# Real-time Porosity using computer gaming technology.

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*ABSTRACT: 'Porosity' describes the publicly accessible spaces within privately owned parts of the city. Any mixed use building is necessarily Porous; for example, clients must be able to visit their dentist's surgery on the 14th floor, their lawyer on the 5th floor, or a restaurant on the roof. A building's Porosity is a measure of the quantity and quality of pathways to a given destination. The authors have developed and tested two prototypes that translate the movement of a person in the real world into the virtual environment of a computer game; note the pedestrians' participation is entirely passive (i.e. they are not knowingly playing a computer game, they are simply going about their business). The movements of a Non-Player Avatar, standing in for the pedestrian, are then represented with a range of textures, geometries and behaviours. The authors call these representations of movement and time 'Porosity Lenses'. In one lens the movement of the avatar constructs a facsimile of a space as sensors passively capture a person's movement through the real one. The paper compares the lenses developed with recent representations of movement over time to highlight strengths and weaknesses of the approach. Finally, the paper describes preliminary testing of the system within a scientific research facility.*

*KEYWORDS: Real-Time Porosity, Computer Games, Sensors, Representation, Mapping.*

## 1. INTRODUCTION

A growing list of urban mapping projects suggests there is an urgent need for a deeper understanding of the dynamic relationship between public access and the inhabitable spaces of the city (see Reades et al. (1), for a representative range of these, Nold's (2) work is worth a special mention). In many cases these projects represent dramatically changing patterns of use, mobility, and security. The term *Porosity*, coined by Richard Goodwin (3), describes the publicly accessible spaces within privately owned parts of the city. With the support of an Australian Research Council Discovery Grant from 2003-2005 Goodwin and his research team mapped these *Porous* spaces within the Sydney Central Business District. The results suggest new opportunities for pedestrian movement through the city. In contrast to many of the urban mapping projects cited above the *Porosity* maps are fully three dimensional. By recording the member of the public's duration of stay they also capture the dimension of time. However, due to the manual data gathering techniques employed, the first incarnation of the *Porosity* maps were only able to create a snapshot of the buildings selected. To understand how the *Porosity* of a specific building might change over time the mapping process would need to be automated. This prompted questions such as; can *Porosity* be represented over time, and ideally in real time? What should that representation look like? Can the combination of computer gaming technology and environmental sensors automate the representation of *Porosity*?

In this paper the authors describe a new way to map the *Porosity* of a building by modifying off-the-shelf computer games and using sensor controlled Non-Player Characters (NPCs). In a typical single player computer game the player knowingly controls an avatar (which is the player's embodiment within the virtual world) and may compete against or be assisted by NPCs that are controlled by artificial intelligence. In a multiplayer game the player is usually competing against or being assisted by avatars that are knowingly controlled by other real people. See Bartle's (4) *Designing Virtual Worlds* for further information and clarification. In contrast to these typical situations the authors have created a prototype where a real pedestrian's presence in the virtual environment is entirely passive i.e. they are not using the computer or knowingly playing a computer game, they are simply going about their business. This also contrasts the Gemeinboeck et al. (5) approach where the space of the game develops in an interplay between the player and their avatar. To clarify this distinction the authors have coined the hybrid term *Non-Player Avatar* (NPA). The movements of a NPA are driven by sensors recording a pedestrian's movement within a real environment and simultaneously traced in virtual space and time with a range of textures, geometries and behaviours. The authors call these representations of movement and time *Porosity Lenses*.

The *Porosity Lenses* are designed to facilitate an analysis of NPA movement from many different points of view thereby taking advantage of research by Sun et al. (6) that notes the importance of three dimensional space and point-of-view in shaping human behaviour in urban spaces. In an extension to the work by Sun et al., the authors propose that if three dimensional space and the first person point-of-view is important in shaping human behaviour in urban spaces then they may be equally important in understanding and analysing human behaviour in these situations.

This paper will describe the theoretical context, design and development of the *Porosity Lenses*, while comparing and contrasting them to recent representations of movement over time. In one example the movement of an avatar generates three dimensional building blocks that construct a facsimile of the pedestrian's environment in real time as sensors record their movement through it. It will also describe the development and preliminary testing of two prototype sensor solution that use off the shelf computer gaming hardware.

As noted above there are many examples of projects that map the movements of people in cities and the developers of *Halo 3* (*Bungie Studios* in collaboration with *Microsoft* (7)) have mapped and analysed over 3,000 hours of game play. The research presented here uses off the shelf computer gaming software, computer gaming hardware and low cost wireless sensors with a view to creating a unique hybrid.

## 2. THE POROSITY STUDIO

In 1996 artist-architect Richard Goodwin established the *Porosity* studio within the College of Fine Arts (COFA) at the University of New South Wales. Goodwin notes that the public space of the city doesn't end at the building envelope; that any mixed use building requires access by the public and is necessarily *Porous*.

