

# Sense-Enabled Mixed Reality Museum Exhibitions

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## Abstract

*During the past few years museums and other cultural heritage institutions have started making use of handheld technologies to provide tourist guides to their visitors. For open-air sites, a number of experimental and commercial applications have been developed based on location-based guides. However, in museum environments static audio-visual guides are the dominant technologies used. In this paper, we present a novel pervasive mixed reality framework to a sensor network capturing ambient noise that can be used to create tangible cultural heritage exhibitions. Localisation of the visitors can be established in a hybrid manner based on machine vision and a wireless sensor network allowing visitors to interact naturally or with the help of sensors. In terms of interface design, a multimodal mixed reality visualisation domain allows for an audio-visual presentation of cultural heritage artefacts.*

Categories: Mixed Reality, Pervasive Sensing, Heritage Exhibitions, Interactive Environments.

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## 1 Introduction

Museums and other cultural heritage exhibitions have started making use of different types of guides in order to provide relevant information to their visitors on the spot. The most exciting part of heritage guides is advanced visualisation and interactivity and especially the ability to be part of the environment rather than to be simply an observer. For open-air heritage sites, the use of global positioning system (GPS) is sufficient for the provision of advanced location-based services (LBS). However, in indoor exhibitions such as museum environments, technologies like GPS can not operate and thus alternative technologies must be used that can offer a similar type of service. The alternatives include either computer vision techniques [ART\*07] or hardware solutions such as sensor networks.

The domain of sensor networks has been overtaken by that of pervasive computing, and a new vision has emerged, that of pervasive sensing or sensor webs. Pervasive computing is not a new field but it has grown enormously over the past few years due to the advances in advanced electronic, wireless technologies and the Internet. This rapid evolution of pervasive computing technologies allows the development of virtual heritage applications to a new level of user participation [FB\*05]. Most applications of pervasive sensing come into the category of field sensing – that is the use of an array of

sensing devices to determine the value of some measurand over a surface or volume. Mostly, applications studied so far are concerned with surface measurements.

Mixed reality (MR) refers to the combination of virtual and augmented reality (AR) technologies into a single interface. The construction of an efficient MR system consists of various processing such as real-time video capture, high-speed image processing, virtual world handling and realistic rendering [UT\*02]. This paper presents a novel pervasive MR framework capable of supporting a sensor network that captures ambient noise and can be used to create tangible cultural heritage exhibitions. Localisation of the visitors is established in a hybrid manner based on machine vision [ART\*07], [ART07] and a wireless sensor network allowing visitors to interact naturally or with the help of sensors.

The remainder of this paper is organised as follows. Section 2, presents an overview of wireless sensor networks as well as the most relevant museum exhibitions. Section 3, illustrates our novel pervasive MR framework. Section 4, shows how the sensor infrastructure operates in practice whereas section 5 presents the computer vision component and section 6 the graphics part of the system. Section 7, illustrates some example visualisations of the MR interface while conclusions and future work are presented in section 8.

## 2 Background

### 2.1. Wireless Sensor Networks

There is occurring a generalisation of wireless sensor networks from an esoteric, engineering based concept, concerned primarily with measurement, into a part of the pervasive computing mainstream. This trend is seen most immediately in the form of initiatives such as Sensor Planet, sponsored by Nokia [TSN07]. Here sensor networks are just part of a global resource, incorporating mobile phones, displays and other devices in the pervasive computing ambit. In a way, this is the natural extension of Pister's influential 'smart dust' concept [PKB99] in which the world was seen as being suffused with dust-size sensing devices, in an unending, ad-hoc, ever available information sensing network system.

Although the 'dust' concept is impracticable for real networks (mainly for pollution and health hazard reasons) the idea of a global, multi-mode sensing network is in some ways becoming a reality. There are already many wireless sensing systems operative in the form of weather stations [SW88]. ROADNet [HT\*06], which operates in southern California is an internet of sensor nets, combining oceanographic, seismic and meteorological networks. ROADNet makes the combined information of these different nets available to research institutions throughout the USA. By the standards of Sensor Planet, ROADNet is a static, constrained system. It also requires a considerable number of people for its maintenance and operation. The type of combined sensor net envisaged in Sensor Planet will be huge in scale, ad-hoc and multi-purpose. Its user function will be defined at the user level, rather than being designed in. It is no accident that Tuulos et al, [TSN07] refer to their application as a 'Mashup' – whilst not strictly a 'mashup' in the normally used sense, the title looks forward to a time when the various sensor information sources will be accessible using web API's and mixed together, as needed for a particular application, in a true 'mashup'.

