

Comparative Navigation System for Experiencing 3D Digital Archives of Cultural Heritage

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ABSTRACT

We have developed a method that enables a user to better understand and enjoy the contents of 3D digital archives, thereby enhancing the user's experience. The system's interactive interface, built using virtual reality technology, enables the user to "walk through" the archives, comparing two or more contents. The user can compare, on the same screen, different contents or different versions of the same content at different points in time. For example, a user can compare the proposed design for a building with the actual building and can compare the states of restoration of a cultural heritage site over time. This ability to perform multilateral comparisons enables the user to clarify the relationship between contents, the influence of one content on another, and the causal relationship between contents. Testing of a prototype system for a 3D digital archive of cultural heritage sites showed that it worked smoothly and that the users could easily operate the navigation system.

Key words : 3D digital archive, Experience, Comparison, Content, Virtual reality, Real-time simulation, Interactive

1. Introduction

Continuing advances in computing technology and the Internet are accelerating the digitization of various types of information and the utilization of that information. The storage of this information in digital archives enables anyone with a computer and Internet access to easily use it. These archives are widely used for study, school, social education, and regional development as well as for recording, preserving, and restoring items of cultural heritage such as historical buildings, art works, and archaeological sites.

Digital archives initially included only text and photographs, while they now include photographs, videos with text explanations, and 3-dimensional computer graphic (3D CG) models. In the architectural field, for example, the use of 3D digital models for

computer-aided design/computer-aided manufacturing (CAD/CAM) has improved the efficiency of design, construction, and management. Furthermore, 3D CG models of historic architectural structures and archaeological sites are now being created for a wide range of purposes.

Generally, the 3D data for a historical structure are acquired using 3D measurement equipment. Distances are measured using laser devices, etc. Comparatively large objects comprising such structures can be measured using a 3D measurement device, e.g., a 3D scanner. Previously, 3D digital archives had to be created from photographs, which were scanned and then converted into digital data. This is expensive and inconvenient. Advances in the performance and reductions in the cost of 3D scanners, along with improvements in digital photogrammetry, have made it practical to measure and record the shape of target objects directly in digital form. In addition, 3D scanners can automatically calculate the form of an object and the size of the image required and can directly record the information onto digital media. My research group has conducted several 3D measurements of archaeological sites in Japan and abroad and has created various 3D models and digital archives. The 3D model can be of a huge

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object that one can walk around, such as places with historical architecture or archaeological sites. The digital archives described in this paper assume a 3D model, hence the term “3D digital archives”.

Many case studies reflecting the expansion of 3D digital archives have been presented at international conferences^[1-4]. The main focus of these studies has been the construction of the archives. There have been few reports of research into how such archives can be used or how they can be experienced.

The main feature of 3D digital archives is that users do not simply see a flat 2D image of the contents out of context—they can see the contents from all angles in a natural setting. In addition, users can experience the contents as if they were in the real world. Moreover, they can run simulations and scientific investigations that would not be possible in the real world.

On the basis of this concept, we are developing a system to support comparative experiencing of 3D digital archives. As a first step towards achieving this goal, we have developed a prototype system for a digital archive of 3D data for historic architectural structures. This system is based on virtual reality (VR) technologies and offers an interactive interface.

2. Basic Concept

Digital archives store various types of contents (e.g., 2D images, 3D models, texts, and drawings) in digital form in an organized manner. We refer to the user's acquisition of information from digital archives as the “digital archive experience”. The conventional digital archive experience is a visit to a museum, and only the content and information currently being exhibited can be viewed. Many digital archives have been created using 3D CG that contain data on historic architectural structures and cultural heritage sites. However, simply displaying 3D data from a digital archive in virtual space is not sufficient for a user to gain an understanding of it. The user cannot experience the exact information they want and the content they want to see. The user can only acquire the information that is offered. These systems are like an encyclopedia in that they only give information about a subject rather than discuss it as in an educational program. This means that users without specialized knowledge might find it difficult to grasp the relationships between content elements.

Especially in the case of a historical structure, there are many portions of the structure that a user needs to learn about through experience. For example, an understanding of the original structure of a building can be gained by looking at the present structure. Systems are thus needed to help users understand the contents of digital archives.

Our proposed digital archive experience system is based on comparison. A user compares a certain content in the archive with related contents in the archive in order to better understand it. By considering the similarities and differences, a user can come to recognize and understand the content. The user can clarify the relationship between contents, the influence of one content on another, and the causal relationship between contents by multilaterally comparing them. In addition, the user can deepen his or her understanding of each feature of the contents being compared, resulting in a better overall understanding of the content.

