Archeoguide: An Augmented Reality Guide for Archaeological Sites

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Archeoguide offers personalized augmented reality tours of archaeological sites. It uses outdoor tracking, mobile computing, 3D visualization, and augmented reality techniques to enhance information presentation, reconstruct ruined sites, and simulate ancient life.

Recently, researchers have introduced computers to archaeology and cultural heritage either as tools for promoting scientific work or as electronic aids providing users with information. During the past decade, CD-ROMs and Web sites have provided public access to virtual museums, archaeological sites, and works of art. Audio CD guides installed in cultural heritage sites let visitors participate in prerecorded audio tours, and information kiosks provide interactive historical, artistic, and other information. The latest developments include portable devices capable of providing guided tours with audiovisual information and limited interaction.[1,2]

Most of these tools, however, lack intelligence, user friendliness, and the ability to provide accurate navigation. Each solves only part of the interactive visualization problem and fails to integrate many features users might expect such as guidance and navigation information, information personalization, access to objects stored at remote locations, life animation, and so on.

We developed Archeoguide, short for Augmented Reality-Based Cultural Heritage On-Site Guide, to bridge the gap between recreation, education, and scientific research. This article shows how a well-designed mobile system can provide a personalized electronic guide to outdoor archaeological sites, help users navigate and make the most of their visit, and enable the collection, exploitation, and updating of archaeological data on any given site. The system exploits recent advances in mobile computing, augmented reality, 3D visualization, networking, and archiving to present users with on-site and online tours of the physical site according to their profile and behavior during the tour.

Site preparation

We have installed the Archeoguide prototype at Greece's Olympia archaeological site for testing, demonstration, and user evaluation. We chose this site because of its importance as the birthplace of the ancient Olympic games, its high popularity among visitors, and the fact that it lies mainly in ruins.

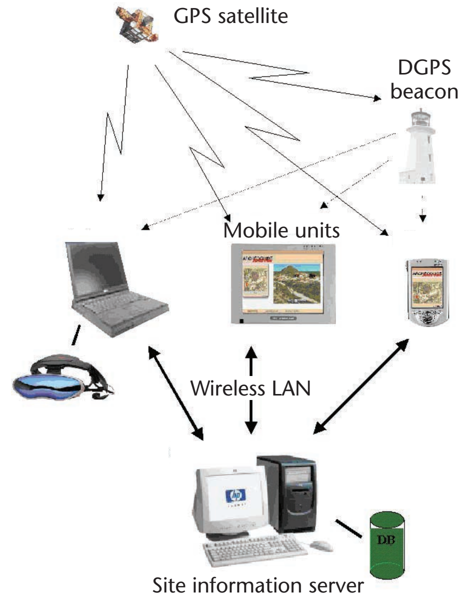
Before implementing the system, we performed a site survey to collect necessary data and plan the hardware installation. We collected aerial photographs and surveying data and entered them in a geographical information system (GIS) used to construct a digital elevation map. We used this 3D site representation to identify major monuments and corresponding viewpoints with unobstructed views. This data helped us define suitable tours and capture high-definition photographs of the ruins from the predefined viewpoints along the tour paths. For each viewpoint, we took a set of tiled photographs to simulate user movement around it. We stored the full dataset in the server database, along with 3D reconstruction models (in Virtual Reality Modeling Language format; http://www.vrml.org) of the ruins designed from architectural drawings and archaeological sources.

We used the same elevation model to define suitable positions for the communication infrastructure installation.

System architecture

Archeoguide uses a client–server architecture with three basic subsystems, shown in Figure 1: the site information server (SIS), mobile units, and the network infrastructure.