The hardware resource that makes such systems possible is the new generation of motes (the commonly used name for a wireless sensor node) exemplified by the SunSPOT [SSW07], iMOTE2 [CI07] or the authors' own [NK07]. This class of mote features a 32 bit applications processor, plenty of memory and a powerful software infrastructure, rendering it quite capable of serving its information on the web and collaborating with other nodes in complex and sophisticated ways. Despite the high computational power, these devices are small in size, inexpensive and have a low power requirement, making it feasible to install very many in a locality. As to what is sensed, in a true web services way, this is a matter of what is built

by the web community, and will tend to depend on the availability of small and low cost sensors. Cameras, microphones, gyroscopes, accelerometers, pressure sensors, electronic noses are all possible types of transducer which will become ubiquitous in such an environment.

### 2.2. Mixed Reality Museum Exhibitions

Over the past few years, there has been an explosion of MR museum exhibitions and a good description of the most characteristic is described in [WP\*07]. In terms of pervasive museum exhibitions there has not been done a lot of research though. A simple example can be considered to be the Meta-Museum visualized guide system, which tries to establish scenarios and provide a communication environment between the real world and cyberspace [MK\*97]. The Meta-Museum mixes virtual reality (VR) and artificial intelligence technologies with museums to provide an interactive, exciting and educational experience. An AR system that could be used as an automated tour guide in museums is the automated tour guide, which superimposes audio in the world based on the location of the user [Bed95]. The aim of this application is to enhance the social aspects of museum visits, compared to taped tour guides.

Augmented Reality Ocular [LB\*04] is an extension of the traditional coin-operated binocular with AR capabilities allowing for exact registration of the direction of view from a fixed viewpoint. The main disadvantage of this system is that mobility of the user is limited due to the fact that the AR equipment is embedded into a traditional coin-operated binocular. LIFEPLUS [VP\*03] was one of the first systems offering advanced interactive audiovisual presentations to visitors of ancient Pompeii in Italy using AR and mobile computing. However, only 2D video tracking was achieved in this approach.

In terms of more advanced pervasive heritage applications, Farella et al, [FB\*05] developed a platform for interactive virtual heritage applications that integrated a VR system with wireless, connected portable and wearable computers. The system facilitates and enhances user navigation, visualization control, and peer-to-peer information exchange. Furthermore, a study of visitors to a science museum who are equipped with wirelessly connected handheld devices examines the use of technologies for 'bridging the physical and virtual worlds' [SK01]. The museum exhibits are augmented with information and services in the form of web pages and the users can access those pages conveniently when in the proximity of the exhibits as well as from outside the museum.

## 3 Pervasive MR Framework

The pervasive MR framework is the authors' prototype system for experimentation with sense-enabled AR. It

has been developed over a seven week period by a mixed-capability team which has included programmers, 3D modellers, hardware engineers, games programmers and AR experts. The trial operates within a room which is equipped with fixed-location wireless sensing devices as shown in Figure 1.

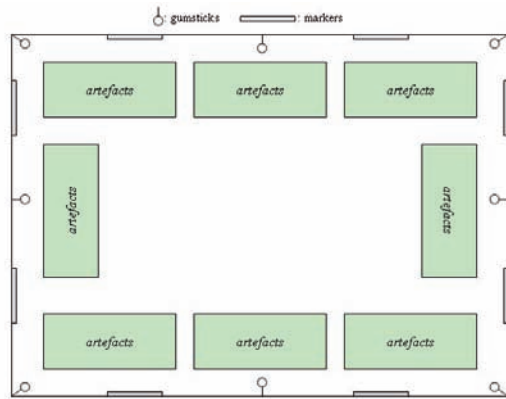


Figure 1: Pervasive configuration

These nodes are multi-modal although the system makes use of the microphone only. The main objective of the framework is to display 3D representations of the audio data contained inside the room blended with 3D virtual artefacts. This trial has been designed to test at least some aspects of the AR presentation system, using easily available sensors and display devices. The overall architecture of the sensor-based MR interface is presented in Figure 2.

