Mission and Recent Projects of the UCLA Cultural Virtual Reality Laboratory

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Abstract : The UCLA Cultural Virtual Reality Laboratory (CVRLab; www.cvrlab.org) was founded in 1997 with the mission of creating scientifically authenticated 3D computer models of cultural heritage sites around the world. This paper will present an overview of the lab's projects, methodology, and the applications of the lab's products to research and instruction.

Key words : Virtual reality, cultural heritage, digital archaeology.

1- Mission and structure of the CVRLab

1.1 – Mission

The Cultural Virtual Reality Laboratory was founded in 1997 at UCLA by Classics Professor Bernard Frischer in collaboration with Architecture Professor Diane Favro (for papers written by lab staff, see http://www.cvrlab.org/research/research.html). The mission of the lab is three-fold: the creation of scientifically authenticated 3D computer models of cultural heritage sites; the development of applications of the models to instruction, research, and commerce; and training students in the application of virtual reality technology to cultural heritage.

1.2 – Virtual reality focus

The lab specializes in the creation of models that are designed to be compatible with virtual reality hardware systems such as the CAVE, HMD, augmented reality, virtual set technology, desktop VR, etc. At UCLA, models produced by the lab are typically shown in the Visualization Portal, a SGI reality center maintained by Academic Technology Services as a campuswide resource (www.ats.ucla.edu/portal/ default.htm).

1.3 – Organizational affiliations

At UCLA, the CVRLab has developed a number of other important relationships, including affiliations with the Center for Digital Humanities, the Center for Digital Innovation, the Center for Medieval and Renaissance Studies, the Cotsen Institute of Archaeology, the Department of Architecture, the Department of Information Studies, the Institute of Social Science Research, and the Office of Instructional Development. These relationships help the lab to tap existing research and instructional resources at UCLA such as space allocation, contract and grant administration, and network support. They also facilitate our interaction with the various organized research units specializing in areas of interest to the lab (archaeology, art history, etc.). One obvious area of weakness in our UCLA relationships is in the area of computing. A goal for the near future is to identify a colleague in Computer Science who shares our interest in virtual reality technology.

The lab has also actively sought out external partners, and these now include the Department of Archaeology at the University of Bologna, the Ingeborg Rennert Center for Jerusalem Studies at the Bar-Ilan University, the MRSH at the Université de Caen, the Vis.It CINECA Visualization Group, and the Institute for the Application of Technology to Cultural Heritage at Italy's National Research Council. The CVRLab undertakes specific collaborative projects with its partners, and it works with its partners on matters of general interest such as the development of technical and metadata standards for 3D computer models of cultural heritage sites.

In the next stage of our evolution, we hope to encourage faculty and students whose career takes them away from UCLA to found branches of the lab at their new institutions. The first such branch should open in January, 2004 at the University of Kuwait.

1.4 – Funding

The lab is self-sustaining, receiving its funding from external gifts, grants, and contracts. Major sponsors and granting agencies to date have included: the Andrew W. Mellon Foundation, Intel, the National Science Foundation, the Creative Kids Education Foundation, Johanna and Daniel Rose, and Mr. Kirk Mathews. The lab hopes to increase its sustainability by building a permanent endowment and by eventually spawning a related academic program.

1.5 – Staff

The lab's director is Bernard Frischer, a Classicist with a long-standing interest in topography and the director of an archaeological excavation in Italy. There are two associate directors: Diane Favro, an architectural historian who has served as president of the Society of Architectural Historians and who has been a pioneer in the use of 3D modeling in teaching architectural history; and Dean Abernathy, a registered architect with experience as a site architect of an archaeological excavation. Frischer and Favro serve on all of our scientific advisory committees. Abernathy oversees the actual production of digital models. Most modelers working for the lab are advanced students of architecture at UCLA, though several come from other programs such as Classics and Archaeology, and others are freelancers in Los Angeles and elsewhere.

2- Methodology of the CVRLab

As might be expected, the lab's methodology is closely related to its mission.. The creation of scientifically authenticated 3D computer models involves three interrelated but logically distinct activities: using appropriate software tools to construct models; offering scientific oversight to the modeling process; and publishing the model in such a way that the user can understand the nature and quality of the evidence and conjectures used to create it.