For example, clients must be able to visit their dentist's surgery on the 14th floor of a building, their lawyer on the 5th floor, or a restaurant on the roof. A building’s *Porosity* is a measure of the quantity (and quality) of pathways to a given destination (3). The primary concern of Goodwin's research was the amount of time that the *Porosity* researcher could spend within a privately owned building without detection. After comprehensive fieldwork detailed three dimensional maps of three major zones within the Sydney Central Business District were produced. Architectural data on the buildings within those three zones, combined with the results of the field work, gave each building a qualitative *Porosity Index*. In the original *Porosity Index* Goodwin cited orientation, duration of stay, adjacency to lifts, stairs and other distinctive architectural qualities as factors that contribute to a building's *Porosity Index*.

Goodwin proposed that reading these *Porosity Indexes* could give planners and architects direction as to the way in which new linkages may be made which enhance the public space in the city. But from a slightly more sinister point of view the *Porosity Indexes* can also measure and qualify the dilemmas of security versus access in relation to public and private space. In other words the *Porosity* of a building relates to the ease by which a building might be accessed and evacuated.

## 3. GAMING TECHNOLOGIES TO REPRESENT REAL TIME POROSITY

Rather than being fully spatial many urban mapping projects still represent the city in two dimensions. A few projects supplement those dimensions with other, non-spatial, dimensions such as information about the users itinerary (Polak's *Amsterdam RealTime: Diary in Traces* (8)) and physiological responses (Nold's *Biomapping* project, 2004 – ongoing (2)). In *The Language of New Media* Lev Manovich (9) argues that navigable space is central to new media aesthetics and goes even further when he says "the 3-D virtual space combined with a camera model is the accepted way to visualize all information". Demonstrating the pragmatic advantage of visualizing information in this way Sun et al. (6) recognised the importance of point-of-view in shaping human behaviour in urban spaces. By using a head cave and three dimensional virtual environments they found that some assumptions about human behaviour in urban spaces could be challenged. It is interesting to note here that their research utilized an environment that was inspired by the video game *DOOM*. In contrast the authors did not use something *like* a first person shooting game, they actually used an off the shelf computer game. So why take Sun et al. so literally and use an off the shelf technology designed in the first place for entertainment? The answer lies in the underlying sophistication of computer games and, more recently, their versatility regarding modification; not to mention the widespread encouragement to do so by game developers and large modding communities where users create custom game dynamics and content.

Microsoft Research (10) noted in 2005 that computer game technology has been pushing the technology envelope for 30 years. Also recognising this, the game developer *Virtual Heroes* (the developer of the groundbreaking simulation/marketing tool *America's Army*) has recently licensed the *Unreal Tournament 3* (UT3) game engine to develop an urban training simulation called *Zero Hour: America's Medic*. Illustrating the growing institutional acceptance of repurposing entertainment technology *Virtual Heroes* are also working in collaboration with the *American Department of Homeland Security*. In 2006 Price (11) provided a useful summary of the recent applications of game engine technology for education and training, noting that their use in such ways has occurred only since 2003. Bouchlaghem et al. found that the application of virtual reality in the construction industry has been under investigation since the early 90's but had been unable to reach maturity in the decade since then (12). Ten years on from the study by Bouchlaghem et al. we find that industry heavyweight *Autodesk* has recently become a member of the *Integrated Partners Program* with *EPIC games*. This may be a concession that their real-time interactive engine for their building information modeller, Revit, could still be some time off (13). In contrast *Archicad* (by *Graphisoft*) has incorporated a real time interactive engine in its latest release (14). While the authors applaud the initiative they remain sceptical that Graphisoft's resources and culture will facilitate their engine's comprehensive development (or importantly, many alternative developments in the case of computer game modding). The use of virtual reality technologies in the construction industry is still not mature, but many of their technical constraints may be overcome … somewhat ironically, by the entertainment industry.

In the discussion relating to human behaviour in public spaces Sun et al. (6) state their assumption that in an unfamiliar environment humans respond to, prioritise and form strategies based on the set of architectural elements that they can see. In the context of this project as humans perform navigational strategies within a real environment NPAs mirror them within a virtual environment. The *Porosity Lenses* described below are mechanisms that add persistent traces of movement to the set of architectural elements in view so that analysts can develop an understanding of the movement of NPAs; and by extension the pedestrians that are unknowingly driving them. By utilizing computer games analysts can take advantage of the positive benefits of video game play that include an increased ability to visualise both space and three dimensional forms from different points of view (15).

## 4. WHAT SHOULD THE POROSITY LENSES LOOK LIKE?

In the following examples the authors critically examine recent efforts by researchers to represent the presence and movement of people through space. This investigation is required to determine the field of representational strategies that are available to represent *Porosity*.

