ARCHAVE: A Virtual Reality Research Environment for Scientific Applications

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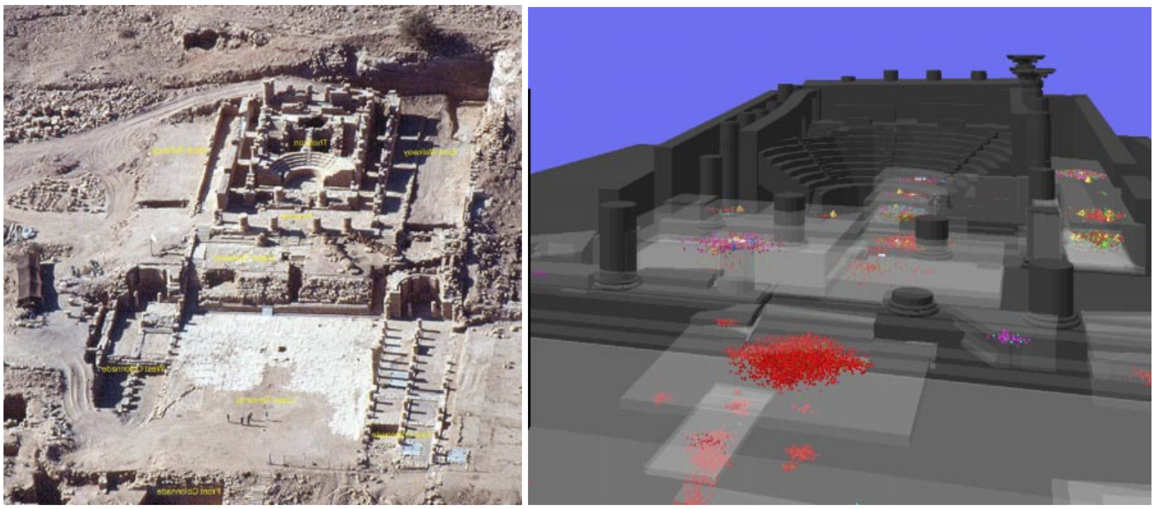

Figure 1: From real to virtual: ARCHAVE's target application is archaeological analysis, providing researchers access to excavation data (Left: Aerial view of the excavation site to which we applied the system, the Great Temple site [6] at Petra, Jordan) from a virtual reality environment (Right: snapshot from the system showing the temple model with several trenches and artifact information)

Abstract

We have created the ARCHAVE system, a novel virtual reality research environment, as a framework to evaluate virtual reality interaction and data visualization techniques for scientific applications. During its initial development, we applied the system to archaeological research, and the results obtained from this evaluation confirm the usefulness of the environment in providing researchers with new insight over the recovered information, allowing us to advance in the development of novel interaction techniques and visualization methodologies. Both users and developers of the system are now in a privileged position to advance in both its archaeological and its computational side: users understand the possibilities of this new technology in their field, and developers can confidently research new methods and techniques applicable to it.

1 Introduction and Motivation

Several factors motivated the creation of the ARCHAVE system. First, the goal of advancing in the fields of virtual reality interaction and scientific visualization led us in a search for new and interesting scientific areas in which these techniques could be applied, and in which we would be able to develop novel methodologies.

A second factor was that Eileen Vote, my collaborator in this project, developed in her PhD dissertation thesis [23] the archaeological hypothesis that supports the project. That hypothesis is that providing archaeologists with an environment in which they would have a three-dimensional representation of their data from the excavations, would allow them to perform analysis in ways they cannot do now, and would enhance their understanding of the information.

We therefore had clear research goals, both on the computational side and on the scientific side. We could develop our research environment in the context of a specific application. This would give us the opportunity of working with real users, facing the problem of creating an advanced scientific application not only novel from the virtual reality research point of view, but also useful and relevant from the scientific field to which it is applied.

Computer scientists tend to forget users and their real problems [7], but the only way we will know if we succeeded in our project is when users of the tool we are creating succeed with its use. That is the reason why we developed ARCHAVE with a clear application in mind.

1.1 Our Research Plan

We started the development of ARCHAVE in November, 1999. Our approach consisted of several steps:

- We gathered information about what archaeologists do now when they analyze their data, what they cannot do, and why, and what they would like to do.