2.1 –The modeling process

In terms of technology, the CVRlab is committed to the principle of using commercially available software and hardware whenever possible, thereby reducing development time and costs. Creating real-time computer models with highly accurate dimensions and photorealistic textures requires a combination of software since, at present, no single package contains all the functionality we ideally need. Most real-time systems support OpenFlight file format, an industry standard for real-time 3D. Typically, our models are built using MultiGen Creator on the Wintel platform (see www. multigen.com/products/database/creator/index.shtml). Multi-Gen Creator's output is the optimized OpenFlight format, and it is a tool that permits the construction of highly accurate geometry. It also supports many essential features of virtual reality applications including level of detail (LOD) control, culling, priority ordering, and logical switching. On the other hand, Creator is weak in creating photorealistic textures. These we therefore make in Autodesk's Lightscape, a program designed to provide lighting studies with radiosity and global illumination. To convert files from MultiGen to Lightscape format, we use Polytrans, software designed for 3d model/NURBS/CAD/animation translation, optimization and viewing (see www.okino.com/ conv/ conv. htm).

2.2 – Scientific oversight

The CVRLab can be likened to a university press in the sense that its products are scientific publications. As such, they must conform to basic norms of scholarship, just as would be expected of a traditional print publication. Models must have a qualified author; the author must cite his sources and note any conflicting evidence and opinion; fact must be rigorously separated from hypothesis; and a bibliography must be given.

While the author of a CVRLab model could conceivably be an individual scholar, in practice the authorship role has so far always been played by a small committee of experts. We call these experts the *Scientific Committee*, and typically the experts are recruited with a view to providing the following: 1) a working relationship with the cultural agency responsible for the monument; 2) archaeological and/or architectural-historical knowledge about the construction techniques, design, and building phases of the monument; and 3) general cultural-historical information about the monument.

The Scientific Committee works closely with the CVRLab's modeling staff to ensure that the data modeled are reliable and up to date. Typically, this process is iterative and collaborative—the modelers in the lab not only passively accept guidance from the committee but, as experienced archaeologists and architects, propose creative contributions for consideration by the committee. The members of the committee often find that after taking a virtual tour of a monument, their conception of how it originally looked changes. At the end of the modeling process—which typically goes through several phases as errors are corrected and new ideas are proposed, tested, and (if considered valid), incorporated—the members of the committee are asked to sign a form releasing the model for publication.

2.3 –Metadata

The 3D computer model is the end product of lab's activities, but it is important to note that the lab's digital productions include not only the bare 3D model but also the associated scholarly apparatus that would be incorporated into a traditional print publication. In the case of the latter, this includes the title page, with the name of the author or authors; the notes, including acknowledgement of sources and citation of disagreements among authorities; and a bibliography. In the case of our models, this information is provided as part of the 3D database constituting our product: if the model is made of "primary data" (geometry, textures, etc.), then the scholarly apparatus offering reflections on the primary data can be called the "metadata."

We typically provide three categories of metadata within our products: catalogue metadata, commentary metadata, and bibliographical metadata.

Catalogue metadata include the Dublin Core elements (see http://dublincore.org/documents/ dces/): title, creator, subject, publisher, etc. These are useful as finding and citation aides for our users (or potential users). *Commentary metadata* include information about the evidence for the various elements of the reconstruction, from the foundations to the roof. It alerts the user to the fact that evidence may be poor or entirely lacking, in which case it explains the basis for the hypothesis used to make the reconstruction. Alternative views in the scientific literature are noted, and the reason for rejecting them are given. *Bibliographical metadata* include all the sources—published and unpublished—used in making a model.

In our first attempt to offer metadata to the user, we simply created a PDF file to accompany the MultiGen file of a particular model. We are now working on a more elegant solution in which the metadata is included within the MultiGen file or as part of a unified information system. We look forward to the day in the not too distant future when a user can simply click on the feature of a reconstruction and immediately open a record with all pertinent metadata.

2.4 –Typology of Models

Of crucial importance in the whole modeling process is an initial decision about exactly what is to be represented. The lab has therefore developed a taxonomy of model types in order to clarify the various possibilities and issues, something experience has shown to be useful both for the modeler and his client. The taxonomy currently has six dimensions: (1) sensory dimension; (2) model-temporal dimension; (3) historical-temporal dimension; (4) dimension of equipment; (5) dimension of interactivity; and (6) dimension of recon-structedness.

The *sensory* dimension relates to the kinds of sense data offered in a model: visual data is most common, but auditory data is increasingly used as it has become possible to incorporate 3D localizable sound sources into our models. To date, we have not experimented with touch, smell, or taste.

By *model time*, we mean--not the building phase depicted in a model (something handled by the third dimension)—but the role of temporality within the time-space world of the model itself. Hence some models may be *static*, i.e., frozen at a given moment in time; others are *dynamic*, i.e., capable of showing the unfolding of time at a given site. The time increment may be very small—seconds, minutes, or hours—or very long, measured in terms of years, decades, or centuries.