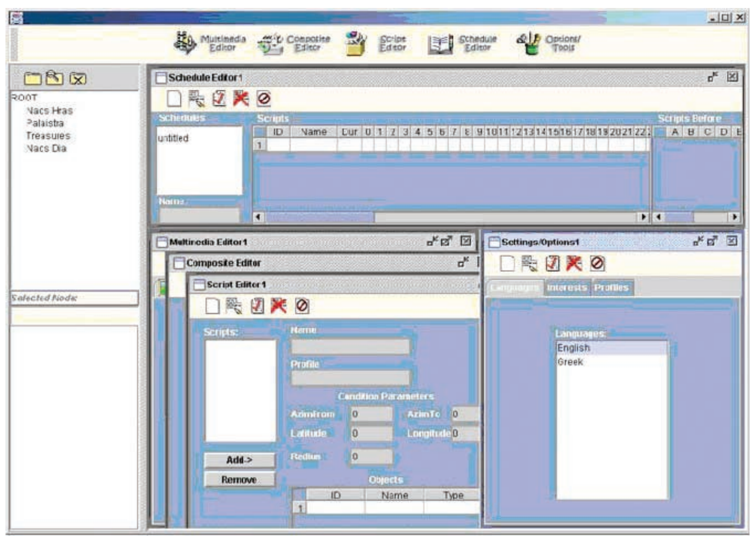
We built the server on a high-end PC with sufficient storage space to implement a multimedia database. It serves as the system's central repository for archiving the multimedia information used to construct augmented reality[3] tours. The SIS communicates this information to the clients via a wireless local area network (WLAN). Touring users in the archaeological site carry the mobile units, which are based on laptop, pen-tablet, and palmtop computers. The mobile units request multimedia information from the SIS based on user position and other parameters as calculated by the Global Positioning System (GPS) signals received from satellites at geostationary orbits. The system corrects the calculations' accuracy using a reference signal transmitted by a Differential GPS (DGPS) beacon located at a precisely known position.



1 **Archeoguide architecture.**

Site information server

We consider the SIS to be the heart of the Archeoguide system. It administers a multimedia object database storing 2D images, 3D models, audio and video clips, and text objects on the archaeological site. These objects are organized in a hierarchical tree structure, enabling grouping according to the information they represent. The tree's roots represent the whole site and its branches correspond to specific areas such as temples. Moving down the structure, we can reach the level of building parts (such as a temple's *pronaos*) or artifacts (such as a statue) originally found in the monument. The multimedia objects are stored along with attributes aimed at facilitating context-based searches using natural language—for example, "marble statues dating from the 5th century BC." These attributes include name, type, dating, geographic location, category, and detail level, and also help us select suitable material to construct personalized tours based on the user's profile, preferences, position, and orientation.



2 **SIS graphical authoring tools.**

The SIS also hosts a suite of authoring tools for creating and editing multimedia content and defining virtual and augmented tours. We developed the application's graphical interface (shown in Figure 2) in Java for maximum portability in a three-tier architecture. Virtual tour developers use six subwindows to create and organize new database content: toolbar, object editor (multimedia, composite, script), schedule editor, options editor, site node editor, and GIS editor.

The repository facilitates exchanging scientific findings and updating the stored information, which can then be used to create many things, from virtual Internet tours to CD-ROMs and media articles.

Finally, the SIS provides Internet access to virtual tours and the database content for recreational, educational, and scientific use. Users can draw their own tours on a digital map, navigate in 3D, and request related audiovisual information.

Mobile units

The mobile units provide Archeoguide's substance and more advanced functionalities. These portable devices provide all information stored in the central database to the touring users and incorporate a hybrid system for identifying the user's view. DGPS and compass readings provide initial estimates, refined by the technique presented in the sidebar, "Image Tracking" (next page). This information helps the system render 3D reconstructed models of monuments, artifacts, and life on top of ruins and natural surroundings.