- It was essential to get archaeologists used to seeing things in

VR; therefore we showed them any advances in the system and annotated their new suggestions.

- We tested different visual representations of the data. After studying users' reactions and analyzing how they understood the information, we analyzed the cognitive factors that were affecting our visualization.

- We prototyped different graphical user interfaces for accessing data and navigating the site.

The process described above was iterative and required us to work closely with archaeologists. This has been done consistently during the development of the system. We kept the focus of the project on getting users to understand the technology. That way we got feedback from them that allowed us to improve our visualization and interaction schemes based on goals from a real research application.

The main goal of this iterative process is two-fold. On one hand, we want to create new visualization and interaction techniques, adequate for this specific field of application, but having in mind other fields. We also need to evaluate how archaeologists will benefit from a system like this. The purpose of displaying excavation data in a virtual environment is to be able to study it in depth to extract new theories and create new hypotheses. That is the goal of any scientific visualization technique, but we need to test these techniques to be able to establish their usefullnes in their final field of application. Again, following what Fred P. Brooks says in [7]: only if users succeed, we succeed.

1.2 Archaeological Basis of the Project

Given the wide range of spatial, statistical, and temporal relationships archaeologists look for when studying site information [23], this scientific field presents to us the opportunity of evaluating virtual reality visualization methods and interaction techniques more broadly. On the other hand, the research methodology currently used in archaeology has a large component of creating and evaluating hypotheses. This makes it difficult for us to develop a general application that would predict, in advance, how the exploration of a certain site would go.

When archaeologists analyze data from an excavation site, they do it based on the physical descriptions recorded in trench reports, site plans, drawings, and photographs. Although three-dimensional information is also recorded, current methodology in archaeology does not typically allow researchers to take full advantage of it.

One of the main tasks researchers have to face is understanding the complex spatial relationships existing between the artifacts, the architecture, and the stratigraphy from the site. These provide crucial clues in comprehending how a particular site was used, when it was abandoned, or what activities were taking place in it [5].

The term *Virtual Archaeology* refers to the use of virtual reality techniques for archaeological research [15]. Indeed, although archaeologists are not often the originators of totally new visualization tools, they are extensive users of such tools and can have an important role in driving the development of novel approaches as users [16]. In this spirit, we created the ARCHAVE system, to evaluate the hypothesis that providing archaeologists with an immersive virtual reality system to visualize and analyze spatial data, together with artifact attribute data, will allow them to realize the site information's full potential. They will also be able to generate evidence to establish new hypotheses and provide evidence to prove existing ones.

In this report, I will be presenting the system, focusing on its components of multi-scale navigation in virtual environments, data interaction and user interface design. The implementation will also be discussed here. Eileen Vote, in her dissertation, developed all the underlying archaeological and methodological concepts that are the basis for this research. She also created all the three-dimensional models used in ARCHAVE and designed the main visualization techniques for the archaeological data we have.

2 Contributions

The main computer science contribution of this project is an environment in which we are now able to develop and test new visualization and interaction techniques. Approaching through the archaeological problem gave us the opportunity to establish a process of creating new visualization and interaction tools in an area that we believe could benefit from it.

A secondary contribution of the project comes from the fact that we created and successfully evaluated a novel archaeological analysis tool with which researchers can approach their data in a more comprehensive way than they can now. This tool has to be developed further so it can address more complicated research scenarios than the ones we tested. But the fact that users are engaged in a fluent dialog with us, the developers, and both parties understand the possibilities of the system in this area of application, is a fundamental step that we have already taken with ARCHAVE.

There are a number of specific issues we were able to identify with ARCHAVE as they apply to archaeology. They can be included in four different categories: archaeological issues, data visualization issues, data interaction issues, and virtual reality interaction issues. I will explain these areas along with the related work for each one of them in the next section.

After the related work section, I will describe the development process for the system, explaining how we created a first prototype of the system that we tried to test and why this approach failed. Then I will present, in detail, the current version of ARCHAVE and, after that, the test case we prepared for archaeologists. I will finally discuss the results obtained.