In Nold's (2) work participants are fitted with a lie detector like device to measure their emotional arousal. In addition the device uses GPS to locate the participant in space. This combination provides data for Nold to create maps that geographically locate emotional responses. The resulting maps of Stockport, Greenwich and San Francisco are two dimensional. The map for San Francisco uses stacked red disks and at first appearance bears some similarities with the sprite based *Porosity Lens*. This similarity is short lived however as the colour intensity isn't built up in layers but comprises arbitrary steps on a scale; each disk is opaque. In another example a sample animation shows a three dimensional structure built over *Google Earth*. The line in the xy plane traces the participant's movement through the environment while the z-axis is used to represent emotional arousal. The effect is similar to a line graph, with solid fill beneath, which is folded so that it might stand up unsupported. Figure 5. The height in the z-axis plays the same role as the density of the *Hansel and Gretel* sprite trail, but this approach would quickly become confusing if the ground plane was not completely flat (i.e. a point on the terrain, or within a building, with a higher elevation could give the impression that the experience there is more intense). Expressing the data as a cross section area perpendicular to the direction of movement may alleviate that confusion and suggests a future direction of research for the authors.

Insert Figure 5 here:

*Figure 5. Screen capture from [www.biomapping.net](http://www.biomapping.net) showing C. Nold's geographical mapping of emotional responses.*

The project by Polak et al. (8), *Amsterdam RealTime*, tracks people equipped with GPS enabled devices in real time and projects the resulting lines onto a black background. The map is two dimensional but expresses a direct precursor to a key strategy of the *Porosity Lenses* (using people movement to build an environment); as explained by the Waag Society (16) the emphasis is on the movement of real people rather than the recording of static architecture. The time lapse animation (16) shows the map glowing and pulsating at points where multiple pathways cross. The representation of intensity is unmistakable in a qualitative sense but vague quantitatively. This may be a strength and weakness of all strategies that rely on multiple two dimensional layers.

Bungie Studios, the developers of Halo 3 (in collaboration with Microsoft), have developed tools to extract gameplay data so they could map and analyse over 3,000 hours of game play (7). In one example (shown on page three) the location a player dies on a map of the level is represented by a dark red circle; Bungie called this a *Heat Map*. Alison Mealey (17) uses a similar approach to create portraits by recording and representing the movements of NPCs in the game *UT2004*. Another example (shown on page five) from Bungie shows the locations of multiple players at five-second intervals over a period of half an hour. Each time interval is represented by a dot in a new colour and superimposed on the same map. When the dots are clustered by colour it demonstrates that players move through the environment along similar paths and at the same rate. Currently the *Porosity Lenses* do not implement a similar facility; not only would it show consistency of movement through an environment it would also confirm the direction of that movement. Once again these examples are two dimensional, but the final example from Bungie shows the importance of understanding actions from a player's perspective in three dimensions. In this example Bungie's analysts noted a high rate of apparent suicides in a particular area of a map; the *Heat Map* would show them in a particular location but the action in this case was not shaped environmentally but locally ... attackers were able to get too near the tanks that the players were in, their resulting cannon fire killed the attackers but inadvertently killed themselves at the same time. In this example two dimensional orthographic views and real-time spatial experience combine to give a more complete representation of the causes and effects of a user's navigation through an environment.

Within these examples three major parameters arise; the qualitative vs quantitative advantages of utilising colour, intensity and size as mechanisms to represent duration of stay in any one place; the obscuring of data by subsequent entries by the same person or by entries from another person; and the representation of the activity workspace (18). The obscuring of data is seen in Nold's work (Figure 5) and in the work of the authors (Figures 1, 2 and 6) and is a consideration in the development of a cross sectional area representation mentioned above. In a paper regarding workspace conflicts in the construction industry Mallasi (18) notes the difficulty of specifying workspace requirements dynamically. To mitigate this problem in his research he uses a technique that represents the activity workspace in a series of three dimensional boxes. Each box defines a workspace (such as above, below, or surrounding a typical room for example) that generically represents different workspace requirements. While the second *Porosity Lens* is similar, in that it utilises rectilinear blocks, it indexes them to the size of the construction worker him or herself. By doing this a more fine grained understanding of the activity workspace would result (see Figure 2).

As a result of this investigation the three lenses described in section 5 employ two broad representational strategies; the sprites and tiles are additive, the rectilinear blocks are subtractive.

## 5. DESIGNING 'POROSITY LENSES'

Modifying off the shelf computer games, or game modding, is made possible because many computer games are shipped with world builders (alternatively known as level editors). The list of computer games with integrated world builders or have third party world builders available is extensive (19). A particular subset were chosen as possible candidates for this project and can be characterised by being multiplayer, having cutting edge graphics, robust physics engines, extensive particle systems, first and third person player points of view and large online communities supporting modding. Three world builders satisfy these requirements; *Hammer* (*Valve Software*) *UnrealEd* (*Epic Games*) and *Sandbox2* (*Crytek*). While the real time physics capability made available by the Hammer world builder is still industry leading (as best seen in mods such as *GarrysMod*, and *WireMod* (20)) the underlying engine is showing its age in other ways. Most significant of these are the long compilation time between world builder and playable environment and the lack of a visual scripting editor so that multiple iterations of complex real-time interactivity can be prototyped and tested efficiently. It should be noted here that most documentation for these world builders is created by each of their communities and while every effort is made regarding accuracy often information regarding more advanced (or less entertainment centric) modifications is conflicting, out of date and/or partial. This means that an incremental and iterative approach was understood to be critical when developing atypical mechanisms (i.e. mechanisms that run counter to, rather than improve, typical game play). The compilation times for UnrealEd and Sandbox2 are only a few seconds and both have visual scripting capability. UnrealEd was chosen to develop the first *Porosity Lenses* and was linked with a Nintendo Wii Balance Board to demonstrate proof of concept regarding linking to environmental sensors. More recently a plugin system for the Sandbox2 world builder has provided a more sophisticated and extensible system to link a computer game to environmental sensors. This will be developed further in section 6.