All client components (tracking, rendering, controller, data manager, and user interfaces) operate concurrently, with the controller continuously instructing the renderer based on the tracking system data readings and user interactions. We therefore implement the mobile unit as a multithreaded process with the multimedia synchronization unit being the main control thread. This approach forces us to write all client com-

Image Tracking

To track users at the archaelogical site, Archeoguide uses an image tracking algorithm based on frequency domain analysis and matching of 2D images. This algorithm is optimized for execution speed, allowing real-time operation.

Translation

Let f_1 and f_2 be two images differing only in a 2D translation $t(t_x, t_y)$. The images are related as follows:

$$f_2(x, y) = f_1(x - t_x, y - t_y) \tag{1}$$

The Fourier functions F_1 and F_2 of the two images are given by the Fourier shift-theorem:

$$F_2(\xi, \eta) = e^{-j2\pi(\xi t_x + \eta t_y)} F_1(\xi, \eta) \tag{2}$$

F_2 and F_1 are two arrays of complex numbers.

The power spectrum of the Fourier transform F_1 does not change if the function f_1 is shifted by an amount of (t_x, t_y). The power spectrum is translation invariant.

The translation vector (t_x, t_y) can be easily isolated by computing the cross-power spectrum of F_1 and F_2 :

$$\frac{F_1(\xi, \eta) F_2^*(\xi, \eta)}{\left|F_1(\xi, \eta) F_2^*(\xi, \eta)\right|} = e^{j2\pi(\xi t_x + h t_y)} \tag{3}$$

where $F_2^*(\xi,\eta)$ is the conjugate-complex value of $F_2(\xi,\eta)$.

Recalling that the inverse Fourier transform (IFT) of an exponential function is a Dirac function, we can estimate the maximum of the IFT of Equation 3 which provides the image shift (t_x, t_y).

Rotation

If image f_1(x, y) is transformed into image $f_2(x, y)$ by a translation $t(t_x, t_y)$ and a rotation with angle φ, then the relation between f_1 and f_2 is defined as

$$\begin{aligned} f_2(x, y) = f_1(&x \cos\phi_0 + y \sin\phi_0 - t_x, \\ &-x \sin\phi_0 + y \cos\phi_0 - t_y) \end{aligned} \tag{4}$$

According to the shift theorem of the Fourier transformation, we obtain

$$\begin{aligned} F_2(\xi, \eta) = e^{-j2\pi(\xi t_x + \eta t_y)} &F_1(\xi \cos\phi_0 + \eta \sin\phi_0, \\ &-\xi \sin\phi_0 + \eta \cos\phi_0) \end{aligned} \tag{5}$$

A rotation in the spatial domain generates a similar rotation in the frequency domain. The magnitude spectra M_1 and M_2 of F_1 and F_2 are related as follows:

$$\begin{aligned} M_2(\xi, \eta) = M_1(&\xi \cos\phi_0 + \eta \sin\phi_0, \\ &-\xi \sin\phi_0 + \eta \cos\phi_0) \end{aligned} \tag{6}$$

Scaling

Let $f_2(x, y)$ be the scaled image of the image $f_1(x, y)$ with the factors (α,b), so that

$$f_2(x, y) = f_1(ax, by) \tag{7}$$

Then, the Fourier spectra of both images are related as follows:

$$F_2(\xi, \eta) = \frac{1}{|ab|} F_1\left(\frac{\xi}{a}, \frac{\eta}{b}\right) \tag{8}$$

If the horizontal and vertical axes of the frequency domain are scaled in a logarithmic way, the scaling parameters can be found as a translation in the frequency domain. This can be written as

$$F_2(\log \xi, \log \eta) = \frac{1}{|ab|} F_1\begin{pmatrix} \log \xi - \log a, \\ \log \eta - \log b \end{pmatrix} \tag{9}$$

By applying the phase-correlation technique, the translation ($\log a$, $\log b$) can be found and thus the scaling factor (a, b).

In conclusion, the power spectra are invariant for translation but variant for scaling and rotation.