Comparing one type of content to another using existing systems is difficult because users have to locate contents and observe them from separate viewpoints. With this in mind, we developed a browser that simultaneously displays various types of content while automatically controlling the viewpoints, enabling the user to easily compare the contents. In the real world, people can walk through only one space, while in virtual space, a user can walk through many spaces at the same time. This is a key concept of our system, and it is intuitive and effective.

3. Digital Recording of Cultural Heritage Sites

In this section, we describe the laser scanning and photogrammetry and their combined use for digitally recording cultural heritage sites in terms of the accuracy and expressiveness of the models and their efficiency in data processing. The data used here were obtained from our 3D measurements of the Byzantine ruins on Gemiler Island, off the southwest coast of Turkey.

3.1 Sites

Gemiler Island is located along the Lycian coast of southwestern Turkey and faces the Mediterranean Sea. The sites of a wide variety of buildings from a bygone medieval city are scattered all over the

island. Several of them have been studied by the Research Group for Byzantine Lycia, a Japanese joint research project whose members include art historians, archaeologists, architectural historians, photographers, and students. They started excavating Church III, one of the four basilicas on the island, in 1995, after several years dedicated to surface exploration. Over ten years of research has revealed that the city was built in the late 5th to early 6th centuries, i.e., during the early Byzantine era, and that there is a close relationship between the island and St. Nicholas^[5,6].

Of the four basilicas on the island, Churches II and III have kept their original form relatively well and hence they were selected as the first targets for 3D recording and modeling in the Gemiler Island project. Church II, which stands halfway up the western slope of the island, has three aisles and measures about 20×10×9 m. The semi-dome of the apse and the north wall are well preserved (Fig. 1, left). Church III, located just below the top of the island, and hence easily visible to ships sailing on the Mediterranean, also has three aisles and measures approximately 30×15×9 m. Generally, the south and west of the basilica, i.e., the atrium and west and south walls, are well preserved, whereas the north and east, i.e., the semi-dome of the apse and the east wall, are not (Fig. 1, right). The wooden roofs of both basilicas have completely disintegrated.

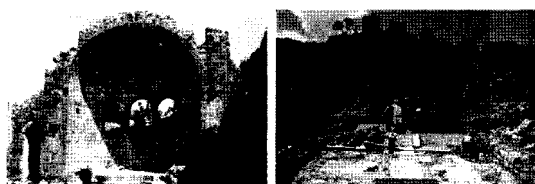


Fig. 1. Church II: interior view (left); Church III: west wall and nave (right).

3.2 Data Collection

In addition to measuring the two basilicas three-dimensionally using laser scanning, which was the main task, we also surveyed them using real-time kinematic GPS and took photographs of them with digital cameras.

3.2.1 Laser scanning

We used a Riegl LPM-25HA laser scanner to scan the two basilicas due to its battery-driven capability, portability, and sufficient accuracy for our purposes.

Although the basilicas are relatively large, the architectural historian required a sampling step of 1 cm or less, assuming that the plans would have been drawn to a scale of 1:100. Table 1 summarizes the specifications of the laser scanner.

Table 1. LPM25HA laser scanner specifications

Specification	Value
Measurement range	2-60 m
Measurement accuracy	±8 mm
Measurement rate	1000 points/sec
Measurement resolution	1 mm
Beam diameter	15 mm @ 10 m 20 mm @ 20 m 60 mm @ 60 m
Beam wavelength	near infrared
Horizontal scanning range	±180°
Vertical scanning range	±150°
Positioning accuracy	±0.009°
Angle readout accuracy	±0.009°
Scanning speed	36°/sec
Dimensions	25×30×32 m
Weight	9.5 kg

We scanned Church III 55 times from 29 different locations. The number of measurement points was approximately 34 million, and the total data amounted to about 470 MB, including the RGB value of each point. For Church II, we positioned the scanner at five locations and scanned it seven times (about 5 million points; 70 MB). It took about 55 hours to scan Church III and about 7 hours to scan Church II. Sample images are shown in Fig. 2.

The sampling step was adjusted from 0.06 to 0.15 gon depending on the importance and condition of the target, though most targets were scanned with a sampling step of 0.1 gon due to the limited time available. When the sampling step was 0.06 gon and the target was 10 m away, the sampling step on the target was about 1 cm, while it was about 1.6 m



Fig. 2. Sample laser-scanned images of Church III.

when the sampling step was 0.1 gon.