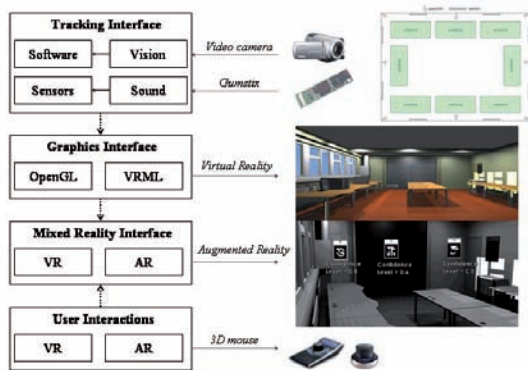


Figure 2: Pervasive mixed reality architecture

MR presentation of the sound field occurs within a 3D computer model of the room in which the sensors are located. It can take a variety of forms from a sound 'mist' to 'objects' representing the sound, which hang in space. The Gumstix processors sample the sound field local to them using a simple microphone. They have sufficient processing power to measure both the sound level, and the frequency, using fast Fourier transforms. In a classical mapping system, a two dimensional map

would be produced using interpolation between the data points, to build up the image a contour or shaded map.

In the case of the system under discussion here, the map is three dimensional, and the data is represented by an object or objects placed in the virtual space of the room model. These objects are overlaid on the image of the real room, to create virtual objects in real space, allowing the user to 'see' the sound. This gives rise to some interface design decisions discussed in section 7.1.

### 3.1. Hardware Infrastructure

Due to limits on hardware availability, the system is restricted. In particular, there are eight sensor nodes (Figure 1), one in each corner of the room, and the remaining four organised in a ring around the centre of the long dimension of the room. With this arrangement of sensors, the sound field is quite coarsely mapped in this example – the ramifications of this are discussed later. The hardware used for the sensor nodes is a Gumstix Connex processor card [GV07]. This is a tiny, powerful but inexpensive computer system, equipped with a 400MHz XScale processor, 64MByte RAM and a Bluetooth radio connection. Each card is equipped with a microphone although other sensor boards can be added which would enable the application to visually represent different sense modalities.

The Gumstix boards are programmed using a version of the in-house SenSor simulator [MN\*05], [MN\*06] for pervasive computing environments (section 4.2). This development environment, which we call Distributed SenSor, enables the hardware/software co-design of pervasive sensing systems. High-level code is written on a PC in the Python scripting language and this can either be run in software simulation on the host machine or distributed to pervasive devices (such as the Gumstix platform) and run on a remote execution environment which sits on each network node. Moreover, Gumstix are placed next to the visual markers used by the MR interface. For the MR interface, a standard computer equipped with a high-resolution digital video camera was used.

### 3.2. Communication

We used Bluetooth to communicate from the wireless sensors to a central PC. Bluetooth provides a cheap and easy way to receive data, but does not allow for a large amount of information to be transmitted. By reducing the size of messages from each sensor to be simply a state between 0 and 5, indicating that the amount of sound received lay between set points, this problem was overcome. This vastly reduced the number of times the sensors contacted the server, as they would only report when they changed state. The state value could then be passed into the MR interface to directly effect the onscreen augmentation. As a result of the report

suppression, the computer can respond more quickly to changes noted by the sensors because there is less to process, but the onscreen images are also more stable due to a reduced number of minor changes to the sound levels.

### 3.3. Presentation

The presentation device is a laptop computer with a camera attached, which will be replaced with personal digital assistants (PDAs) in the near future (section 7.2). The camera detects the scene behind the computer and displays the cultural heritage information on the screen in real time. Simultaneously, the camera image is correlated with the computer model of the room, allowing the localisation of the camera in the virtual room. This is done by the recognition of visible features in the room and localisation against the matching features in the model. In this initial prototype, this task is made simpler by the placement of distinctive patterned 2D objects at different known locations in the room. These are first detected and then triangulation methods allow the localisation of the camera in real space. The camera in virtual space can then simply be detected in the same way at a relative location.