Rotation and scale

In most cases, the horizontal and the vertical scale factors are equal. A rotated and scaled copy of one image can be found by a log-polar transformation of the magnitude images (see Equation 7):

$$M_2(\log r, \phi) = M_1(\log r - \log a, \phi - \phi_0) \tag{10}$$

ponents in the same language (C++) but also optimizes response times, which is critical for a real-time system such as Archeoguide.

Keeping these components on the mobile unit was a fundamental design choice. It implies a fat-client architecture where the mobile unit handles heavy processing (required by the renderer and the tracking system) but minimizes network traffic overhead and doesn't overload the server with many concurrent visitors' service requests. The design therefore works if the mobile unit can process information faster than the server can and transmit it to the mobile units through the WLAN. Simple calculations (considering that the WLAN can operate at a maximum of 11 Mbps in shared mode and that the mobile unit's CPU clock speed is at least 800 MHz, while a high-end server may have dual Pentium 4 CPUs running at more than 1.5GHz) show that for even a few concurrent visitors, the fat-client approach wins.

Communication infrastructure

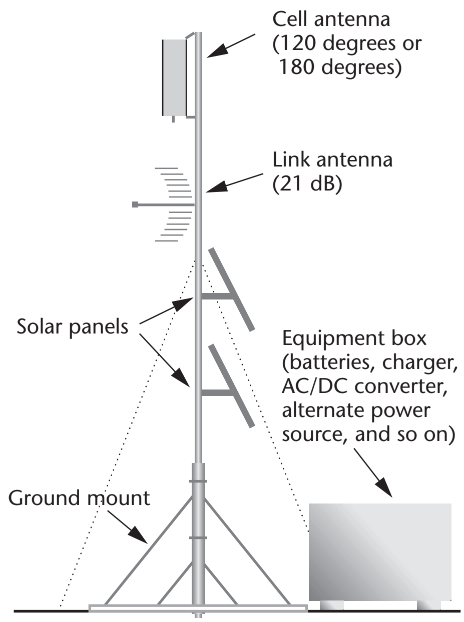
The communication infrastructure forms the backbone for the SIS and mobile units to exchange multimedia data and control information. The site's dimensions (300 × 500 meters) and remoteness from wired communication and power networks call for a wireless solution. We chose an IEEE 802.11b WLAN to permit expansion and upgrades should the need arise after installation. The archaeological site's delicacy required that we install the hardware outside its perimeter so as to eliminate physical damage and minimize visual disturbance. We used a total of three access points to cover the whole site, and measurements showed sufficient coverage for all areas accessible to visitors.

The access points use directional antennas to implement the WLAN but can also link to their neighbors using secondary point-to-point links. To power the remote access point, we installed solar panels that charge battery packs and converters that convert 12V DC to 220V AC.

Figure 3 depicts an access point, which we camouflaged in vegetation behind the temple. It stands 4.3 meters high.

The DGPS reference station uses an additional wireless link to communicate correction signals to the mobile unit's DGPS receivers. This station is a low-frequency DGPS beacon transmitting data over the wireless link in the 300 kHz band under the RTCM (Radio Technical Commission for Maritime Services) SC-104 specification.

The network runs at up to 11 Mbps and can support up to 50 users at a time. It handles the multimedia traffic asynchronously in that it downloads information to the mobile units in chunks corresponding to the preselected viewpoints. As a user approaches a new viewpoint, the corresponding information is downloaded (if not yet in the device's hard disk). To minimize wait time (in seconds), the system downloads much information at the tour's start and updates it when required.



3 **Access point placement on an archaeological site.**

4 **Map of ancient Olympia. Green–red compasses indicate major monuments' viewpoints and orientations. The solid red–yellow (upper left) compass indicates the current user's position and orientation.**

Position and orientation tracking

The DGPS position data give an accuracy of less than 1 meter and estimates the viewing angle with an accuracy of 0.5 degrees. Archeoguide displays this information on a digital map of the archaeological site together with the most important monuments' positions. Figure 4 shows a sample map from the Olympia archaeological site. The colored compasses indicate the user's position and viewing angle and the site's most important monuments.