The UT3 world builder, UnrealEd (21), comprises a set of tools that enable importing custom designed content (models, textures, animations etc.) and its integration with real-time rendering and physics engines. The interface resembles traditional CAAD software. While the editor offers limited modelling ability (the developers of these games, Valve Software, Epic Games and Crytek all integrate third party modellers for content creation) it does include many sub-editors that allow one to create atmospheric effects, real-time interactive opportunities and build materials. The sub-editors used to design and develop the *Porosity Lenses* include *UnrealKismet*, *Matinee*, *Cascade*, the *Material* and *Static Mesh* editors. User guides, which include explanations of the purpose of each sub-editor, are published by Epic Games under a section of their mod creation webpage entitled Content Creation (22). In short: UnrealKismet is a visual scripting editor which enables designers to script complex interactions between dynamic entities within the UnrealEd and other sub-editors; Matinee enables key frame animation, allowing a user to animate the properties of entities over time; Cascade is a particle generation system that controls the amount, duration and physical interaction of particles emitted for a particular effect; the Material editor uses a flowchart approach to building materials from many types of textures (diffuse, specula, normal map, etc.) and vector inputs; the Static Mesh editor enables a user to set the properties of imported geometries (including, collision, mass and material usage, etc.).

Many of the toolsets require information generated in third party software (textures or geometry for example) and from other toolsets within the editor itself. While this parametric interdependence adds to the complexity of modifying the game it does provide many opportunities to link different types of parameters and contributes to the sophistication of the interactivity.

For the first *Porosity Lens* the Kismet toolset was used in conjunction with the Cascade toolset to attach, detach and control the emission of a sprite particle emitter that was attached to a NPA (a sprite is a two dimensional surface that always faces the player). The Material editor established translucency as a parameter, with Matinee animating its rate of change. In this and the following examples visual scripting in Kismet was used to create a mechanism for interactivity that didn't exist previously within the UT3 game. The result is that as the NPA moves around the environment it leaves a trail of translucent squares that traces its movement through space and time; much like the breadcrumbs left by Hansel and Gretel in the well known fable (23), figure 1. As the custom material applied to the sprite contains a variable opacity parameter the translucency can be adjusted to balance between the clarity of the avatars path and the density of its representation. The density of the path at any one point represents the overlaying of multiple translucent sprites that build opacity and represent the duration spent at that point; a key factor to understanding *Porosity*.

Insert Figure 1 here.

*Figure 1. Shows the results of the Kismet sequence created by the authors that controls the relationship between a particle emitter and a NPA.*

Extending from the notion of parametric interdependence mentioned above, every element within the game environment contains parameters that can be customized. Identifying parameters and referencing them within Kismet enables many to be changed over time. These changes can be pre-scripted (much like conventional animation) or can occur in real-time. For the second *Porosity Lens* a Kismet sequence was designed that modified a scalar parameter which controls the opacity channel of a material applied to a rectilinear block within the environment. The collision properties of the block are set to register touch events with NPAs but will not collide with them physically, so that they do not impede their progress. Every time a block is touched by a NPA its opacity drops by 0.2 (where 1.0 is opaque and 0 is transparent). The sequence continues reducing the resulting opacity, upon subsequent touch events, until it reaches zero; i.e. until the material is completely transparent. Figure 2. shows a simple arrangement of corridors filled with the blocks.

Insert Figure 2 here:

*Figure 2. Shows blocks that have their opacity controlled by a Kismet sequence.*

Multiple touches by one or more NPAs give the impression of their movement slowly carving out the space of the corridors. One can see that as long as walls, floors, ceilings and doorways limit a pedestrian's movement in their real environment there would be no need to represent them within the virtual environment; the presence or absence of rectilinear blocks can perform this role. The authors imagine an environment totally filled with these blocks in a complete three dimensional matrix. The virtual representation of space that is occupied by pedestrians in a real environment would become clear as the NPA, paralleling their movements, travelled through it.

The third *Porosity Lens* adopts the additive approach of the Hansel and Gretel Lens with the three dimensional geometry of lens two. In contrast to the Hansel and Gretel Lens however the mesh is only emitted when the avatar is moving; i.e. it records position rather than position and duration. The emitter could be set to emit mesh particles constantly, but the additional processing required by three dimensional geometry over a simple sprite slows the computer significantly when count rises into the thousands. At the current stage of its development the mesh elements do not collide with the NPA. Ultimately the authors intend that the mesh will collide with the footsteps of the NPA so as the pedestrians negotiate a real environment they passively construct a version of it beneath their feet in a virtual environment. See figure 3. Note figure 3 shows blocks leaping over ones previously laid avoiding an intersection; in those cases the NPA literally leaped over the earlier path. This demonstrates that environments that change in the vertical dimension (stairs, ramps, etc) are able to be replicated.