3.2.2 Photo shooting

We used a Hasselblad 555ELD camera body equipped with a Kodak Professional DCS Pro Back 16-megapixel charge-coupled-device (CCD) array and a Distagon 50-mm F4 FLE lens to record high-resolution images suitable for use as texture data for the 3D models. The CCD was 36.86×36.86 mm and produced 4072×4072 pixel images. Around 1300 images were taken in total for both churches. This large number of images was due to the 60% overlap required for adjacent pictures.

To complement the 3D models created from the laser data and high-resolution images, we used photogrammetry. Photographs for this purpose were taken with a Nikon Coolpix 885 camera. The quality of the photographs, however, was not satisfactory, so we created 3D models using the high-resolution images and Topcon's PI-3000 photogrammetry software. We used this software because it can process pictures taken with a standard digital camera, it runs on a note PC, and it can calculate digital surface models fully automatically. Moreover, it does not require a fixed base or other support if sub-millimeter accuracy is not needed. This was very important for us because there was limited time for support setup.

3.3 Data Processing

3.3.1 3D model creation

We used InnovMetric's Polyworks™ to align and merge the 3D images. We first created 3D models using only the laser-scanned data. The model of Church II in the POL format comprised about 2,560,000 polygons. The file size was approximately 70 MB. It would have been even larger if the model were saved in VRML^[7] format.

Since the point cloud data was too much to handle for the 3D model of Church III, we first partitioned the church into several sections, i.e., the apse, the south wall, and other areas, and then created a 3D model corresponding to each section. These separate models were then merged into one. Some section models used the original point cloud data, and the others used a reduced amount of data. The total size of the 3D polygonal model of Church III was approximately 7,143,159 polygons in POL format. The file size was about 178 MB.

Sample views of the 3D models are shown in Fig. 3.

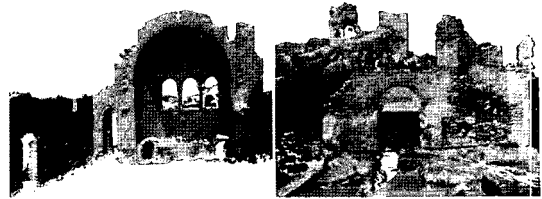


Fig. 3. 3D models of Church II (left) and Church III (right).

3.3.2 3D model with texture mapping

To improve their appearance, we added texture to the polygonal models. The texture images were created from high-resolution image data using the PI-3000 software^[8]. As there was a huge number of points, reduced point-cloud data for Church II in ASCII text format was imported into PI-3000. A photograph was chosen, imported into PI-3000, and analyzed using bundle adjustment. To align the 3D polygon model and texture images, three reference points, with global coordinates obtained from a topographical survey, were used. Fig. 4 shows a textured 3D model of Church II.



Fig. 4. Textured 3D model of Church II.

3.3.3 Digital archive

We have been developing a system that is capable of displaying 3D models and managing an image database. The database includes about 16,000 images, along with floor plans, maps, and 3D models of Churches II and III.

The user can retrieve images through the image database by pointing to floor plans or maps as well as by entering keywords. Using the floor plans and maps, even someone who does not have knowledge about the sites and/or is unfamiliar with Byzantine art and architecture can easily access images of interest. Experts can easily retrieve images without

having to be overly concerned about the search terms to input. The interface is shown in Fig. 5.

The system can be used to enter image data and edit keywords; the search results can be printed in the form of an image catalog. A unique function of the system is that users can add information about the camera position and direction for each image. With this interface, once a floor plan is selected, the system can display it in a window (the upper window on the left side of Fig. 5), and the user can indicate the start and end points of the desired route. Arrows showing the position and direction of the cameras are also displayed.

The most important feature of this archive is that the user can browse not only images in the database but also 3D models, such as those for Churches II and III, as shown in Fig. 5 on the right. Since each image shows only a two-dimensional view, several images are needed to see the structure of interest from all viewpoints in order to obtain an overall grasp of the structure.

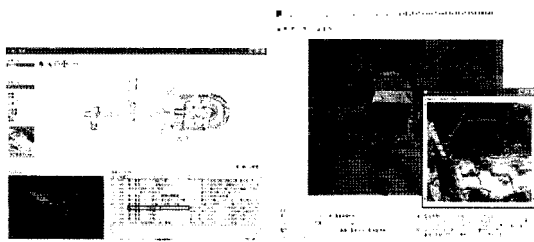


Fig. 5. Digital archive interface (left); image close-up window and 3D model viewer (right).