This information gives an accurate first estimation of the monument the user is looking at, along with the viewing distance and angle. This is further refined by the optical tracking method we describe next.

Optical tracking

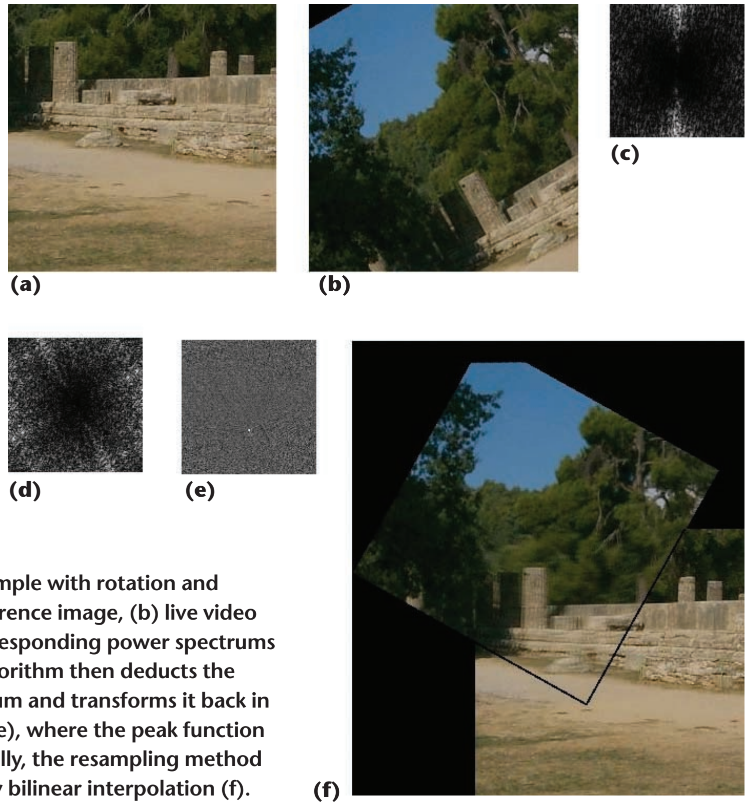
Markerless optical camera tracking is a complex task. Several approaches using image-processing operators[4-8] produce good results for offline applications where all features are available at once. In real-time applications, however, abrupt and unpredictable motion makes sequential approaches uncertain and fragile. We therefore propose using a set of calibrated reference images captured from the user's viewpoint. This method compares the user's view—the current live video image—to all reference images and computes a correlation score. It retains the best score and evaluates the 2D transformation between the current video image and the reference image, then passes this to the rendering system to create the augmented world.

The algorithm's reliability represents the most important aspect of our registration technique choice. Many changes may appear between the live and reference images as new objects, or visitors may be present in the scene, or new lighting conditions (due, for example, to changing sun direction or clouds) may create new shadows or highlights in the images. Therefore, we prefer to use algorithms that exploit global rather than local image properties. Basically, this corresponds to algorithms working directly on the whole image's pixel intensity or in the frequency space.

We opted for a Fourier-based approach because of its robustness and fast calculation. This approach allows the recovery of only rotation, scaling, and translation, effectively limiting its application to predefined viewpoints and restricted camera motion.

Implementation

For any given reference image, we consider that



(a) (b) (c) (d) (e) (f)

5 Registration example with rotation and translation: (a) reference image, (b) live video frame, and the corresponding power spectrums (c) and (d). The algorithm then deducts the cross power spectrum and transforms it back in the space domain (e), where the peak function is well defined. Finally, the resampling method adds two images by bilinear interpolation (f).

- the 2D image shifts are due to pure 3D rotation,
- the 3D translation and perspective distortion are negligible,
- a (moderate) scale change corresponds to a motion along the camera's optical axis, and
- the image's 2D rotation is due to the camera's 3D rotation around its optical axis.