The dimension of *historical time* refers to the date of each building phase shown in a model. Often it is assumed that a model shows a cultural heritage site as it appeared when new, but there is no reason why the model cannot show other phases, ranging from a site's prebuilt condition to its current state today.

The *dimension of equipment* takes account of the various degrees of furnishing with animate and inanimate objects that can be included in a model. People might or might not be included; furniture and textiles, food, everyday tools, etc. may or may not be shown in a model.

By the *dimension of interactivity*, we indicate the ways that users can directly manipulate the model. Manipulation can encompass something as simple as the apparent motion through the model (including speed, direction, and spatial attitude as well as the blocking of apparent movement through collision control); but it can also relate to more complex user interventions such as moving objects within the virtual world or even changing features of the user interface.

The sixth, and final, *dimension of reconstructedness* is based on the degree of hypothesis permitted in a model. For example, is the model limited to showing simply what survives from a certain building phase or human activity with absolute certainty, or does it reflect a looser standard of what can be incorporated in the model that goes beyond the evidence? In showing reconstructions or restorations, the model should observe the conventions of the Venice Charter for the Conservation and Restoration of Monuments and Sites (http://www.icomos.org/venice_charter.html).

The interaction of all six of these dimensions gives a model its unique characteristics, and all six should be well pondered before the actual modeling begins in order to ensure that the final product will meet the client's needs and expectations.

3- Major projects of the CVRLab

The lab has created models of cultural heritage sites ranging in space from Peru to Israel and in time from the late Bronze Age in the Old World to the Colonial Age in the New World.

No conscious plan has dictated the projects undertaken by the lab: the number of models potentially needed to cover all cultural heritage sites in all six dimensions of modeling is practically infinite. No single lab—however well financed and however well-conceived its modeling program—could ever hope to create computer models of *everything*. Particularly because the lab has up to now been self-financing, our approach has accordingly been opportunistic, not utopian: we have accepted clients' commissions as long as they fall within the broad limits of our mission.

3.1 –Rome Reborn

Whenever we have had the chance to utilize resources as we wished, we have invested them in the Rome Reborn project, mainly because ancient Rome is the academic speciality of the lab's directors. *Rome Reborn* has the goal of creating a computer model of the entire ancient city of Rome from the Iron Age (ca. 900 B.C.) to the Gothic Wars (535-553 A.D.). We are acutely aware of how enormous this task is and fully expect it to take many decades. In fact, we view Rome Reborn as more analogous to an ongoing scholarly journal than as a single book.

Our approach to modeling Rome is, to the extent practically possible, to start from the city center and to work out from it in ever larger concentric circles. We also work from the late-antique phase back toward the earlier phases. Thus far, major elements of the late-antique city have been recreated, including the Roman Forum (fig. 1), the Colosseum (fig. 2), and the Basilica of Santa Maria Maggiore (fig. 3), (foot of the page, on the right). Most of the component parts of these models were created by Dean Abernathy with contributions by Alessio Mauri, Philip Stinson, Mayra Valenciano, and Rebeka Vital.

Fig. 1 : The Roman Forum, ca. 400 A.D. Copyright 2003 by The Regents of the University of California; created by the UCLA Cultural Virtual Reality Laboratory

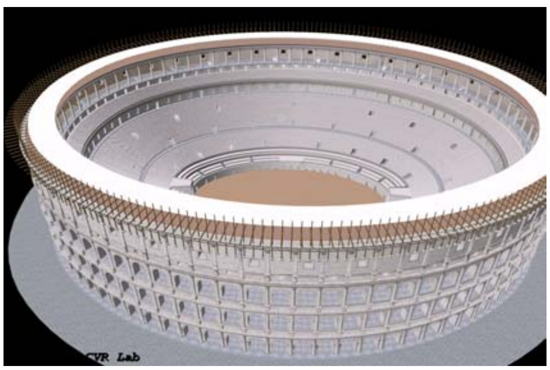

Fig. 2 : The Colosseum, ca. 400 A.D. Copyright 2003 by The Regents of the University of California; created by the UCLA Cultural Virtual Reality Laboratory.

Fig. 3 : The Basilica of Santa Maria Maggiore, ca. 435 A.D. View from the left aisle to the nave. Copyright 2003 by The Regents of the University of California; created by the UCLA Cultural Virtual Reality Laboratory.