On the one hand, the 3D models can provide a complete view of the structure from arbitrary points of view. For example, if the user wants to observe how two walls are connected, he or she simply needs to rotate or translate the model until a good angle is found. That is, using the 3D models as 3D maps, users can gain an intuitive understanding of the object(s) in an image.

On the other hand, the images usually have higher resolution and thus are usually more suitable for close inspection of an object's surface. The images and 3D models thus complement each other, so, by offering the advantages of each, our system serves as a useful presentation tool.

Our image database now contains more than 15,000 images, each of which has several associated keywords. This database can be accessed via the

Internet, and the images can be retrieved by entering keywords, a file name, or a year. The user interface is shown in Fig. 6. This database has not yet been released to the general public; access is limited to the project members.

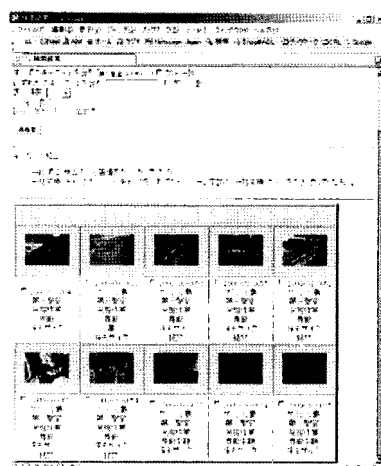


Fig. 6. Image database interface.

4. System Description

In this section, we describe the development of our comparative navigation system for a 3D digital archive experience and our prototype system.

4.1 Development

We used various tools, including an authoring tool, a modeling tool, and an image-editing tool, to develop this system. We used the Microsoft® DirectX Graphics-Application Program Interface (API) based Vrttools®, an authoring tool commonly used to develop computer games, to develop the internal scripts (Fig. 7) comprising the real-time simulation graphical user interface (GUI). Using this tool, we can perform high-speed rendering using a massive number of polygons and vertex colors.

We used a note PC with a 4.3-GHz CPU, an ATI Radcon® 9800 GPU, and 2-GB RAM. To enable us to perform the rendering in real time with smooth movement, the rendering had to be done at no less than ten frames per second (FPS). The amount of data thus could not exceed 700,000 polygons with vertex color information.

The system had to meet three conditions in particular for it to support real-time simulation.

1. *High-speed rendering*: There is a trade-off between a high sense of reality and high-speed rendering as the system may not have sufficient performance for both. Priority was thus given to rendering at high speed to archive real-time simulation. The system also had to ensure the highest sense of reality.
2. *Lightweight 3D data*: One way to increase the rendering speed is by reducing the weight of the data. A balance needs to be found between sufficient data speed and a sense of reality. Moreover, the user should not feel impatient while using the system through the Internet. That is, the system should be able to read 3D data in less than 90 seconds. This can be achieved by selecting suitable hardware and software.
3. *Easy operation interface*: The interface should be easy to operate. In situations where operation does not keep up with the rendering, the rendering speed should be reduced. Moreover, the interface should be immediately usable, even by a first-time user.

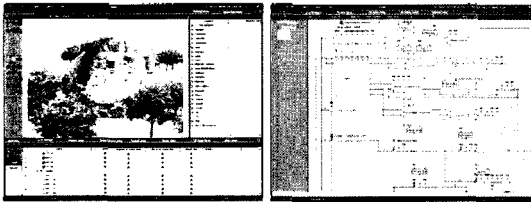


Fig. 7. Scripts of real-time simulation interface developed using Virtools®.

4.2 Data Preparation

The most serious problem in meeting the conditions described above is editing the data. The 3D data for this system must be lightweight, and there must be a sense of reality. However, the base data, obtained from the laser scanning survey, is point cloud data. Moreover, there is a huge amount of data, as explained in 3.3.1., and it is even larger if the model is saved in VRML format. This means that the point cloud data must be edited before it is converted for use by the navigation system. We thus use the following procedure for editing the data.

1. *Compensate for insufficient data*: The point cloud data obtained from the laser scanning survey is read by Polyworks™, which automatically generates polygons comprising a

model representing the data. If insufficient data is obtained there may be holes in the generated polygons. When this happens, the compensation function of Polyworks™ is used to fill in the holes by generating tops over the holes on the basis of the relation to the shape of each top in the surrounding when working about (1). This is done in one of two ways.