## 4 Sensor Infrastructure

### 4.1. SenSor Simulator

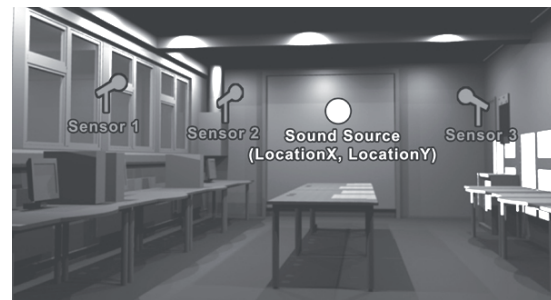
As this application is required to gather information about the surrounding environment a framework was required to 'listen' and 'process' sound events and deliver data about them to the AR application. SenSor, a WSN development environment was used [MN\*05], [MN\*06] exactly for this reason. SenSor is an algorithmic simulator for wireless sensor networks, allowing the programmers to both develop the algorithm to be used in a controlled environment and test for robustness using simulation. Distributed SenSor is an extension to the SenSor simulation package offering a novel 'mixed-mode' where the algorithm can be executed using either a combination of real and simulated nodes, or offering a pure deployment environment. SenSor applications are written in the Python programming language, which is a powerful cross platform interpreted language and allows the rapid development of code, without the complexity associated with traditional compiled languages, making Distributed SenSor ideal for the rapid prototyping of sensor network algorithms.

In a sensor network deployment there are generally several layers of network protocol before the top level application, some of these layers deal with the packaging of data for transmission, message passing protocols and the routing of data within the network. Although Distributed SenSor has been developed to allow algorithms to be developed at all levels of

abstraction, the testing the higher level algorithms is its primary function, if the user is creating a data processing algorithm, it is possible to allow the simulator to handle all communication and routing. In other words, the user is free to test the application without concern for complex lower level protocols. Here using SenSor's mixed mode to provide an environment for the sound sampling and communication code to be executed, it was possible to develop and test the data gathering algorithm without having to work with the complexities traditionally associated with the development of software for WSN. This allows users without the specialist understanding required deploying and developing sensor networks to prototype a working system, allowing much more time for the development of the algorithms required for data processing and visualisation.

### 4.2. Detecting Sound

Localising a sound is an ongoing research problem in the field of wireless sensor networks [AG\*06]. Various sophisticated algorithms exist to accurately locate sounds in 3D space. In our approach, a proof-of-concept heuristic technique was used which demonstrates the effect of localisation without the accuracy gained by other algorithms. The weighted average of the measured sound volumes is calculated by the simulated SenSor node running on a PC and the resulting 3D point is transmitted to the visualization software in the usual way. In particular, by using comparing sound levels across several sensors, we have been able to gain an approximate location for the sound source. An example configuration is shown in Figure 3.



**Figure 3:** Audio localisation

Once the application is started, a socket is created and starts listening on a desired port for new sound levels to be detected. Until a client is connected, sound values of 0 will be applied to each sensor. When the SenSor program is executed, it communicates with the program via the open socket. The visualisers open the socket and then listen for data being sent. It has a thread constantly waiting for a 2 character string, the first character being the ID of the sensor which has a volume, and the second the volume level that accompanies the sensor ID. When a new sound level is detected, it will be placed in an

array called Sensors. If the sensor which located a sound had an ID of 0 and a volume of 2, it would take up Sensors[0] with a float of 2, and if the sensor had an ID of 3 and a volume of 5, it would take up Sensors[3] and fill it with a float of 5. This array is constantly being updated as new data is being received. The pseudo code for the localisation is illustrated in Figure 4.

**STEP 1:**  $LocationX = ((\text{sound level at sensor 1} / \text{combined sound level of sensors 1 and 2}) * \text{distance between sensor 1 and 2})$

**STEP 2:**  $LocationY = ((\text{sound level at sensor 3} / \text{combined sound level of sensors 2 and 3}) * \text{distance between sensor 2 and 3})$

**STEP 3:**  $Sound\ Source = (LocationX, LocationY)$

**Figure 4:** Pseudo-code for audio localisation

In the above example (Figure 4), the sensors calculate the location of a sound on a 2D plane before drawing the object in 3D space. However, with more sensors in the room, it would be possible to approximate the exact 3D location of a sound source. Each Gumstix device records 0.1s of sound data from the microphone every 0.2s. Every 0.25s the RMS of the current buffer of volume samples is compared to the last calculated RMS. If the difference exceeds a threshold value, then the new value is reported back to a simulated network node running in Sensor on the PC. Then data are transmitted via a User Datagram Protocol (UDP) socket from the 8 Gumstix in the room to the visualization software which displays a representation of the detected sound on a 3D model of the physical environment.