All of these models have been used in classes in Architecture, Art History, and Classics at UCLA. The Santa Maria Maggiore model was also used as the major asset for a video documentary about the history of the church shown at *Aurea Roma*, an exhibition held during the Jubilee Year in Rome in 2000. The Colosseum model was featured in a recent program shown on The Discovery Channel.

The Scientific Committee for the Roman Forum included Cairoli Giuliani (University of Rome "La Sapienza"; cf. [1]) and Russell Scott (Bryn Mawr College; cf. [2]). Serving on our committee for Santa Maria Maggiore were Sible De Blaauw (University of Leiden; cf. [3]), Paolo Liverani (Vatican Museums; cf. [4]), and Arnold Nesselrath (Vatican Museums). The Scientific Committee for the Colosseum was comprised of Heinz Beste (German Archaeological Institute, Rome; cf. [5]), Mark Wilson Jones (University of Bath; cf. [6]), and Lynn Lancaster (Ohio University; cf. [7]).

In partnership with Daniela Scagliarini of the University of Bologna's Department of Archaeology (cf. 8), we have also modeled the first century B.C. House of Augustus on the Palatine Hill, an exceptional project because it falls outside our initial time period. The purpose of this subproject is to develop standards for representing physical and digital restorations (see fig. 4).

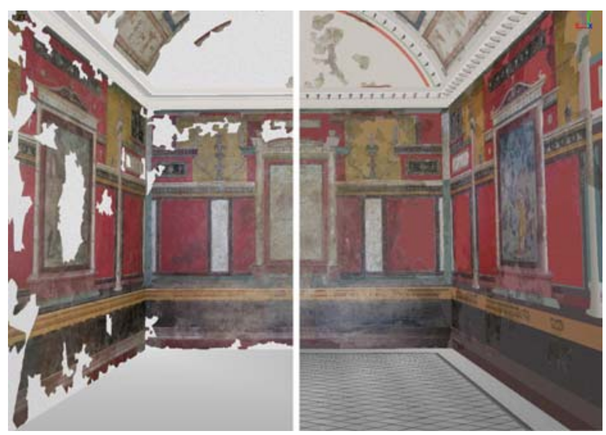

Fig. 4 : The "studiolo" of Augustus, House of Augustus, Palatine, Rome, ca. 20 B.C. The image on the left shows the state of the room today; the image on the right shows a digital restoration of elements of the floor and wall painting that can be reconstructed with high probability. Copyright 2003 by The Regents of the University of California; created by the UCLA Cultural Virtual Reality Laboratory

Thanks to the generous support of the Andrew W. Mellon Foundation, the lab is enlarging its model of ancient Rome to include: the Tabularium on the eastern slope of the Capitoline Hill; the Forum of Julius Caesar, which is adjacent to the Roman Forum (see Amici [9]); the Sacred Way, with related buildings (the Basilica of Maxentius, Arch of Titus, and Temple of Venus and Rome), running from the Regia to the area of the Colosseum; the Baths of Trajan on the Oppian Hill overlooking the Colosseum; and the Circus Maximus. These enhancements to our Rome model should be complete by the end of 2005. Serving on our Scientific Committee are Clotilde D'Amato, Fulvio Cairoli Giuliani, Paolo Liverani, Russell Scott, and Fikret Yegul (cf. [10]).

Two major problems with Rome Reborn are the inordinately long time it will take to model the entire city—even just in one phase—building by building. Secondly, even those sites and buildings that are completed stand isolated in what we not very fondly refer to as "the Gobi Desert," i.e., they have no urban context but emerge from a flat, brown landscape. This is not what the real city of Rome ever looked like, and no one wants to wait for decades to see the individual buildings coalesce to form the urban fabric.

To address these two problems, the lab decided to digitize the greatest pre-digital model of the ancient city: the Plastico di Roma Antica (fig. 5; cf. Liberati [11]) in the Museum of Roman Civilization (EUR/Rome). Working in collaboration with the museum, Leica of Italy, SDS3D of Vancouver, Canada, the Department of Electronics and Telecommunications of the University of Florence, and the Institute of Information Technology Applied to Cultural Heritage of Italy's National Research Council, the lab has recently been digitizing this plaster-of-Paris urban model, constructed over three decades by Italo Gismondi, using two different approaches : laser scanning and photogrammetry. It remains to be seen which approach is better, or whether a hybrid method combining both approaches might give the best results.

Fig. 5 : Detail of the Plastico di Roma Antica, showing Rome's city center in ca. 320 A.D. Photo copyright 2003 by Bernard Frischer, used with permission of the Museo della Civiltà Romana.

