touring Machine (Feiner 1997) that allowed users to freely walk around a University campus with overlaid information. The user would carry around a backpack mounted computer system, GPS tracker, and power supply. The user also donned a helmet with a head orientation tracker and HMD. Tourist information would be displayed to the user on both a head mounted display and a handheld computer. As they explored the campus, the system would overlay labels on buildings and help them with navigation. The user's position and head orientation controlled the AR view of graphical information, and the handheld computer allowed the user to enter commands to change the content of the displayed information.

The Tinmith system (Piekarski 2003) is a outdoor 3D modelling environment, which allows the user to construct complex 3D shapes using body position, head orientation, and hand gestures as the interface. Figure 3 shows the latest backpack which is used to operate this system outdoors. The simplest interaction is to physically walk around the environment and view existing 3D information. Rather than being limited to only the viewing of information, Tinmith also allows the creation and editing of new geometry in real-time while outdoors. The mobile user is able to place down existing primitive objects, and manipulate them using the hands. Furthermore, new objects can be created from scratch using a variety of techniques entitled 'construction at a distance'. Using line of sight techniques, projection of points against AR working planes, and various carving and painting methods, complex objects can be created with relative ease. Existing physical objects can be captured into the system, or new objects can be created from scratch.

2.2 Indoor Augmented Reality Gaming

There have been a number of previous HMD-based AR games. Ohshima et al. developed a collaborative augmented reality game AR2Hockey (Ohshima 1998), a virtual air hockey table game. An interesting feature of this game is the ability to play in either video or optical see-through mode for the HMD. Another virtual air

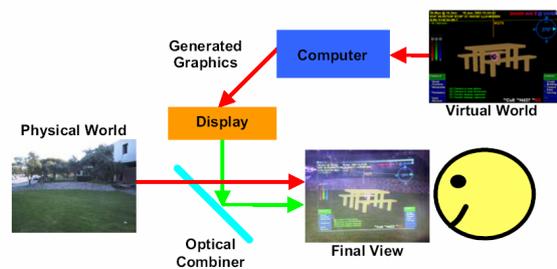


Figure 2. Optical see-through AR schematic

hockey game was created using the Hi-Space table at University of Washington (May 1999). The Hi-Space table uses a rear-view screen mounted at desk height with tracking performed by three cameras fixed at ceiling height. Interaction is performed with the table using touches of the surface and gesture recognition. The Hi-Space table allows two players to use their hands as virtual paddles to interact with the virtual puck, and each player can place two physical objects on the table to act as virtual defenders. Their position is calculated and a virtual representation of them is added to the game. Touch-Space (Weihua 2002) is a mixed reality game that is situated in a physical room-sized space. A key aspect of the game was the seamless merging HMD-based AR, 'virtual window' AR, and virtual reality. Sato and Koike (Sato 2002) developed a force feedback mixed reality version of the famous Rubik's cube puzzle. The user places their hands in a string-based haptic device with an LCD monitor at a comfortable viewing height. The user "sees and feels" the virtual cube puzzle, and they are able to rotate the faces in a similar way to the real physical puzzle.

AquaGauntlet (Tamura 2001) is a multiplayer game where users wear video see-through HMD's and shoot monsters in a room. When players look at their team-mates they see them with an augmented helmet and gun. This helps increase the atmosphere, and helps hide the HMD and tracking devices on other players which could possibly reduce the gaming experience. This system also implements realistic looking shadow and environmental effects on the real environment. MIND-WARPING (Stamer 2000) involves 2 players, one wearing a traditional HMD and the other (the "wizard") sits at an



Figure 3. The latest Tinmith Backpack 2004 design for supporting high-fidelity augmented reality



Figure 4. ARQuake screenshot

interactive workbench which has images projected on to it from underneath. Objects on the workbench are tracked by monitoring reflected infrared light. The wizard has a top-down view of the game, and by physically moving monster objects they can attack the HMD wearing player who must defend themselves from a first-person point of view.