- (1) Polyworks™ does it automatically by appointing an area to cover on Polyworks™ beforehand (Fig. 8).
 - (2) If Polyworks™ cannot do it automatically, the operator does it manually (Fig. 9).
2. *Reduce number of polygons*: The IMCompress™ tool of Polyworks™ is then used to automatically reduce the number of polygons. This tool removes excess information from large 3D models. Table 2 shows the number of polygons before and after reduction for Church III. As shown in Fig. 10, the reduction did not degrade the display quality.
 3. *Export to VRML model*: The data is then exported to the model in VRML format, which is a general-purpose one. This model will then be used in the comparative navigation system.

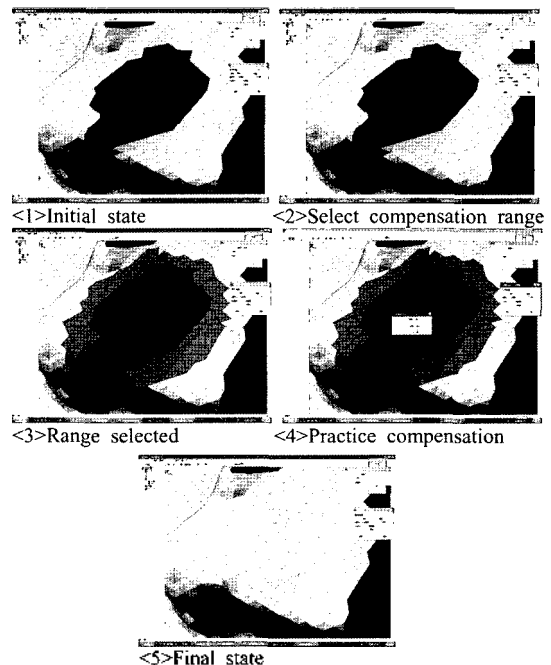


Fig. 8. Compensation using automatic compensation function of Polyworks™.

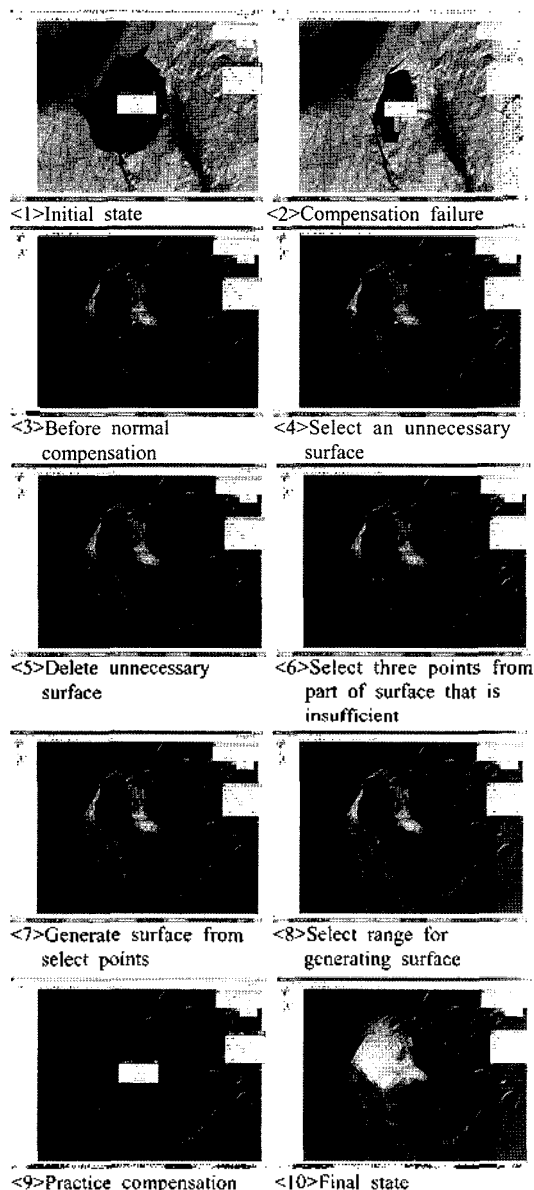


Fig. 9. Compensation using Polyworks™ manually.

4.3 Prototype

The prototype system supports a traditional walk-through simulation and is especially aimed at enabling users to experience the archive information through browsing in the following ways.

- As the user freely walks through the archives, the system provides on-demand comparative views of related content.
- If the user 'collides' with a model wall, a collision detection function generates a rebounding effect,

Table 2. Number of polygons before and after polygon reduction

	Before	After
Apse	431,951	42,329
Apse_back	222,211	21,775
Apse_all	655,437	64,230
Atrium	766,051	75,070
Chapel	392,875	38,500
Inside	877,061	85,948
North	387,258	37,950
South	540,022	52,921
Terrace	1,476,197	144,661
Upper_part	349,656	64,265
West_wall	1,044,440	102,351
Total	7,143,159	700,000

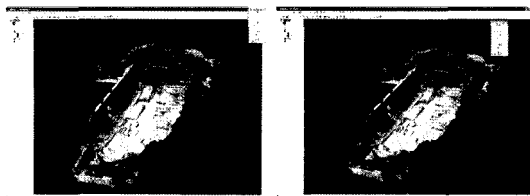


Fig. 10. Polygon state before (left) and after polygon reduction (right).

similar to the impression received when colliding with a wall in an actual building.