Insert Figure 3 here:

*Figure 3. Real-Time construction of an environment.*

The working prototypes above address the first aspect of the question 'can *Porosity* be represented in real-time?' Goodwin collected the data to establish access and duration of stay over a three year period. His *Cactus* models represent this *Porosity* data in static architectural scaled models by being colour coded to indicate the degree to which they are accessible to prolonged stays (24). The *Cactus* model is colour coded from red (very Porous) to blue (impenetrable). The skin and the parts of the building that are not accessible to the public are removed. In a typical *Cactus* model the vertical yellow elements are elevator shafts and the elements that reach out from the core of the building to its skin suggest opportunities for public space to leap from one building to the next. See figure 4.

Insert Figure 4 here:

*Figure 4. A Cactus model of a building in Sydney, Australia. From Goodwin (3).*

The working prototypes above demonstrate that contemporary computer gaming technology is able to represent the movement through space and time of an avatar in a virtual environment in real-time. However, to represent *Porosity* in real-time there must be a link between the avatar within a virtual environment and a pedestrian in the real world. In other words, to represent *Porosity* rather than movement through virtual space and time the avatar needs to be driven by real world data. Section 6 describes two methods for establishing links between environmental sensors and the computer games UT3 and *Crysis Wars*.

## 6. AUTOMATING THE COLLECTION OF DATA

In a typical computer game the avatar translates the actions of real people into the virtual environment. Conventionally one controls their avatar directly and might use a computer keyboard and mouse or gamepad to do so. In addition the computer controls various other characters within the game environment with artificial intelligence. A third category, sensor controlled avatars, has recently emerged. These avatars are controlled by sensors that pick up the movement of a person in a real environment and translate it to a virtual environment. Groenda et al. (25) use tracking and motion compression to allow the exploration of an expansive virtual environment while the user moves around a small room. While motion compression would be useful for play in gaming halls or at home it takes this tracking technology in the opposite direction to the authors' project. The authors' project prioritises a one to one relationship between a pedestrian's movement in the real world and virtual environments. In other words, while Groenda et al. saw one to one mapping of the players movement as limiting the range a person was able to explore in the virtual environment the authors see this as an opportunity to map the limits of a real environment by tracing pedestrian movements through it.

At this point a brief review of pedestrian location systems will be useful. In 2001 Hightower and Borriello (26) described three major techniques for location sensing. These include triangulation using distance or angular information from known points; proximity, which measures nearness to known points and; scene analysis, which examines views from particular vantage points. He also tabulates a range of location sensing technologies that were available at that time. Hightower uses the taxonomy he develops earlier in the article to aid comparison. The taxonomy describes the technology, technique, physical/symbolic/absolute/relative positioning/location, the location of the computation, recognition by the system, precision of the measurement, scale of the system, cost of the system and primary limitations. Technologies include: *GPS* (satellite), *Easy Living* (computer vision), Avalanche transceivers (radio signal strength), *Smart Floor* (physical proximity), Automatic ID systems (RFID) and *E911* (cell phone). In a paper published the following year Welch and Foxlin (27) note the proliferation of possible tracking products and research projects (their paper deals specifically with motion capture which focuses on tracking body parts relative to each other rather than location systems which focus on the bodies relationship to the environment but many of the techniques/technologies work on the same principles and have similar strengths and weaknesses). Their central thesis is that the wide array of systems available is due to the fact that every tracker then on the market falls short on at least 7 of the 10 parameters they identify as desirable. Given that many of the mechanisms used in motion capture and location sensing are similar it isn't surprising that there is no silver bullet in location sensing technology either. For example GPS, possibly the most widespread location technology, relies on direct line of sight to satellites overhead and therefore does not work indoors. In another example we see that a smart floor's primary advantage is that it does not require the pedestrian to carry any device; but while Mori et al. (28) argue that floor pressure sensors are low cost and can be distributed in large numbers this seems to disagree with Hightower and Borriello's (26) earlier assessment that the cost in these systems is high. Further enquiry shows that Hightower and Borriello agree that the sensors themselves are low cost but argues that the substantial cost in these systems is in the installation of the devices in buildings. After their own survey of tracking technologies for virtual environments Rolland et al. (29) finds that scalability is a major challenge for tracking technologies. He optimistically states that the theoretical and practical challenges to scalability can be overcome if cost is not an issue and hybrid technologies can be used. Regarding tool tracking on the construction site Goodrum (30) finds that cost is becoming less of an issue in the use of active RFID tags with the tags themselves dropping from $150 to $10 each in two years (in this case the tags did not have identical specification, but achieved the same results). The massive reduction in cost of RFID tags raises an important point; that both the individual qualities and amount of technologies in this field are changing rapidly. While the measuring principles and performance metrics in Liu et al. (31) reiterate those from Hightower and Borriello (26) the focus of their 2007 survey paper is on the location subcategory of wireless indoor positioning systems. In terms of scalability Liu rates wireless systems between good and excellent. The table that compares a range of systems relies of specifications published by the developers of each system and as such should be approached with caution. For example, the wireless local area network received signal strength solution, *Ekahau* (32), is reported to have good robustness (meaning that locations can still be computed in less than optimal conditions). In 2008 after determining that Wireless Local Area Network systems did not require additional infrastructure (in their application), offered good accuracy (here the claim was up to one meter) and offered the opportunity to take advantage of high bandwidth for other data, communication and tracking features Behzadan et al. (33) tested the Ekahau system on a simulated construction site. Unfortunately, while they achieved the one meter accuracy in a stationary office space the measurements in their simulated construction site lacked stability. This was due to changes in site conditions that distorted the underlying received signal strength map. Given that a construction site is defined by changes in conditions the authors concluded that further development would be needed before the Ekahau system would be robust enough be implemented in this context. Such development may come in the form of hybrid sensing solutions or, as Hightower and Borriello (26) puts it, sensor fusion.