Locating games indoors greatly simplifies the development process for many reasons: commercially available accurate trackers designed for indoor virtual environments can be easily integrated, users are typically tethered and restricted to a fixed area indoors, HMDs are mainly designed for indoor operation, and the availability of powerful CPUs and 3D graphics chips to support high quality rendering. An indoor setting is by its very nature a highly controlled environment; thereby relieving the developers from worrying about difficult conditions associated with working in outdoor environments (Azuma 1999).

2.3 Outdoor Augmented Reality Gaming

Performing outdoor AR is a much more difficult task than implementing the indoor AR systems described previously. Designing a system that is powerful enough, uses mobile power sources, is able to work outside, and able to withstand tough environmental conditions is difficult and introduces tradeoffs. Due to these difficulties, there are much fewer outdoor AR systems and even less numbers of outdoor AR games developed. ARQuake (Thomas 2000) was a pioneering game in this domain, and was later followed by others such as Human Pacman (Cheok 2004).

In ARQuake, the popular PC-based game Quake (Id Software 2001) was converted to work with the Tinmith system described previously (Thomas 2000), as shown in Figure 4. ARQuake replaced relative movements from the keyboard and mouse with absolute positioning from a GPS unit. The game player's movement was controlled by physically walking around outdoors. The viewing direction of the user was obtained from a three degree of freedom TCM2 digital compass which was also passed into the ARQuake game. By creating virtual models of all the buildings on the campus and then texturing them black (so they would appear transparent in the optical HMD, allowing the view of the real building to be seen) the game managed to achieve proper occlusion of virtual

objects in the world when monsters were located behind buildings.

Human Pacman is a second example of an outdoor AR game (Cheok 2004), with its overall game play emulating the original 2D Pacman arcade game. The mobile AR system was very similar to that used by other outdoor AR system, but there were new physical interactions supported by the game. The Human Pacman player picks up both virtual objects, and also special objects which are implemented as small Bluetooth devices with touch sensitive pads. When the user physically picks up one of the objects, the wearable AR system detects this action and communicates with the game that it has been collected.

These two games have a design where the players move freely using their body (and accurate tracking devices) to control the game. ARQuake and Human Pacman both require the user to walk over virtual objects smaller than the accuracy of current low cost GPS systems however, and so the systems are not able to be produced cheap enough for the consumer market. Also, by aligning the virtual game pieces to the ground the tracking errors are very noticeable, particularly with low-cost sensors. These two games were designed to be played on a campus-sized game area, but this size game area possesses the following two problems: firstly, this area size is not convenient or accessible to everyone, and secondly, the games are designed for a specific location and not playable in other locations. If the game were to be played in a new location, a new game level would have to be developed for the environment.

3 Low Cost Outdoor Augmented Reality

As previously mentioned, we have developed a system constructed from the minimal set of required components to be able to make outdoor AR games. The target total cost for the components is low enough to be affordable on a consumer level. We have based this cost as roughly equivalent to the cost of a games console, which when first released are generally between A\$500-A\$1000. We make the assumption the consumer already has a computer or games console to connect to our system, and so the cost of the computer is not taken into consideration. The AR gaming system consists of a head mounted display, an orientation sensor, position tracker, power

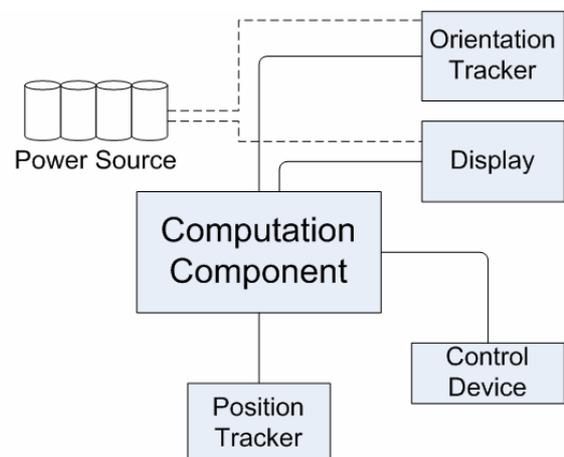


Figure 5. AR gaming system component overview

supply, and a user input device. Figure 5 provides an overview of the AR gaming system components and how they are connected. The dashed lines show the electrical power connections, and the solid lines show the data connections. The position tracker and control device, in our system are powered via the data connections from the computer. A detailed description of a set of core technologies (display, sensing, power, and input) in terms of their limitations and purely technological solutions is presented in this section.