These factors reduce complex 3D scene tracking and user motion to a 2D problem. They introduce a small error in visualization of the resulting reconstruction models because the actual viewing angle may differ slightly from that assumed for the augmentation of the natural user's view. However, this error is hardly perceptible and should be rectified as we transition to full 3D tracking in the future.

For the algorithm we compute the Fourier transformation using the fast Fourier transformation (FFT)[6] method. Hence the image must be square and with dimension 2^n. Our implementation[9,10] cuts the left and right borders equally and scales the image down to the next 2^n dimension. This retains the image's principal point and introduces no error in the 2D image shift computation (that is, 3D rotation around the optical axis).

Because the Fourier transform assumes a periodic function and truncated image, we must apply a window function, such as the Hanning window,[11] to the input images. The numerical instability for coordinates near the origin presents another implementation difficulty, so we apply a high-pass filter to the logarithmic spectra. (We could, instead, directly set to zero the points near the origin and inside a circle of radius e.[4])

The system doesn't account for the digital compass' tilt measurement, as the algorithm treats it as a simple translation.

The optical tracking algorithm runs sequentially at 15 frames per second on an 800-MHz laptop PC and for a camera resolution of 320 × 240 pixels. Figure 5 shows an example where a translated and rotated video frame (Figure 5b) is registered to a reference image (Figure 5a) from the database.

At every preselected viewpoint, the system uses a total of five to 10 calibrated reference images, providing more accurate results corresponding to a user's movement about the viewpoint within a radius of approximately 2 meters.

So far, this approach seems to hold the best promise for accurate head-pose estimation in wide outdoor areas. The tracking method is far more robust than landmark recognition-based methods because it can cope with occlusions of up to 60 percent and lighting changes, and provides almost real-time motion tracking. It also eliminates the need for artificial landmarks and consequent visual disturbance of and physical damage to archaeological sites. However, it does require considerable memory space and processing capabilities from the mobile units.

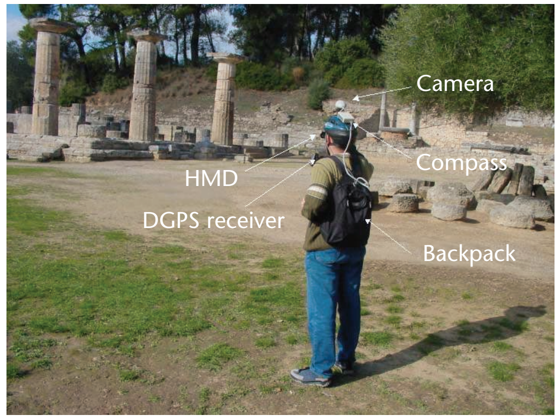
The algorithm works reliably for smooth user motion and rotation. Fast or abrupt motion may result in momentary tracking loss or lag between real motion and computed output. This necessitates processing the maximum number of frames in the video stream as opposed to differential approaches. For a more detailed discussion of the algorithm, see the sidebar "Image Tracking."

Rendering

We can use the results from the image-tracking method to define a warping transformation from the reference image to the live video image. A matrix containing the translation, rotation, and scaling parameters describes this transformation.

Recalling that the reference images are stored along with (aligned) 3D models of reconstructed monuments, the same transformation applies to these models. The renderer can thus render the transformed 3D models on top of each live video frame and present the user with an augmented view.

Figure 6 shows a typical example, where the natural view from the user's viewpoint precedes the same view augmented with the 3D model. This image appears on the augmented reality glasses the site visitor wears. The rendering process follows his or her movement, turning around the predefined viewpoint within a radius conveniently set to 5 meters (to avoid having to perform full 3D tracking).



7 Touring user with laptop and AR HMD at a viewpoint.

6 Rendering example. (a) Ruins of the temple of Hera in their present state and (b) augmented temple with rendered model on top of live video.