The authors' first two implementations of sensor technology to link pedestrian movements to NPA movement within the computer game environment reflect the range of sensors described above. The first working prototype utilised the *Wii Balance Board* by *Nintendo* (34) and while it presents similar strengths and weaknesses as conventional floor sensing networks it does this within the broader conceptual context of computer game modding.

Allen et al. (35) note the widespread availability of low-cost computer game peripherals and see an opportunity to adapt them for use in clinical science and rehabilitation engineering. A major advantage for Allen et al. is to break free from the limits of the clinic; a key limit being expensive equipment. For the authors there are two major advantages in adapting technology from the computer gaming industry; the notion of widespread availability suggests that there may be a good chance that a pedestrian might already be carrying the sensor we could use to track them (clearly not the case with the Wii Balance Board, but certainly possible in terms of mobile platforms such as the *iPhone* or *PlayStation Portable*). The second advantage relates to broadening the use of sensor technology and implicates the ethics of surveillance developed further in section 7.

With the notion of repurposing off the shelf computer game peripherals in mind the authors tested a Nintendo Wii Balance Board that employed a custom script to interface with a laptop computer. The first version of the code that connected the Balance Board with a personal computer (PC) was written by Nedim Jackman (36) as a part of his undergraduate degree in Computer Science. Jackman originally wrote the software to measure the deterioration of aged people's balance. Jacob Schwarts, a Masters of Architecture student studying with Lowe, worked with Jackman to adapt the code so that it translates motion on the Wii Balance Board to a set of configurable keyboard signals.

Both Schwarts and the authors have used the first version of the code to control the movements of avatars within the computer game UT3; Schwarts to design and demonstrate his graduation project and the authors to create a three dimensional real-time map of a person's physical movement within a virtual environment. In the first iteration the test subject's movement was very limited; leaning forward/backwards/left/right replaces taking actual steps. While this represents an alternative way to interact with the computer (i.e. not a traditional keyboard or game pad, Shaw and Groeneveld's (37) *Legible City* is probably the most well know early example of this) it does not capture the act of walking passively. Subsequently the authors worked with Jackman to enable the connection of up to 7 balance boards with the PC. A video clip shows author 1 (38) walking forward across three boards with his movement being translated to the NPA in real time. The second part of the clip shows the author (and NPA) walking to the left. These clips demonstrate that the steps by the author in the physical environment produce a related number of steps by the NPA in the virtual environment. Demonstrations on the video sharing site YouTube (39) show a Nintendo *Wii Remote* being used to interface with Half-Life 2 (a first person shooter game in many ways similar to UT3) and suggest a further related area for investigation i.e. the integration of multiple gyroscopic devices. In the context of sensor fusion noted above Chow (40) points out that the low cost Wii Remote which combines an infrared sensor, accelerometers, vibration feedback, a speaker and many buttons in the one device, is at an advantage over the many single function sensors that have emerged over the years. Chow also notes that because of the Wii Remote's widespread popularity its controls are familiar to many people. This is in contrast to many of the technologies described above (26-27, 31).

The authors' second implementation of a sensor technology to drive the virtual NPA uses a technology that contrasts the Wii Balance Board on almost every level. The technology, called *WASP* (Wireless Ad hok System for Positioning) was developed by the wireless localisation team led by Mark Hedley at the *CSIRO ICT Centre*, Sydney Australia. The system, described by Hedley et al. (41), uses radio tracking and time of arrival technologies. Originally designed to track emergency personnel (fire fighters, etc.) the system was required to deliver high accuracy (one meter or better), rapid deployment without existing infrastructure, have mobile tags that must be small, low cost and long lasting, provide a data channel and work in challenging environments characterised by severe and time varying multipath problems (due to smoke, etc.). The system created by Hedley et al. satisfies all of these requirements. The authors note that with support from the *Australian Institute of Sport* Hedley has developed the system to provide robust localisation of cyclists on a velodrome (42).