3.1 Display

For our system we use an IO-Glasses optical see-through HMD, which is shown in Figure 9. This display is very low cost due to its operation at PAL resolution and being non-stereoscopic. Optical see-through uses cheap optical combiners rather than expensive and power consuming graphics hardware required for video see-through. Optical combiners allow the use of much simpler 3D graphics support and also reduced size of the components. The image is passed through a half-silvered mirror or prism, and combines the image of the physical world with computer-generated images provided by an LCD screen inside the HMD. Although the LCD display in the HMD is quite small, mirrors and lenses are used to produce fields of view that are wide enough for the user to see the projected information.

Video see-through displays require a small video camera to be mounted to the front of the HMD. The images of the physical world are captured by this camera, and then are combined with the computer generated images via image processing capabilities of the graphics hardware in the computer or games console. Using a video-see through display requires extra hardware (in form of the camera) and more complex graphics hardware support. A second method of combination of images may be accomplished by chroma-key hardware such as used to render backgrounds on TV. This type of functionality is not normally present in games consoles, although recently the Sony EyeToy has demonstrated that platforms such as the Sony PlayStation 2 possess this capability. In the future we may explore the use of video see-through displays.

When comparing different HMD types, there has been quite a lot of in-depth research in this area (Rolland 2000, Rolland 1994). Although we have chosen to use optical see-through displays, there are a number of limitations which will be summarised here. The first is that the intensity of the images produced by the LCD does not appear as bright as the physical world. The luminous contrast between the HMD image and physical world visual feedback is often quite low, producing dull and “ghosted” images. In lower light conditions, such as under shade or on an overcast day, optical see-through works well. The additive process of combining light from the physical world and light from HMD does not allow for proper occlusion of the physical world from the virtual world. Figure 6 is a view of AR rendered information with optical see-through combination, and this image highlights the ghosting effect previously described; the physical world appears through apparently transparent virtual objects and colours of the virtual objects appear to

be “washed out.” Figure 7 illustrates the use of video-see-through technology, with the virtual objects completely occluding the physical world and the colours being much more vibrant. However, this comes at the cost of having to view the world only through the reduced resolution of a video camera with a limited field of view, and many cues which are normally used by the user from the physical world are severely attenuated.

The main reason that we have selected optical see-through displays for our consumer-level system is that they are inherently much safer. Any number of problems could cause a display to stop working, whether it is loss of power, loss of signal, or hardware/software failure. When an optical see-through display loses power, only the computer image stops being displayed and the user may still view the world through what appears to be a dark pair of sun glasses. When a video see-through display stops working however, the user can no longer see the physical world and must remove the HMD to be able to see properly. With the user losing sight of the physical world, they could injure themselves by falling over or hitting nearby objects which could be very dangerous.

3.2 Orientation Tracker

There are a variety of orientation trackers available, varying in price and accuracy. We investigated three different trackers: the TCM2 digital compass, InterSense InterTrax2, and InterSense InertiaCube2.

The TCM2 is a magnetic sensor which measures the Earth’s magnetic field to estimate the user’s heading, and



Figure 6. Example view of optical-see-through augmented reality in use outdoors



Figure 7. Example of video-see-through augmented reality in use outdoors

uses accelerometers to measure pitch and roll. During testing, Azuma et al. found that the TCM2 produced errors of up to ± 3 degrees, and values that fluctuate ± 0.5 degrees (Azuma 1999). When this tracker is being used for orientation on even a very stable AR system, this fluctuation will cause the screen to “jitter” a very noticeable amount by the user. As pointed out by Azuma, ± 0.5 degrees is quite a large angle and is equivalent to the relative width of a full moon when standing on earth. The use of a TCM2 digital compass mounted on a dynamically moving user’s head produces even worse jitter, especially when they are walking. We have found during testing that when a user is walking or making rapid head movements, the shock associated with these movements produces even worse errors than the sensor claims to produce, and makes the system unusable. In a game system where users expect images to be stable in order to aim accurately and select virtual objects, errors like this would confuse and irritate them.