At any rate, once the digital Plastico (d-Plastico) has been created, our goal is to insert our new born-digital models into the d-Plastico, which will immediately give our buildings a semblance of urban context, including roads, vegetation, and even geology. Of course, this is simply a temporary solution since the Plastico—for all its excellence—is lacking is some important respects : whereas our new models are conceived on a 1 :1 scale, the Plastico's scale is only 1 :250 ; whereas many of our models have interiors (we only forebear to create the interior when there is a complete absence of data), none of the Plastico's buildings do ; and our surface textures are digital samples of the actual building materials used by the Romans, whereas the Plastico's surfaces are covered with a simple coat of paint, which (after thirty years or more) is very faded paint.

3.2 – Other major projects

3.2.1 –Island of the Sun, Lake Titicaca (Bolivia)

The Island of the Sun project has the goal of reconstructing the sacred Inca precinct and solar markers on the Island of the Sun in Lake Titicaca, Bolivia. The sacred rock at the center of the precinct was the mythical birthplace of the sun and attracted pilgrims from throughout the Inca empire. The simulation is intended to facilitate tests of the solar alignments of buildings, monuments and features of the precinct throughout the solar cycle. These alignments were proposed by B. Bauer and D. Dearborn (see [12]), whose work was accepted by project collaborator, C. Stanish, in the book he co-authored with B. Bauer (see [13: 207]). Changes in the earth-sun alignment owing to factors such as eccentricity, obliquity, etc., have made it impossible to test the validity of the Bauer-Dearborn thesis today by observation. A digital model was therefore needed that combined geographical, archaeological, and solar data, recreating the situation of ca. 1500 A.D. when the precinct of the Sun was constructed. The model was built by Dean Abernathy; azimuthal data was programmed in by Chris Johanson. Kent Volkmer of NASA's Jet Propulsion Laboratory provided helpful advice.

3.2.2 –Second Temple (Herodian Phase), Jerusalem (Israel)

This modeling project presents the famous Jewish sanctuary rebuilt by Herod the Great and destroyed by the Romans in 70 A.D. Our model, created by Rebeka Vital, shows the Temple at its final stage of development before the Jewish Revolt started in 66 A.D. The Second Temple Project is the first step of the larger Jerusalem Reborn Project founded by Prof. Joshua Schwartz and undertaken jointly by Bar-Ilan University, the Ingeborg Rennert Center for Jerusalem Studies, and UCLA. The purpose of the Second Temple modeling project is to recreate a digital model of the building in order to test the accuracy and feasibility of Josephus' famous description of it in the *Jewish Antiquities* (15.3.-7).

3.2.3 –Northern stables, Megiddo (Israel)

On the northern end of the important Biblical site of Megiddo a ninth-century B.C. structure was unearthed whose original function is unclear (fig. 6). The purpose of this project is to reconstruct the structure and to test the hypothesis that it was used as a stable for horses. The project was undertaken in conjunction with Tel Aviv University and the Pennsylvania State University. Chair of the Scientific committee is Megiddo excavator Israel Finkelstein, whose recent book (see [14]), deals extensively with the site. Also serving on the committee is Anne Killebrew (Pennsylvania State University).

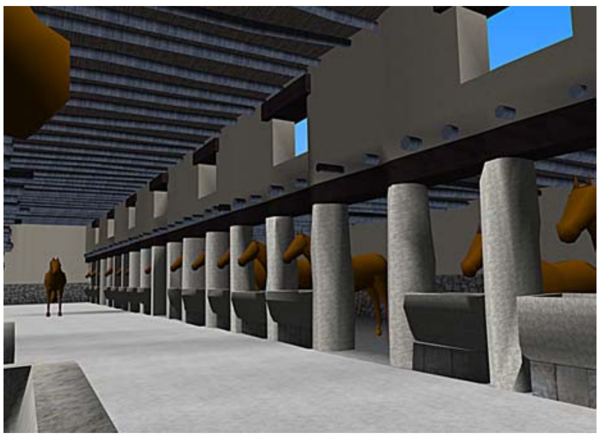

Fig. 6: The northern stables at Megiddo, ca. 825 B.C. Copyright 2003 by The Regents of the University of California; created by the UCLA Cultural Virtual Reality Laboratory.