For this implementation the authors modified the computer game Crysis Wars, by game developer Crytek, using the Sandbox2 world builder. The Sandbox2 world builder satisfies the requirements identified in Section 4 and (via a community designed modification (43)) supplements these with an important development that allows the visual scripting environment (in this case called the FlowGraph editor) to read and write to XML format files in real time. The link between a pedestrian's movement in the real world and the NPA movement replicating it within the virtual environment is as follows. Base sensor nodes are placed in known locations. The movement of a mobile node or nodes is calculated using time of flight data. These positions are output as x/y/z coordinates to an XML type file. This file is interrogated at one second intervals by a particular FlowGraph within Crysis Wars. The FlowGraph moves a target point to the location specified by the file and instructs an AI controlled character to move to that position. In this way we use the AI to smooth the motion between each target location, which is linked in one to one scale to the distance the pedestrian moves in one second. Due to the fact that the XML file is interrogated at one second intervals the link between pedestrian movement and NPA movement is not truly in real-time, which requires virtual reactions to be synchronous with real world actions, but does satisfy the definition of interactive speed by Rolland et al. (29) which is the case for most computer game peripherals. The venue for this implementation was the offices of the CSIRO ICT Centre in Sydney Australia. The offices consist of partitioned rooms and corridors with walls made variously from plasterboard, glass and concrete. In this implementation the physics of the model has been modified so the NPAs do not collide with the walls. The material properties of the walls have been adjusted so they are translucent, aiding ones understanding of the pedestrians' pathways through the facility. Figure 6 shows three NPAs with the Hansel and Gretel *Porosity Lens* in action; the aerial view on the bottom right clearly shows the room where the authors and research assistants had set up a temporary office.

Insert Figure 6 here.

*Figure 6. Composite image showing four views of the CSIRO ICT Centre with three pedestrians being tracked.*

While the second implementation is clearly more extensible its major drawback is the exclusive nature of the sensors (each is hand built and there are perhaps 100 in existence). Chow (40) notes that widespread availability, sensor fusion and easy connection to a computer were key factors in a large new modding community springing up around the Wii Remote and resulted in a wide variety of applications beyond those released by Nintendo. Most papers on motion tracking cite the entertainment industry and especially computer games as primary sites for the applications of their research (27). Location tracking papers tend to be a little broader in the possible applications of their research, citing emergency services through construction to social networking (33, 44-45). It shouldn't be surprising then to find that in both of the implementations by the authors we see the involvement of the entertainment industry. The following section picks up on this issue and notes upcoming findings and directions for further research.

## 7. BROADER ISSUES AND FUTURE WORK

Recalling Goodwin's (3) definition of the term *Porosity*, which describes the publicly accessible spaces within privately owned parts of the city, we see a blurring of the line between public and private spaces. Michael et al. (46) considers the emerging ethics of tracking people using GPS and tends, due to the nature of GPS tracking, towards the outdoors and, with an underlying assumption, to public spaces. Given that many indoor spaces are privately owned (and understood by members of the public as such) the emerging ethics in those spaces may be different. However, she does describe four primary ethical issues which might usefully be considered here; privacy, accuracy, property and accessibility.

The consideration of privacy in regards to emergency services personnel and construction site personnel overlap only slightly. One could appreciate that tracking that provided warnings related to a fire fighter's or construction worker's safety (such as a man down warning when a worker is stationary for an overly long period of time) is as beneficial to the worker as to the employer. In other productivity related areas Michael et al. notes both the dominant power position of the employer and the few laws that govern workplace surveillance in the U.S. and Australia (here Michael et al. cites Papasliotis (47)).

Who is responsible for the accuracy of a system that uses GPS is more complex than in the case of a system relying on a WLAN or RF system as used by the authors above. This is because the providers of services that rely on GPS (outside the U.S. government) do not control the availability of the underlying system or the authenticity, fidelity or accuracy of the data collected (46). One question is whether tracking and analysis is an addition to current safety procedures or do manufacturers, often optimistic, claims of accuracy suggest an implied guarantee of safety; will an employee take additional risks on the basis of those claims? Michael et al. claims that the potential for positional inaccuracies are negligible when compared to inaccuracy that might be introduced in processing by accident or intentionally. Drawing on Burak and Sharon (48) Michael et al. notes that the digital nature of a tracked persons location can be subject to instant analysis and inferences can be drawn in ways the first hand observation is unable to do. Clearly inferences in these cases depend on human or statistical capability and can also be subject to manipulation (for example; an employee's positional history could be adjusted to place them in an area they were not authorised to be in, or near equipment that has been stolen, which could lead to unfair dismissal).

The third ethical issue relates to property, or who owns the information regarding a person's movements. Michael et al. looks at the legal implications of a company that has data implicating a worker in a crime and their responsibility to supply that information to the police. At the other end of the spectrum, tracking may reveal a particularly effective procedure a contractor uses to carry out their work; how can the contractor be assured that their intellectual property isn't compromised?