We also investigated 2 trackers produced by InterSense, the InterTrax2 and InertiaCube2 (Foxlin 1994). These devices use magnetometers and accelerometers like the TCM2, but also use gyroscopes to improve performance. Although gyroscopes drift over time, they produce smooth and accurate values in the short term. By combining these three sensing technologies with a Kalman filter, the results from these InterSense devices are much smoother and more accurate than the TCM2. The two InterSense products use similar types of technology, with the main difference being price and the quality of the components.

We have used both of the InterSense trackers and believe that the InterTrax2 is most suitable for this system because it is much cheaper and can theoretically perform within the requirements that have been defined for this gaming system. It was found however, that the InterTrax2 has multiple limitations which prevent it from being ideal in a gaming system. These include being unusable if the pitch exceeds 80° and also if the tracker is not stationary when the software is initialised. Until we can more accurately understand and deal with these limitations, we are using the InertiaCube2 tracker for testing.

3.3 Position Tracker

When working in outdoor environments, there are very few options to choose between for performing position tracking. While there has been some work with tracking natural features (Chia 2002) and tracking known environmental features (Behringer 1998), the results are not good enough to be used in general purpose AR systems yet. There are currently no known vision tracking algorithms which are able to perform in unknown environments without the use of some other sensing technology. Based on this, we have decided that the use of Global Positioning System (GPS) receivers is the only way to perform reliable position tracking outdoors.

There are a range of GPS receivers available, and the position accuracy achieved varies depending on the cost of the unit. Real-time Kinematic (RTK) GPS units can achieve an accuracy of approximately 2 cm with update speeds of 15 Hz, but have costs in the tens of thousands of dollars. To achieve this accuracy, the user must set up a

secondary base station at a surveyed location to broadcast corrections to the mobile rover unit. A second possibility is the use of more conventional differential GPS (DGPS) units. The user does not to set up their own base station, but they do have to be within range of a differential FM signal or subscribe to a satellite correction service. An example of a surveying-grade differential GPS is the Trimble Ag132, which has an accuracy of 50 cm and costs a few thousand dollars. This unit achieves its accuracy by the use of complex signal processing to remove multi-path errors and other noise, and also is able to produce 10 Hz updates. Unfortunately this unit is also too costly, and so we have to use consumer grade GPS units. These units are able to achieve an accuracy of 5 metres when receiving a differential signal, with the accuracy limited by the quality of the electronics internally. If there is no differential signal, this accuracy degrades further due to noise introduced by the atmosphere. However, consumer-grade GPS units are very cheap and also very compact, making them simple to embed into our mobile AR system. Figure 8 shows a comparison in the size of some GPS units ranging from 5m+ to 2 cm accuracy.

To support our development work, we investigated the current handheld units that are available, which are designed for use on boats or in cars. The reason we have selected a handheld unit initially is that they contain LCD screens which are able to show status information about current satellite reception and this is useful for debugging. The unit we have chosen to use in our prototype is the Garmin 12XL (shown in Figure 8 and Figure 9), because of its ability for an external antenna to mount on the user’s HMD to get a clear view of the sky. Like all consumer grade GPS units, this device reports values accurate to around 5-10 meters with a single update per second. In a commercially viable system, the handheld unit would be replaced with an embedded GPS unit such as the Trimble Lassen SK8 (shown in Figure 8) which is a fraction of the cost, size, and power consumption.

GPS has a number of known problems which may cause problems with our mobile AR system. When the GPS starts up, it must first acquire signals from at least 4 GPS satellites in the sky before it is able to calculate reasonably accurate 3D positions. After obtaining signals from these satellites, the GPS must synchronise its internal clock to calculate its actual position. This startup process may take a few minutes to occur before receiving position data, and may be as long as fifteen minutes when the GPS unit is operated for the first time or moved long distances



Figure 8. Trimble Lassen SK8 5m, Garmin 12XL 5m, Trimble 4700 RTK 2cm, and Trimble Ag132 50cm GPS units shown for comparison of size