- The user's view is fixed at eye level by a 'gravity' function. The user does not 'sink' into the floor or 'float' above it but rather walks around as in the real world.
- The user can compare the various types of archive contents interactively. As soon as the user selects contents to be compared, the system displays them.
- The user can select from several interfaces—a mouse, a keyboard, a game controller, and a space/mouse traveler.

The process of making a comparative navigation system for a 3D digital archive experience can be divided into five steps (Fig. 11).

- Step1: Gather all data created by modeling work; 3D models, GIS models, photos, etc.
- Step2: Convert the data into models using modeling tool. Then group the models together to form scenes within a circumference setting, a material setting, and alterable models.
- Step3: Assign attributes and behaviors to the

objects and scenes in the settings, including camera settings, light settings, collision detection settings, level of detail (LOD) settings, and gravity settings. Also create the GUI and system functions.

Step4: Export the comparative navigation system for the 3D digital archive experience for testing and debugging.

Step5: Save behavior blocks, scenes, etc. constructed during testing in the database.

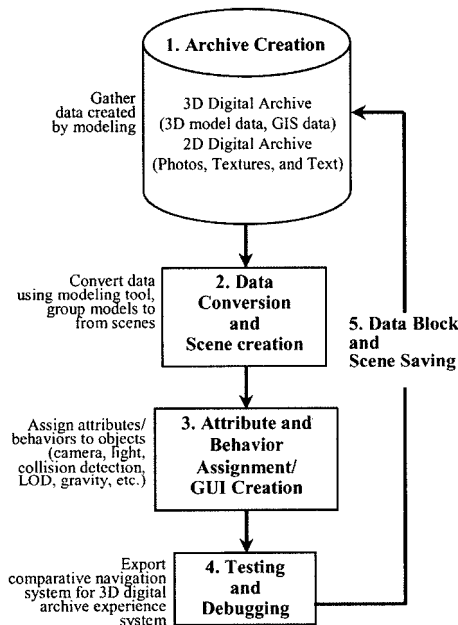


Fig. 11. Steps in creating comparative navigation system.

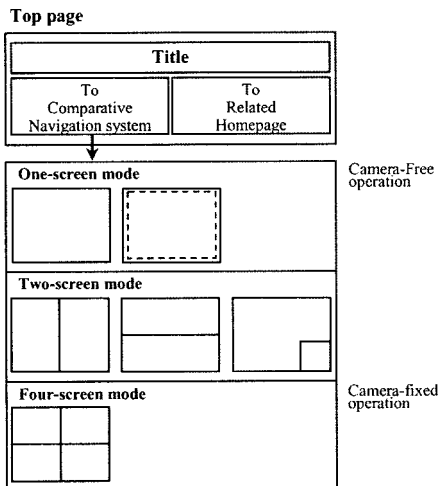


Fig. 12. Operation of GUI.

The GUI operates as shown in Fig. 12. The user can compare various types of content by switching between a one-screen comparison, a two-screen comparison, and a four-screen comparison.

4.4 Functions

The main functions of the system are walk-through, concurrent comparison navigation, and cross-sectional viewing. We illustrate these functions by using the information archived for Churches II and III.

- **Walk-through function:** A user can capture an image while freely browsing 3D digital archives containing information about historic architectural structures. Objects in the structures can be viewed from many viewpoints, as shown in Fig. 13. Both the interior and exterior of a building can be viewed simultaneously. If the interior is narrow, the viewing angle can be adjusted accordingly.

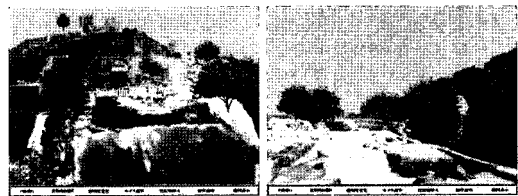


Fig. 13. Walk-through function.

- **Concurrent comparison navigation function:** A user can compare various types of content using different screen modes. For example, the present conditions of ruins can be compared with a virtual restoration on the same screen.