Mobile unit prototypes

We've built three mobile unit implementations, each offering different features based on trade-offs between portability and functionality.

Laptop

This top-of-the-range version uses a high-end Toshiba laptop PC and a Sony Glasstron head-mounted display (HMD) with variable transparency upon which the AR worlds appear. As Figure 7 shows, the user wears a bicycle helmet with a USB Web camera and a digital compass mounted on top, and a backpack containing the laptop, DGPS receiver, battery, power distribution module, and WLAN hardware.

Users position themselves at a viewpoint and stare at the monument of interest. In essence, the system treats them as active pointing devices, and mobile units identify their desire to view this specific monument's augmentation. It transmits a request to the SIS, which mines the corresponding audiovisual data from its database and transmits it back to the mobile unit. The system matches the reconstruction model to the live video stream from the Web camera, transforms it accordingly, and renders it. At the same time, it synchronizes the audio narration to the visual presentation and presents both to the user via the HMD and earphones. Figure 6b shows the image that users see. They can interrupt or alter the information flow by moving or turning away from the viewpoint.

Users can also employ an optional gamepad to display a short menu on the HMD and request navigation information (a digital map of the site clearly indicating location and orientation, as in Figure 4). This also lets them view more detailed item descriptions or information on related topics.

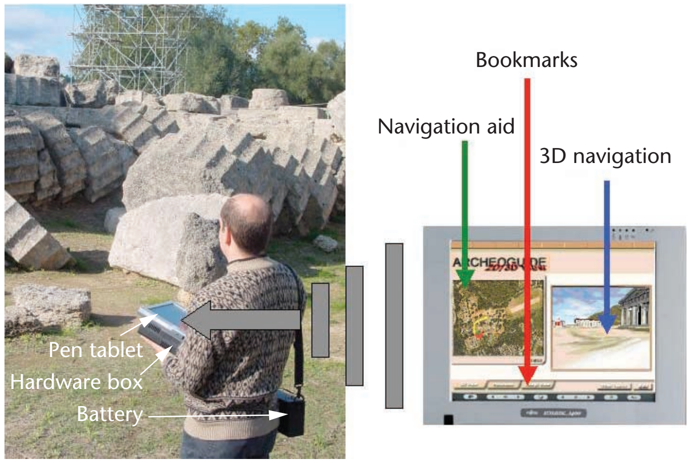
The system automatically personalizes the tour offered according to its user's profile, entered prior to the tour's start. Based on parameters like age, interests, education, and archaeological knowledge, the system draws up a basic tour and enriches it with corresponding information. The user's behavior or gamepad input can alter this tour schedule automatically in real time.

The system downloads the necessary information from the server but minimizes wait times through prefetching and reuse of content left on the device's hard disk from previous tours. As such, only missing and updated items must be transferred. Because all the system's mobile devices use this downloading method, each transfer takes just a few seconds. The device currently offers one hour of use between recharging.

The GPS receiver requires 15 to 45 seconds to start transmitting position information after a cold start. The compass can provide readings as soon as it's powered up based on absolute measurements from a magnetic sensor. This avoids cumulative inaccuracies caused by differential measurements. Provision for calibration and offset correction exists in case strong magnetic fields exist at the site.