## 5 Computer Vision Component

### 5.1. Best Marker Detection

ARTag [ART07] is a computer vision tracking AR system that uses acting on video input from a camera to calculate pose to perform the necessary alignment between real and virtual cameras. ARTag was inspired by ARToolkit [ART\*07], but uses more complex image processing and digital symbol processing to achieve a higher reliability and immunity to lighting. Specifically, the markers are detected in the video image and the correspondences between the image and their known 3D location used to calculate this pose.

### 5.2. Best Marker Detection

Choosing the best marker gives the ability to detect each marker, but ultimately, use the one which is currently easiest to detect, and usually closest, to perform the visualisation. This is done using marker confidence levels. For every frame, the application will iterate through each marker that is in sight, and read the confidence level of that marker, each time storing the

highest one in a variable called *bestmarker*. This variable can then be checked upon later. Figure 5 illustrates an example of how the bestmarker system is used, by representing three markers currently being detected, marker 0, 1 and 2. Each marker has its own confidence level.



**Figure 5:** Selecting the best-marker

The system would detect marker 0 having the highest confidence level, thus assigning best-marker to 0. This allows for a robust navigation inside the room, allowing for the best location possible.

## 6 Graphics Component

### 6.1. Displaying the Gallery

Following the selection of the best marker available, a 3D visual representation of the room (i.e. a museum or a gallery exhibition space) will be displayed in a VR domain. Where it is drawn is based on one marker at a time, the best marker. Figure 6, shows an example of how the 3D gallery is visually presented to the users.



**Figure 6:** Virtual gallery visualisation

The next step is to display the microphone on every marker on screen, and draw the room only on one marker at a time. This method was also used when we displayed the localisation of where the sound was

predicted to be coming from (section 4.2). It is worth-mentioning that when the sound was graphically displayed, it was positioned relative to the current best marker.

## 6.2. Drawing Sensors

Since there is a live list of volume levels for different sensors, the next step was to use them when displaying graphics on screen. For each sensor placed around the room, a marker was attached to the wall right beside it and an ID was given which matched the sensor next to it. The program would then check each frame to detect if any of the markers were in sight. If a marker is detected that matches the ID of a marker that it is expecting to be detected, it will perform various checking operations such as, call the microphone function. This takes the 3D model of the microphone and renders it onscreen in either the VR or AR environment. Along with the microphone visualisation, it will also set a colour interactively depending on the volume of the real sound.

## 6.3. Selecting Colour

It was decided to represent a microphone with no sound level as black and a microphone with a maximum sound level as bright red. As this could all be done using just the red channel, it was a case of developing an algorithm to check the sound level from the sensor ID which drawing was performed. This volume was set to be between 0 and 5. Because the OpenGL API takes a float between 0 and 1, the current value was taken. After trial and error experimentation, it was decided to define the colour function as shown below.

$$\text{RedValue} = (\text{Sensors}[0] * 2) / 10;$$

$$\text{glColor3f}(\text{RedValue}, 0.0, 0.0);$$

This allowed for a quite realistic audio-visual simulation of the sound in the MR domain.

## 7 Interface Component

### 7.1. Design Issues

There are a number of interface design issues that need to be addressed, and this prototype can provide a platform to test different possibilities. Some design choices that need to be made concern the following:

**Metaphor:** The aim of selecting a suitable metaphor is to assist the user in rapid interpretation of the information. In the museum exhibition example, the use of 'virtual objects' to represent the corresponding artefacts is an obvious and useful metaphor. In this prototype system, the choice is less obvious. Of course, since the system is a demonstrator, and does not have a genuine use of it,

there is no natural metaphor, although some particular applications may suggest some.

**Multi-variate data:** in 2D maps multivariate data may be represented using colours or three dimensional representations. In the AR example, there is no additional dimension to use, but there are a number of other options, particularly if the response of the system can be made to be real-time. Movement or behaviour may be one possibility, particularly if coupled with a flocking or swarming metaphor.