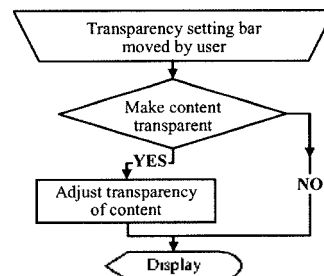


Fig. 14. Superposition comparison.

• One-screen mode

Superposition comparison: Position and size can be compared by layering two types of content and adjusting the transparency of one or the other, as shown in Fig. 14.

Object insertion comparison: Size and scale can easily be grasped by inserting and displaying a 3D model of an object with a known size and scale, as shown in Fig. 15.

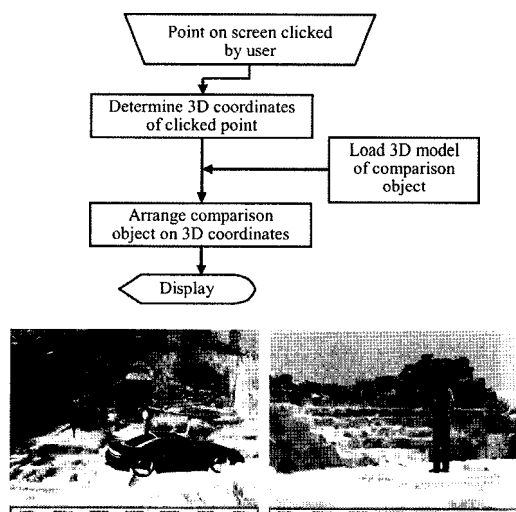


Fig. 15. Object insertion comparison.

• Two-screen mode

Two-screen comparison by vertical/horizontal screen division: A user can compare contents while

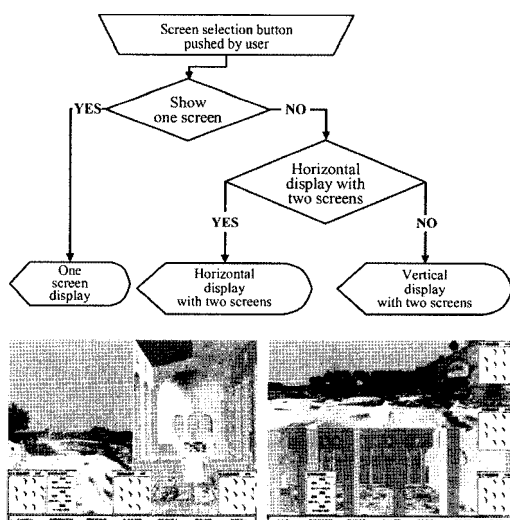


Fig. 16. Two-screen comparison.

walking in a virtual space by displaying two types of content in two spaces on the same screen simultaneously, as shown in Fig. 16. A camera and an aspect are defined for each space, enabling the user to better understand the space composition. A camera controller is displayed in each space, and the user operates it to adjust the view. A controller can also be displayed at the center of the screen for operating the two cameras simultaneously, enabling the user to traverse the same route in both spaces.

Two-screen comparison with guide screen: A third, smaller space can be added to show in more detail one of the two contents being displayed, as shown in Fig. 17. Using this 'guide screen' enables the user to focus on one of the contents and look at it in depth. The contents displayed in the corresponding main space can be changed to match those of the guide screen.

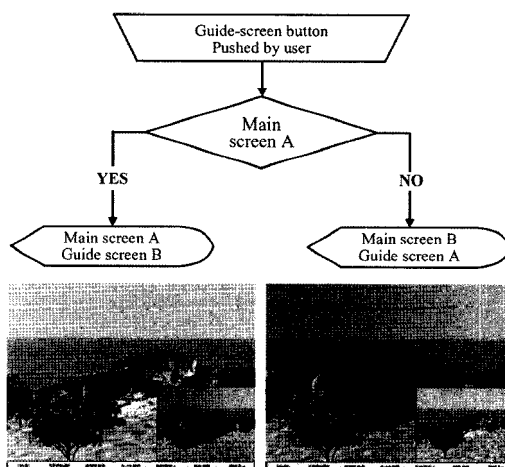


Fig. 17. Two-screen comparison with guide screen.

• Four-screen mode

Photograph/model comparison: The user can select a photograph from a photograph database (Fig. 18, left), and the selected photograph is displayed in the lower left space (Fig. 18, right). At the same time, models with the same viewpoint as the photograph can be displayed in the two upper spaces. Using this function enables the user to simultaneously compare the contents of various media, such as a 3D model of an excavation site, a 3D model of the restoration, and a photograph of a particular spot. It also makes it possible to position the camera at a particular viewpoint.