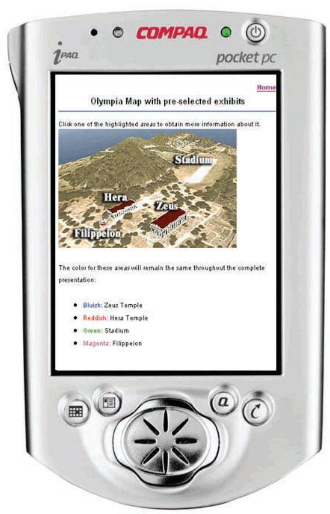
Pen-tablet

A lighter mobile unit implementation uses a Fujitsu pen-tablet PC running at 500 MHz that suits outdoor use and can be carried like a book. It features a pressure-sensitive screen upon which users can write or perform Windows-based operations with a special pen. The device has a DGPS receiver, a digital compass, and wireless communication equipment integrated in a small box attached to its bottom. Designed to deliver the digitally enhanced equivalent of the traditional paper guides carried by tourists, it needs no camera or image tracking software. Instead, it employs measurements from its digital compass and DGPS receiver to synchronize its audiovisual presentation to the user's natural view.



(a) **(b)**

8 **(a) Touring user with pen-tablet mobile unit at a viewpoint (b) See examples of 3D navigation information and available options in bookmark form at http://www.archeoguide.com.**



9 **Sample screen of the palmtop mobile unit.**

10 **Avatar athletes competing in the stadium in ancient Olympia, Greece.**

Figure 8 shows a user standing in front of the ruins and consulting the device. The device's screen shows navigation information and 3D physical site navigation featuring reconstructed monuments and their surroundings. Audio narration in the user's language accompanies visual material to provide historical and other information.

Users can also select augmented panoramic views corresponding to 360-degree reconstructions from their viewpoints. The panorama is automatically loaded and scrolled, as the user turns around, based on the DGPS and compass reading.

The device suits outdoor viewing, even under direct sunlight, and offers one hour of use between battery recharges.

Palmtop

The lightest mobile unit version uses a palmtop computer running Windows CE and is a cheap and easy-to-carry electronic guide. Its current version supports user position tracking but not orientation tracking. It provides information in a digital plan similar to those offered in paper guide, map, and augmented map formats. It also incorporates augmented images and videos, panoramic views, related information, audio narration, and textual information. The information is automatically presented when users approach a viewpoint, as long as they head toward the monument presented on the device's screen. Alternatively, they can read the site plan, marked with their position in the site, and request the relevant data.

Figure 9 shows an example of this device's user interface. Based on a common Internet browser, it offers easy interaction because it's familiar. Users can operate directly on the device's screen with a special pen or the buttons at the bottom of the screen. We took special care to structure the multimedia content in single pages and to avoid scrolling except from the panoramic views.

Figure 10, an example of an augmented avatar video frame, shows avatar athletes competing in the ancient Olympia stadium in a reconstruction of the race during the ancient Olympic Games.[12,13] The avatars appear in the stadium as it exists today, creating more realism.

The device can run for an hour before recharging and is visible under all lighting conditions. A PCMCIA card attached to it with a special expansion jacket serves its networking needs. Additional hardware can also be integrated to provide position and orientation tracking, to automatically present the relevant audiovisual information to the user.

Analysis and future work

We tested Archeoguide at the ancient Olympia archaeological site in Greece and received good reviews from ordinary users, site staff, archaeologists, and technology experts. Users liked the AR reconstructions and the additional information the system offered, such as navigation and audio narration.

Users praised the AR glasses for realism, but some said they felt uncomfortable wearing them while walking. The helmet received a similar critique. We're currently reengineering these and should replace them with a miniature device in the next system prototype.

Users said the avatar animations helped them better understand the site's history and use, and they appreciated personalization features for better time management during their visit. The pen-tablet also received good reviews because it simulated the use of familiar paper guides and the augmented panoramic views helped bridge the gap between its flat-screen presentations and the more realistic ones with the special glasses. Finally, users found the palmtop a cheap substitute suitable for quick visits but criticized its small screen. Based on these comments, we're currently working on a second prototype that will offer users more flexibility.

The system also needs further work on 3D tracking and development of custom-made mobile devices that are compact and lightweight enough to carry around outdoors. We expect these improvements to help Archeoguide become the prime candidate for installation in major archaeological sites. For more information on Archeoguide, go to http://www.archeoguide.com. ■

Acknowledgments

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