3.2.4 –Villa of the Mysteries, Pompeii (Italy)

Substantial ruins of the Villa of the Mysteries, including many famous second and third style wall paintings, survive just outside the urban area of Roman Pompeii, which was destroyed by the eruption of nearby Mt. Vesuvius in August of 79 A.D. The residential rooms of the villa were oriented toward the sea, whereas the working areas stood toward the rear of the property facing the town. Originally built in the second century B.C., villa was remodeled in ca. 60 B.C. and again in the mid first century A.D. The Villa of the Mysteries Project is jointly sponsored by UCLA and the University of Bologna. The chief modeler is Philip Stinson; chair of the Scientific Committee is Daniela Scagliarini. The goal of the project is to create a virtual restoration of this important example of villa architecture on the Bay of Naples. Once created, the model will be used in courses at UCLA and Bologna on Roman architecture and archaeology; it will also be used for studies of the lighting in rooms around the villa, including the bedrooms (fig. 7) and the famous triclinium painted with the cycle of frescoes illustrating the Dionysiac mysteries.

3.2.5 –Port Royal (Jamaica)

Port Royal, the famous pirate colony, was one of England's largest foundations in the New World when it was destroyed by earthquake on June 7th, 1692. Most of the city sunk below sea level owing to soil liquefaction. The project entails a complete restoration of the buildings explored by underwater archaeologists at Texas A&M in the 1980s as well as a reconstruction of the street plan and urban fabric of the entire city (fig. 8). The unexcavated parts of the town were speculatively rebuilt by lab modeler, Natalie Tirrell, who based her work on the surviving evidence of maps, views, and property records; and who was able to benefit from the advice of Port Royal excavators Donny Hamilton (Texas A&M; see http://nautarch.tamu.edu/portroyal/) and Laurel Breece (Long Beach City College). The model was designed to be used as a compelling resource at the Ocean Institute (Dana Point, California), where it can help visitors to visualize the original context of the artifacts found by Texas A&M and currently on display in a gallery of the Institute. A fly-through of the model was shown on German television in a program about pirates.

Fig. 7 : Cubiculum 16 in the Villa of the Mysteries, Pompeii. Study of nighttime illumination with typical Roman oil-burning lamps. Copyright 2003 by The Regents of the University of California; created by the UCLA Cultural Virtual Reality Laboratory.

Fig. 8 : Port Royal, Jamaica. Detail of the town just before its destruction on June 7, 1692. Copyright 2003 by The Regents of the University of California; created by the UCLA Cultural Virtual Reality Laboratory.

3.2.6 –Santiago de Compostela (Spain)

Santiago de Compostela is one of the great pilgrimage basilicas of Europe. Our restoration project shows the building and surrounding town as they appeared on April 3, 1211 A.D. when the newly enlarged cathedral was dedicated by Bishop Pedro Muñoz (fig. 9). In addition to restoring the architecture of the cathedral and placing it within an urban simulation of the town, the model also incorporates the songs and sounds typically heard in the building and town in the thirteenth century. The project was primarily undertaken to support classes at UCLA by project director, Prof. John Dagenais, a medievalist whose many interests include the culture associated with the pilgrimage route to Santiago in the Middle Ages. Project consultants include John Williams (University of Pittsburgh; cf. [15]), Jose Suarez Otero (Archaeologist and Curator, Cathedral of Santiago de Compostela; cf. [16]), and James D'Emilio (University of South Florida, Tampa; cf. [17]). Modelers include Dean Abernathy, Renee Calkins, and Rebeka Vital. David Beaudry designed the localized 3D sound system (see http://www.ats.ucla.edu/at/vrNav/docs/HowToUse_vrNav2_withThe_dbMaxSoundServer.html).

Fig. 9 : The west facade of the cathedral of Santiago de Compostela, ca. 1211 A.D. Copyright 2003 by The Regents of the University of California; created by the UCLA Cultural Virtual Reality Laboratory.

4- Distribution of models

Models are not, of course, created for their own sake but with a specific use in mind (see section 5 below). A key part of any modeling project is thus a plan to move the model from the Cultural Virtual Reality Laboratory where it is created to some technological platform on which it can be delivered to the end-user.

As the lab's name implies, its preferred platform is one involving *virtual reality*. This term is often used imprecisely as synonymous with 3D computer graphics, but we hold to a strict definition of the term as entailing a computer system that offers the user real-time navigation through a virtual environment that simulates key features of the actual place; interactivity with elements in the environment; and a high degree of immersion in the virtual world. Standard delivery platforms to virtual reality include head-mounted displays, CAVEs, SGI reality centers (http://www.sgi.com/realitycenter/), and augmented reality.