**Obscuration of real objects:** if the virtual objects representing sensed data were made completely transparent, they would be invisible. On the other hand, if completely opaque they will be maximally visible but will obscure objects behind. Some considerations would suggest that display systems such as this will be best for patchy phenomena, or ones consisting of discrete and patchy events. If the distribution of the data is even over the three dimensional field, then the displayed data will form a 'mist' enveloping the whole of the field of view. Not only will this make it very difficult to navigate through the mist (as it would be were it real), it will not be possible to appreciate slight differences of the data from point to point. Such data is probably better represented as a traditional map.

### 7.2. Visualisation Issues

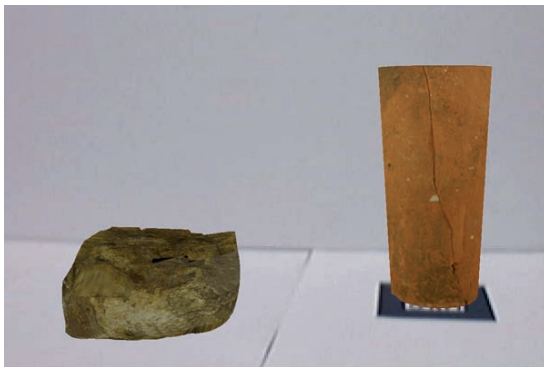
The MR interface is based on the knowledge gained from previous AR [LS\*04], [LM05] and MR prototypes [WP\*07] developed for heritage exhibitions. Although not all of the functionality implemented in these systems was transferred to our MR interface, the main capability is the multimodal switching between a VR and an AR visualisation domain in real-time. Figure 7 shows an example of the VR interface displaying 8 artefacts.



**Figure 7:** Virtual reality kiosk visualisation

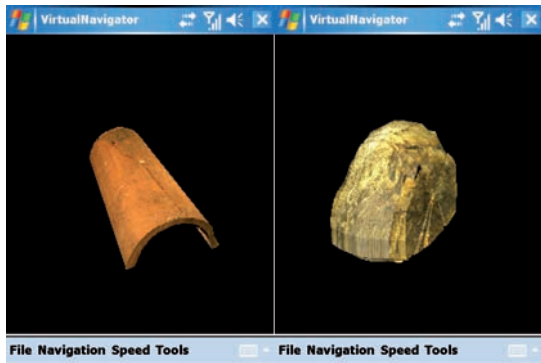
Next, similarly to [LS\*04], [LM05] and [WP\*07] the MR interface allows for seamless integration of 3D audio-visual heritage information such as artefacts and complete museum galleries. An example screenshot of

two heritage artefacts blended with the real-environment is presented in Figure 8.



**Figure 8:** Augmented reality kiosk visualisation

Finally, using 'VirtualNavigator' [GLB07], a mobile navigational system focused for PDAs, 3D representations of heritage artefacts can be displayed in an interactive VR environment as shown in Figure 9.



**Figure 9:** Virtual reality mobile visualisation

For the purpose of visualisation a HTC Advantage PDA was used which offers the advantage of wireless connectivity through Wi-Fi and Bluetooth as well as a five inch touch screen display equipped with two cameras and an embedded mouse. It is worth-mentioning, that the mobile component of our pervasive architecture is not yet fully integrated with the rest of the pervasive architecture. Thus at this stage, interactions are performed either using the stylus of the device, the implemented GUI or the embedded mouse.

## 8 Conclusions and Future Work

This vision of huge, ubiquitous, multi modal and available sensing systems poses a question as to how such an amount of information will be displayed. Of course, there are very many possibilities, but the prospect of finding display methods which will utilise or fuse some of the sensing modalities is an enticing one. Cameras will be ubiquitous, and will prove to be one of the most versatile sensor types, so it is worthwhile

investigating how camera data may be used in combination with other sensor types to yield novel, attractive and informative interfaces.

This paper has presented a sense-enabled MR framework for developing museum exhibitions. The proposed framework demonstrates the importance and usefulness of sensor-based MR technology to intuitive cultural heritage exhibitions. This enables non-specialist developers (who may be engineers, artists or other non-programmers) to rapidly develop and test pervasive applications in a friendly environment, without having an in-depth knowledge of the hardware specifics of the implementation. In the future, more sensor devices will be integrated such as a digital compass and to port the whole pervasive architecture into PDAs and other handheld devices such as mobile phones to allow for mobile sensor-based heritage guides.

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