Figure 9. Some components used in our system, including an IO-Glasses HMD, Garmin GPS, handheld controller, and 6V battery module

(thousands of kilometres). GPS tracking also suffers from interference with the GPS satellite signals caused by buildings or trees, and so the user must always walk in areas with a clear view of the sky. GPS is also unsuitable for use indoors, because the signals are attenuated severely when travelling through building materials. Similarly, walking outside but under the cover of a roof is equivalent to being indoors and tracking will fail here as well. For our system, we are targeting backyards and large playing field as the final playing areas. As these are commonly in areas where building structures are low and there is not much dense tree coverage, we expect the GPS to perform very well.

3.4 Power supply

Rather than use a custom-built battery cell which can be quite expensive for a consumer to purchase, we have tested the use of standard alkaline batteries because they are cheap and readily available. By using four standard 1.5 volt D cell batteries in series, we produced a simple but functional 6 volt power supply which is suitable for our equipment, and is shown in Figure 9. We measured the power requirements of the InterTrax2 sensor and the IO-Glasses display as having a combined power draw of 1.75 Watts. We tested the battery pack with these components and achieved 7 hours of constant use before the batteries went flat. For a final system, we would also power an embedded GPS unit, such as the Trimble Lassen SK8 previously mentioned, which have a negligible power draw which will not affect the battery life. Since the battery was designed to produce exactly the 6 volts required by the InterTrax2 and IO-Glasses, there is no need to use power converters or regulators. Power converters and regulators add both extra expense, and they also waste energy in the form of heat which further reduces the overall battery life.

3.5 Control Device

We used a generic USB game control pad as our input device, as shown in Figure 9. These are generally very robust and provide a minimal set of buttons to operate the system. This means there is much less confusion to the user as to available inputs, which would be experienced with a device such as a forearm keyboard. They also

reflect the type of interface this system would have if it were to be used on a console game system such as Sony Playstation or Microsoft X-Box. The control pad we have used is very generic, and familiar to users of both games consoles and traditional desktop computers.

4 Game Design

As previously described, the HMD, orientation tracker, and GPS unit have a number of hardware limitations that are imposed by the underlying technology. Our main approach to our novel game design methodology is to mask or embrace the limitations, rather than trying to combat the problems by improving the hardware. For example, the *Ghost of Sweet Auburn* project (MacIntyre 2001) is a historic tour system designed to teach people about the town of Sweet Auburn. Users would wear an optical see-through HMD, and through this they could see extra virtual information in the environment. The displays used by MacIntyre et al. had a translucent appearance, and that the orientation trackers would cause virtual objects to float and jitter around an excessive amount. Instead of fighting against these limitations and trying to have realistic looking virtual human entities, they embraced the limitations. They used the idea that virtual objects tend to look *ghostly* as inspiration for using ghosts as the narrative characters. It is also not unexpected to the user to see ghosts float above the ground and drift about considerably. Similar to this notion of working within the strengths of the technologies, we want to develop game designs that embrace the hardware limitations. The ultimate goal of any gaming system is for the user to feel immersed in the gaming experience, and not to be distracted by the problems with the gaming device.

Examination of the ARQuake project revealed a number of design guidelines for AR games (Thomas 2002). Using computer-generated virtual walls in the game was generally seen as ineffective. This is especially true if the user is very close to the wall, and the low field-of-view that the HMD provides meant the wall quite often will completely consume the users view. The use of virtual floors was also found to be ineffective because the inaccuracies in tracking caused them to not align correctly with the ground. The use of floating objects, fire, and explosions were noted to work well however. We postulate that these forms of visual graphics were least affected by the poor tracking technology: floating objects did not have to align with the physical world, and fire and explosion graphics were unaffected by jitter. For these reasons we propose that if possible, games be designed to make use of objects that are either floating or in the sky. The use of fire and explosions would be included if appropriate to improve realism.

In a mobile AR system, the user has the ability to have more physical interaction compared to a conventional computer game, as they may use their body as the interaction device. The evaluation from the ARQuake study showed physical movement was a key factor in the enjoyment of the game, and this form of interaction opens up many new and exciting possibilities to increase the realism and engagement of the games. This increased realism can only be achieved however, if the user feels

that their physical movements are accurately represented in the virtual environment. We believe it is important that the user never feels that the hardware is in any way preventing them from playing the game better.