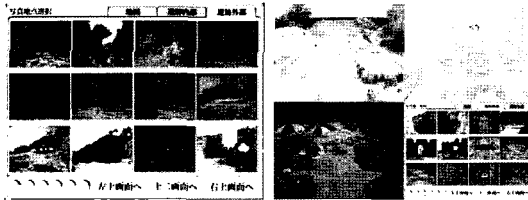


Fig. 18. Photograph/model comparison.

- **Cross-sectional view function:** The user can display a cross-sectional view of a structure by controlling the cutting plane, as shown in Fig. 19. Using this function enables the user to understand the inner structure in detail.



Fig. 19. Cross-section view function.

5. Prototype Testing

We tested the prototype system during NICT's open house days in July 2004 and July 2005. The system was used by a total of 78 children (with parents) and 56 senior citizens. The interfaces available were a keyboard, a mouse, a game controller, and a space traveler. Each user selected the one easiest for him or her to use. Next, like a person visiting a museum or a cultural heritage site, the user was able to freely walk around in a 3D virtual space and experience a cultural heritage site. As the user freely walked through the 3D archives, the system provided comparative views of related content. For example, the user could experience the contents from a different time on the same screen.

Our prototype system worked smoothly, and the users could easily operate the navigation system. The children especially preferred using the game controller and were able to easily master the system, approaching it as if they were playing a game. They thus were able to experience the cultural heritage.

The users made several useful suggestions. For example, some suggested including more detailed explanations of the structures. They felt that the

display of explanatory text would enable them to learn more, thereby enhancing the experiencing of a cultural heritage site using our navigation system.



Fig. 20. Photographs of users during open house.

6. Conclusion

As the first step towards a shared 3D environment in which users can view and understand 3D contents in a comparative manner, we have developed a prototype navigation system for a 3D digital archive experience that contains analytical data from models that have been created. The system has several advantages.

1. Users can experience a cultural heritage site in virtual space rather than actually having to visit the site. That is, users interested in historic architectural structures and cultural heritage sites can understand and view them easily using their personal computers.
2. Users can simultaneously compare, on the same screen, two or more contents, for example, the present condition and the proposed restoration of a cultural heritage site or historical building.
3. Without having to actually demolish a structure, a user can understand its inner structure in detail by viewing a cross-sectional view of it.
4. In contrast to a photograph or text, in which the presence of the cultural heritage is not conveyed, a feeling of position and a feeling of the material quality can be experienced.

Testing at an open house showed that users ranging from children to senior citizens can easily experience digital archives using this system. Our proposed system promotes the use of digital archives and content by enabling users to interact with the archives, thus raising their level of satisfaction. The development of this system has made it possible to use 3D archives for various purposes. This system is thus a crucial academic compilation containing architectural technologies and cultural aspects of

historic architectural structures that have previously lacked clear academic definition.

The most serious problem in the process described here is editing and converting the data obtained by laser scanning. In one case, data could not be well taken from various situations when performing laser scanning. Since we could not use it as is we had to edit and convert it. We worked this time by deciding the process which uses several software, and performs edit and conversion based on the result of various tests. In the future, especially in 3D data creation for cultural heritage sites, laser scanning will be widely used. We thus are developing a system that can automatically edit and convert data obtained by laser scanning.

Another problem in the development of a comparative navigation system is the need to process more than 700,000 polygons for creating a one-frame image. This is not possible with the hardware setup we used, which has a rendering speed of 0.3 FPS. We thus reduced the number of polygons to 100,000, which can be handled by the present hardware. We divided the plane portions from the curved surface portions and used a polygon reduction algorithm to carry out the maximum maintenance of the present form. We also switched to the DirectX[®] rendering engine. Furthermore, we were able to achieve a rendering speed of 10 FPS by applying level of detail and a clipping algorithm.

We plan to develop an improved version of our system as a trial production system. There are several improvements that can be made directly to the prototype system. First, the data format should be changed as VRML is not suitable for huge models of archaeological sites. Formats such as Web3D might be better. Converting the VRML format data into XVL^[9] format data would reduce the model size by about 30%. We also plan to enhance the user interface to enable it to handle other types of media. Furthermore, we are considering the development of a general-purpose function to support access to various types of 3D digital archives. In connection with this, additional 3D digital archives need to be created. Finally, we intend to develop tools that support an expression technique with sufficient reality and that limit the increase in the amount of data and to develop a system that enables smooth cooperation with the database.

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