Finally, Michael et al. raises the issue of accessibility. The costs of tracking systems may lead to their uneven distribution. In this case who decides which people have access to the tracking system? Conversely, is an employer able to opt out of the system? It is conceivable that in some systems an individual opting out will weaken the fidelity of the system of those who do participate.

Welsh et al. (49) deals with these kinds of patriarchal issues and goes on to say that electronic surveillance is frequently associated with the criminal justice system and that regardless of the ethical questions surrounding it electronic tracking will be seen against this background. Even though Manovich (9) saw computer gaming like visualisations as being central to dealing with information in the 21$^{st}$ century they too continue to be seen against a background of violence and the military (50).

Currently the pedestrians carrying sensors in the authors' field trials are members of the research team. Future work will need to continue an ongoing and productive engagement with the issues above when extending field trials to members of the general public.

The use of computer gaming technology to visualise and analyse pedestrian movement that may have critical implications for safety presents an issue engaged with by Rhyne (51) when she asks how comfortable the reader would feel if they were about to buy tickets for a flight that depended on a meteorological report computed on a Microsoft *Xbox*. Rhyne notes that where once scientific visualisations were produced on SGI workstations with developed and purpose built APIs for visualising scientific computations nowadays the market dynamics of computer game applications are influencing computer architectures which is resulting in potentially unsafe levels of instability. Without elaborating, Rhyne comments that software interfaces, navigation and plot lines are also factors that disturb traditional scientific ways of thinking. That these subjective aspects of computer games are drawing in scientists and possibly shifting their ways of thinking about scientific presentations, or even their discoveries, suggests that the *Porosity Lenses* need to do more than simply present information as transparently as possible.

In another project Lowe is collaborating with Newton and Zou (also academics at the University of New South Wales) on an Australian Teaching and Learning funded project called "Learning and Teaching Technical Competence in the Built Environment Using Serious Video Game Technology". While this project does not propose the use of environmental sensors its core aim is give students an immersive experience of site works which would clearly benefit from the presence of construction workers. Future extensions of that work will see students gaining technical competences by working alongside construction workers in virtual environments.

## 8. CONCLUSION

Richard Goodwin's *Porosity* Project (3) contributed to urban mapping in two very important ways; it recognised that public spaces do not end at the envelope of a building and by extension it understood that navigating the city is a three dimensional proposition. A key factor of a building's *Porosity* is the amount of time a person can spend in different parts of a building; and this duration changes over time.

This research finds that it is possible to represent *Porosity* in real-time and that an advantageous medium to use to achieve this is computer gaming technology. Extending from Sun et al. (6) the *Porosity Lenses* add persistent traces of movement to the set of visible architectural elements that analysts would be able to use to understand pedestrian movement and space usage within an urban environment. By using computer games the analysts can take advantage of the positive benefits that emerge from playing computer games such as visualising space and understanding relationships between various three dimensional objects over time (15). The computer games UT3 and Crysis Wars were chosen to construct these prototypes because they represent the latest generation of computer gaming technologies, have comprehensive and interconnected toolsets, fast compilation times and, importantly, the support of a large game modding community. The *Porosity Lenses* develop additive and subtractive strategies and in section 5 they are reviewed in the context of recent urban mapping projects. In this examination three major issues arise; the qualitative vs quantitative advantages of utilising colour intensity and size as mechanisms to represent duration of stay in any one place; the obscuring of data by either subsequent entries by the same person or by entries from another person; and the representation of Mallasi's (18) activity workspace. Both mechanisms have strengths and weaknesses and further work is required to create a hybrid or develop new alternatives. By utilising a base unit of workspace indexed to the construction worker, which follows them and build's (or carves as the case may be) a total model of their space use over time, a more fine grained understanding of the activity workspace would result.

To represent *Porosity* in real-time first one must collect the data in real-time. Allen et al. (35) note the widespread availability of low-cost computer game peripherals and with this in mind the authors the authors sought to extend the modified off the shelf software approach to include hardware. With Jackman (36) the authors connected three Nintendo Wii Balance Boards to a PC and were able to passively control a Non Player Avatar. The second implementation used a contrasting technology developed by Hedley et al. at the CSIRO, Sydney Australia. To link the movements of pedestrians with the NPAs custom visual scripts were implemented that took advantage of a modding community created plugin system.

Future work will include the dissemination of the results of field trials at a major public space in Sydney, Australia. The scope for tracking will be broadened to include opportunities for students to gain technical competencies alongside real construction workers in virtual environments. It is noted that ethical considerations should be a priority in developing the scope of the project and that Michael et al. (46) provides an emerging framework for doing this.

Finally, while Groenda et al. (25) saw that a virtual environment would normally be limited to the size of the users real environment and developed motion compression algorithms to circumvent those limits, the authors see limiting the player to their real environment as an opportunity to map the boundaries of that environment by tracing pedestrian movements through it.

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