The GPS technology we have selected (in a cost bracket for our needs) lacks the accuracy to precisely determine the user's position in the game. This lack of precision limits the ability to provide usable tracking information for rapid continual movement. The GPS device is only able to provide a general notion that a user is within a certain radius of a location. This is one of the most important aspects that need to be designed into the game play itself, so that users do not expect that they should be able to move in the game at a resolution below the accuracy of the GPS device. Games should not be designed around the concept of generalised tracking of user's movement moving, but instead use the GPS to determine which game position they are in from a set known of locations. The user's movement then determines which game "square" they are currently standing in. The game design should encourage the user to move swiftly between these locations so they do not notice the travel between the locations before the game display is properly updated. Therefore we are designing games that have players in a number of fixed positions in the game area. The GPS device enables the user to determine which game "square" they are located on by their location in the physical world.

The first person shooter game genre is very appropriate for an outdoor AR system, as shown with ARQuake (Thomas 2000). These games traditionally involve the user moving around the environment carrying a weapon. To work with poor quality position tracking, this concept needs to be altered slightly however. Instead of carrying their own weapon, the user is only allowed to use weapons at specific locations, such as fixed gun turrets. With this slightly altered style of game play, the users would be more inclined to move quickly from one gun location to another, as they may feel "vulnerable" while they are physically moving from one to another. During this transition period, the AR overlay could be reduced in quality or even made transparent so that the user does not notice the tracking is not working correctly.

By moving quickly between locations, the user is less likely to notice the fact that the game only updates when they are physically in the important locations, but the games are not limited to this. A puzzle game is also very applicable to our system. The user would just have to be aware that it is important for them to be at the important game locations before the game could continue.

5 Gaming Technology

This section details the implementation of our software solutions to overcome a number of the hardware limitations previously described. First of all, we introduce the concept we have named GPS Snap-To. To help with movement between known locations, we describe our new GPS hysteresis algorithm. We next outline our choice of colours for the textures of the game pieces. Finally, we explain how we overcome a number of registration problems.

5.1 GPS Snap-To

There has been some previous work with snapping to coordinate values (Szalavari 2002), but these are more designed to overcome the user's inability to place an object at exact coordinates rather than tracking error. Snapping is also used in desktop drawing applications to allow the user to specify exact coordinates very quickly. We propose to use a similar system of snapping to mask the poor accuracy which is produced by the commercial-grade GPS units we are using.

With relatively-accurate hardware such as a Polhemus tracker, snapping to a small grid can help users line up objects and removes small amounts of jitter, while still maintaining the feeling of free movement of the objects. When snapping GPS values to a grid, the extreme inaccuracies require a grid size of at least 5 meters. Although this method ensures no drifting or invalid readings from the tracker, it becomes very noticeable to the user when they have to take a full 5 steps to make the environment update with their position. The GPS already causes updates to occur every second, and assuming the user is walking between 1-2 meters per second, the time to walk 5 meters is 5-10 seconds. At these walking speeds, a ten second delay will give the appearance of a 0.1 Hz update rate on the display.

For some games, a filtering and smoothing approach may be appropriate to produce better update speeds and accuracies, but the extreme amount of smoothing that would be required would cause the system to be very unresponsive to sudden changes in direction and other unpredictable behaviour. In a gaming system, the users are very likely to be moving in a very unpredictable fashion, making this inappropriate.