4.1–Virtual reality in a theater setting at UCLA

Up to the summer of 2003, the lab's models were primarily made to be shown in the Visualization Portal, a campuswide facility at UCLA created and maintained by Academic Technology Services (http://www.ats.ucla.edu/portal/default.htm). The Portal, which is an SGI reality center, seats up to forty people, has a semi-spherical screen ca. 25' x 8' in size, three triple-gun RGB projectors displaying a single image at 3520 x 1020 resolution, and is powered by an SGI Onyx 3400 supercomputer with InfiniteReality3 graphics. The user interface is vrNav, a 3D scene navigation program that was developed by Academic Technology Services (see http://www.ats.ucla.edu/at/vrNav/default.htm). The Portal permits us to use models in a way that might be called "social VR," i.e., in an environment that offers real-time navigation through the virtual world and which is immersive, interactive, and social. Needless to say, this is an ideal combination of features for most instructional and research applications.

4.2 – Models on the personal computer

Facilities like the Visualization Portal are expensive to create and maintain, and this doubtless explains why they are so rare. In recognition of this fact, the lab has studied ways of re-purposing models through other media and platforms. Of these, the most promising are so-called "desktop VR" and "laptop VR." Owing to recent developments in software (the porting of SGI's Performer and of ATS' vrNav to Windows) and hardware (the dramatic fall in price of videocards in the 256-512 megabyte range), it is now possible to run even complex models like the Roman Forum on the Wintel platform. While performance in terms of frame rate and anti-aliasing does not quite compare to what the Portal can offer, desktop VR and laptop VR have several practical advantages, including dramatically lower cost, portability, and widespread availability. The terms "desktop VR" and "laptop VR" are, of course, misnomers, since models on these platforms are not generally immersive, since the display of a PC or laptop is small and flat. Nevertheless these platforms do offer one key ingredient of true virtual reality: the ability to move through a model in real time. And they can be connected to HMDs or projection systems that support true virtual reality.

4.3– Other ways to deliver content

Thus, the Portal, desktop VR, and laptop VR all offer, or have the potential to offer, real-time virtual reality. Experience has shown, however, that not all end-users require a virtual reality platform for delivery of our models. The lab has experience in delivering the content of its models in less immersive and interactive media such as print, video, and the Internet. Images of our models, rendered in high resolution with radiosity lighting solutions, have appeared in newspapers, magazines, and scholarly books. We have licensed fly-throughs to television; and our models have also been used as backdrops in virtual set shoots for TV, most recently, by The Discovery Channel in its production earlier this year of a program on the Colosseum. On the Internet, our content can appear in any of these forms, and we also use such programs as VRML and Macromedia Director to rescale and deliver our real-time models on the Web.

Finally, from time to time, the lab creates Web sites dedicated to the presentation of a site for which it has made a computer model. The purpose is to create a scholarly reference tool about the site for students and scholars; and also to offer documentation (e.g., metadata) about our model of the site. Such a site is currently being created for the Roman Forum with three years of support from the National Science Foundation. A prototype is available at http://cvrlab. org/forum/index.html.

5-Applications of models

5.1–Instructional applications

Our models have been used in courses at UCLA and elsewhere in Archaeology, Architecture, Art History, Classics, History, Jewish Studies, and Spanish. The main educational advantage of computer models of cultural heritage sites is that they offer the vicarious experience of data that is inherently sensory (buildings, works of art, music and other sounds, etc.). Models enable the instructor to overcome limitations of time and space, taking students to see something that either no longer exists or, if it exists, is located too far away to be visited during an academic term. Since the models can be navigated in real-time and are interactive, they also empower students to control the visit, asking for a closer or longer view of objects. Another advantage to models is that they are rich information systems that enable the user to quickly peer beneath the surface to confront the graphic and textual documentation behind individual elements in the virtual environment. Through the use of switches, alternative reconstructions can quickly be shown when an element is hypothetical; and various phases on a site can be seen. A map window can be opened to show the user's current position on a plan of the site.

5.2 –Research applications

Modelling is often thought of as a form of knowledge representation, which it certainly is. But, in our experience, making a model can also bring forth new knowledge, as well as simply encode the knowledge we already had when we began a modelling project. Moreover, models can permit tests of structures and environments that have disappeared or been greatly altered over time.

Research applications thus fall into two categories: those during the model-making phase; and those after. While a model is being constructed, the need to construct data in 3D that typically has been recorded in 2D (plans, sections, elevations, etc.) often forces a researcher to confront the fact that he has not thought about features of the original building that are unattested by the surviving remains. These features might, for example, be the placement of doors and windows throughout the vanished superstructure; the color of paint on faded or missing surfaces; the placement of works of art within a space from which they are known to have come but for which the exact location is not known. This is not to imply that when data is completely lacking, we must force a researcher to resort to wild hypothesis. To the contrary, gaps in our knowledge can be left as such and indicated through a graphical convention. When hypotheses are proposed, they can be marked as such, e.g., by using simple color without texturing or by using a gray scale.