5.2 GPS Hysteresis

We extend our previous concept of snapping to use hysteresis to increase the overall reliability and effectiveness. By only snapping the position values when the user is much further than half way to the next spot we can avoid problematic areas when the user is in transit between grid locations. As shown in Figure 10, there is an area where the user is near another location, but does not snap over until they leave the influence of the current region. The best size to use for this area is important, as it is a balance between ensuring snapping occurs, while trying to make the granularity of the grid as small as possible. By simply snapping to the closest location, when

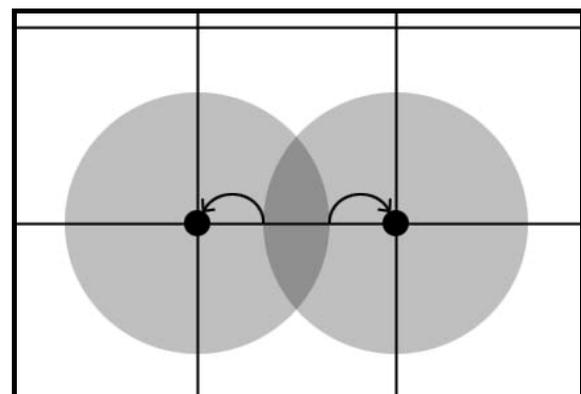


Figure 10. Example of GPS hysteresis

the user is standing half way between 2 grid locations, any jitter in the positions from the GPS could cause the user to jump repeatedly from one location to the other. We found that this was not a problem that occurred very often, as the GPS tends to not report values that jump forward and backward when the user is moving in a constant direction. This technique ensures that whenever a user stands in a location which is halfway, the system will perform in a stable way rather than giving confusing results.

5.3 HMD Colour Choice

The optical see-through display is often very difficult to view when outdoors in certain lighting conditions. We performed some testing of which colours are more visible than others through the display. By displaying objects of a variety of different colours onto the HMD, we discovered that red, yellow, white, and green had the best visibility in most lighting conditions. By using these general colours as guides, all the texture maps for models in the games can be created in these colours, maximising visibility outdoors.

A difficult design problem is avoiding the colour black. Optical see-through displays work by projecting the images generated on an LCD through an optical combiner. Any black or very dark images on the LCD generated by the computer result in light not being projected onto the mirror. Black is typically how we represent the transparent sections on the display so the physical world can be viewed. This causes a problem when the game designer tries to have black components on an entity in a game, because where they intended something to appear black, it will actually appear to have "holes". This proves to be an impossible problem to solve using current displays, and is one of the major limitations of using optical overlays in any environment. Displays such as the ELMO display (Kiyokawa 2003) are capable of achieving true optical occlusion using an extra LCD panel to block out the real world, however this display is only a prototype and is very bulky and expensive. Although video-based overlay allows for black to be used, we have already ruled this out as being both too expensive and dangerous.

We propose that games be designed with much brighter colours in mind. In situations where black would traditionally be used, such as "burnt" areas or shadows, these should be reconsidered, and artwork should be designed to avoid this. For example, instead of displaying burn marks if something has exploded, the burn marks could be avoided and replaced with part of the object being exposed, and brightly coloured internals visible. Shadows cannot be shown, as it would appear that a hole in the ground was next to an object, rather than an actual shadow.

Many games available currently use dark and gloomy environments to increase the atmosphere of the game. These dark environments are difficult to re-create in an augmented reality system. They are also inappropriate because the system is designed to be used in large, open, outdoor spaces, where it may very often be bright and sunny. Although it may seem reasonable to try and use the system outdoors in the dark, this is not practical because

the optical combiner in the HMD acts like a pair of sunglasses and it is impossible to see the real environment through the darkened display.

5.4 Registration

Achieving perfect tracking is currently impossible, and all of the various sensor types described in this paper have accuracy limitations and also suffer from errors caused by the environment itself. Objects will jitter and drift around and this can become disturbing to the user of the system, removing their sense of presence in the environment. The problem is particularly noticeable when objects in the virtual environment are registered against objects in the physical world. For a system such as architectural visualisation, if a virtual building starts to drift away from the real building it is meant to be connected to, any sense of presence is lost. For this reason, we propose that registration against objects in the real environment be avoided. If there is no importance on the correct placement of objects, then as the entire environment slowly drifts or jitters in a particular direction, the user is unlikely to notice. This effect is even less noticeable when the virtual objects are also moving randomly as well, making it hard to tell if the effect was intended or just an error.

The user, however, has to physically move around the environment, so the locations they are moving between need to be represented in the virtual environment. For this reason, some registration still needs to be provided. By loosely registering some objects in the virtual world into the physical world, some sense of realism is maintained. When the user is moving between locations, due to the "snapping" system they will not see the other location get closer to them on their display until they are all the way there. This low granularity means that the other location the user is approaching should be represented as a relatively large object to allow it to be seen from a large distance.

6 The AR Moon Lander Game

We have constructed an example game to demonstrate some of the concepts presented in this paper, named AR Moon Lander. This game puts the user in control of a lander module, which they must manoeuvre to touch down safely on the landing pad. It is based on the 1979 arcade game *Lunar Lander*.

Because the low-end HMD does not have stereoscopic displays, it is very difficult to judge depth, making it very hard to work out if the lander is directly over the landing pad along the Z axis (perpendicular to the screen). Although stereo vision is important (and is not provided by the HMD), Cutting and Viston found that humans are generally unable to accurately judge distances at long ranges beyond 30 metres (Cutting 1995). To compensate for this lack of depth perception, the user can apply AR landmark alignment techniques from different viewpoints which have been shown to be quite accurate (Piekarski 2004). During game play, the user can run around to the side of the lander, where left/right movement relates to forward/back movement from the original location, as shown in Figure 11.

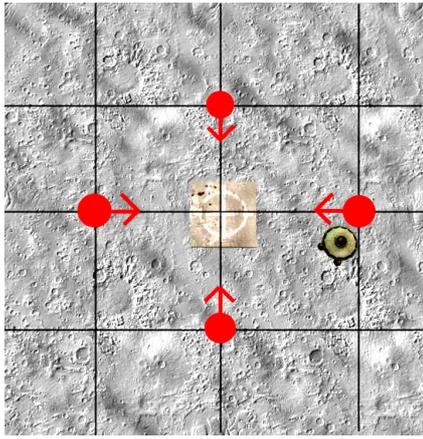


Figure 11. Moon Lander Grid

When the game begins, the user is prompted to physically walk to the location they wish to play from, and press a button on the controller. This location is stored internally in the game engine, and this calibration makes the game playable at any location on Earth where GPS is available. The user then looks in the direction they want to play from, and presses another controller button. The game knows which direction to align its snap-to grid with by using the heading value from the head mounted orientation sensor.

With this information the game then generates a grid which the users' location is snapped to. After the calibration steps described previously, the game starts and the lander appears high in the sky at a random location near the user. The user must then use the left/right controls, along with the 'A' button for thrust, to control the lander's location. When the user has positioned the lander roughly in line with the landing pad, they have to quickly run around to the side of the lander, to control the perpendicular axis.

By centering the game around an object which floats in space, the user does not notice how accurately it is aligned with the ground. There is no tight registration of any virtual objects with 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 objects equally.

Testing of this game has given us an insight into the effectiveness of our game design decisions. Due to the continual movement of the lander while flying around, any jitter that the orientation tracker may generate is unnoticed. If however the objects were stationary, the jitter would be more noticeable as the user would continually have to move their head to counteract it, but when the object is constantly moving the jitter simply appears as extra movement.

Our GPS snapping with hysteresis works well also. Although the handheld GPS unit is only accurate to within 5 meters, we found that when the user suddenly moved around 5 meters in a particular direction, the GPS would report values that roughly reflect this. By using the snapping-to-grid technique, the system was reliably updated to reflect the physical movements of the user.

7 Conclusion

We have presented a set of guidelines and implementation details for making augmented reality games that can be played outdoors on cheap consumer level hardware. By designing games so that they are centred around specific locations rather than continual movement, the player can be guaranteed the game will update accurately as they explore the environment. Games should also try to use floating/flying objects, rather than objects aligned with the ground, as tight registration generally is unsuccessful. By locking the player's location to a grid, rather than using raw GPS values, and by using a hysteresis technique to snap to these values, a location specific game can be easily implemented. Colours used in AR games also need to be carefully considered.

Although the current consumer level system that we have developed does have many limitations, we have shown that our design and implementation guidelines can effectively hide these limitations from the user and still allow enjoyable games to be developed for playing outdoors. The difference between our system and more high-end systems is the hardware limitations, but the game experience can be just as good with careful game design.

8 References

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