Once a model has been built, it can be used to test the functionality of a building or site, making possible a kind of "experimental" architectural history. We can, for example, gauge the carrying capacity of a structure such as the Colosseum, study the circulation of people through the Roman Forum, analyze the statics of a building like the Basilica of Santa Maria Maggiore, whose original apse was replaced for unknown reasons centuries after it was built. We can study the ability of a structure to withstand seismic shock, flooding, fire, or wind. Lighting, acoustics, and ventilation can be measured, giving us a sense of how well a building served the purposes for which it was constructed. Finally, we can study the alignment of a building with other built or natural features in its environment.

Other forms of research undertaken by the Cultural Virtual Reality Laboratory involve what could be called *meta-modelling* issues. For example, *standards* for cultural heritage models, if widely observed, could allow users to "mix and match" models of the same site from different time periods or from different areas at the same time. The study of *best practice* in the use of models in education can enable teachers to get the most out of using models in the classroom. *Empirical study* of users operating models can determine how to improve the user interface of a 3D engine as well as suggesting what new user tools for data collection and analysis might be created to enhance the user's experience.

5.3 –Commercial applications

The lab exists because of our ability to raise the funds necessary to keep it afloat from gifts, grants, contracts, and licensing agreements. The latter two sources of income bring us into the commercial realm, where we have found that our models can be useful to for-profit companies in a variety of ways. First, magazine and book publishers have licensed still shots of our models to be used as illustrations of archaeological, art historical, and historical publications. Documentary TV producers have licensed videotaped fly-throughs of models in order to create a sense of time travel back to an earlier phase of a cultural heritage site. An even greater sense of time travel can be obtained from using our models as backdrops in virtual set systems such as those made by Vizrt (www.vizrt.com/) and Orad Hi-Tech (http://www.orad.co.il/; on virtual sets generally, see Orad's useful paper, available online at: www.broadcastpapers.com/ anim fx/virtual01.htm). The lab can itself produce video documentaries and has done so for several museums and exhibitions. Finally, models can be used as virtual environments for games, and the lab is currently in discussions with one game publisher about licensing its models for a projected series of history-based games.

Thus far, no commercial applications involving true virtual reality can be reported, but discussions are ongoing with a number of companies about possible projects around the world.

6- Future directions

The future of 3D computer technology applied to cultural heritage looks very bright indeed. Only a small percentage of all cultural heritage sites around the world have been the subject of scientific modeling; and of those sites, only a small percentage of all possible phases of interest have been modelled. So much remains to be done just in terms of covering the globe and offering students and scholars a *virtual time machine* for the study of the evolution of human settlements and societies.

Much work, too, remains to be done in enhancing the user's *experience* of the virtual environments that we have been creating: up to now, vision has been privileged over the other four senses, yet a truly accurate environmental simulation would include all five senses.

Beyond the purely experiential side of virtual reality, we also need to enhance the *analytical tools* available to users to facilitate understanding of what they are experiencing in a virtual world. Some basic tools already exist—navigators, maps, databases of metadata, measuring devices, etc. But these represent merely first efforts in supporting users in gathering, processing, and interpreting the data they encounter in their virtual fieldwork. In the near future, it should be possible to offer users the opportunity to read off their current location from a virtual GPS device, to set the time of day and see a corresponding change in lighting conditions; to define weather conditions; and, at night, to see the main astronomical features visible to the naked eye. Tools for the instant analysis of functionality of buildings in terms of circulation, illumination, ventilation, statics, etc. should also be readily available.

Finally, a key issue to be confronted is *sustainability* of virtual reality technology as applied to cultural heritage. There are three key aspects of sustainability that need to be addressed in ensuring that our first, painful efforts pay off in the long run. The first is *technological*: to spur the spread of VR applied to cultural heritage and to hasten the day when the virtual time machine has been constructed, we need to develop standards for file format and modelmaking methodology. The second is *educational*. In fields such as Archaeology, Architecture, Art History, Conservation Science, and New Media Studies, we need to create graduate programs that offer training in and theoretical studies of the use of virtual reality and other digital technologies in the study and presentation of cultural heritage. Finally, we need to provide for our own legacy by creating a *digital archive* for preserving our own work so that it becomes part of the very cultural heritage we are working so hard to hand down to future generations.

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