3 Related Work

Different systems tried to approach the problem of visualizing archaeological data in different ways [1] [3] [8] [14] [17]. Based on Eileen Vote's dissertation [23], our system combines virtual reality techniques and visualization methods in a way that has not yet been applied to archaeological research [22]. We integrate important graphical information from maps and plans, and specific excavation data such as attribute data, location, and relational data between artifacts and site features. ARCHAVE also provides researchers with a multi-scale approach to all this information, allowing them to have a complete and comprehensive picture of the whole site but, at the same time, detailed access to different areas of interest.

Multivariate data visualization techniques were tested and successfully applied to display information from up to six different artifact types from the excavation. We reviewed the literature about the cognitive aspects of data representation, and based on these, we created a new visual language to represent the type of categorical data [2] we were dealing with. We went through different visualization methods that will be explained in the implementation section. We concentrated on understanding how shape, color, texture, transparency and scale affected user's understanding of data displayed in our virtual environment [11] [24] [25] [19].

Graphical methods of analysis have been explored in GIS systems that overlay multiple types of 2D graphic representations of data such as maps, plans and raster images together with associated attribute data in an attempt to present relationships between spatial data [12]. Although the visual processing of excavation data is not an important part of archaeological methodology, we cannot avoid the fact that advances are being made in this field using current statistical analysis and 2D based geographical information systems. The complexity of the analysis of archaeological data is such that creating a general tool archaeologists would use is a long term goal of most of those systems, including ours. There are many types of artifacts and artifact characteristics, and providing full query access to the database of excavation data from the virtual environment is a challenge.

Some applications like the SANDBOX project [4] and the TIDE project [18], explore the concept of accessing a large database of information from virtual environments, but in our case, the process of experimenting with the data that those systems exploit is not applicable. In our case, ARCHAVE provides limited access to the database of information, allowing users to make simple queries. Some interaction with the context in which data will be visualized, that is, thee-dimensional site model, trenches, and excavation layers, was implemented and tested.

Finally, the characteristics of the site in which the system is being tested, the Great Temple of Petra, have provided us with the perfect framework to develop and test new virtual reality interaction techniques [9], including multi-scale navigation, scale perception in virtual scenes, and interaction using different devices, physical props, and gestural interfaces. All of them are well known research problems in VR that we were able to identify in ARCHAVE. This real application served as a motivation for the development of new possible solutions for those problems.

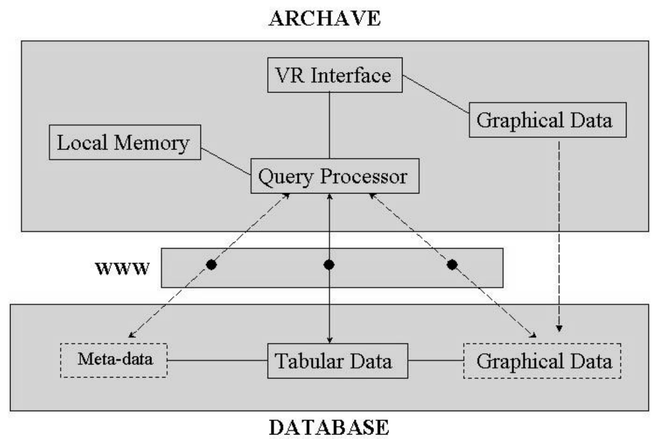

Figure 2: Status of the ARCHAVE system. DB access is performed through Internet connection, allowing for remote access to excavation databases. Meta-data, such as images and video sequences are not included in the current database. Graphical data, such us 3D models, is currently kept locally.

4 System's Design and Development

Previously I presented the iterative four-step approach that we took in developing the system. But the goal for the development process of ARCHAVE can be summarized presenting the ideal characteristics an application like this should have [13]:

- Interactive access to all the data.
- Allow hypotheses criticism: visualize what other researchers concluded and pose new questions and answers.
- Excavation process reconstruction: archaeology destroys evidence as soon as researchers find artifacts on the field and they move them to be analyzed. Our system will maintain a record of excavation facts and research conclusions.

Based on this idealized guidelines and attending to the data we have and how it was organized, we created the main framework for the application (see Figure 2).

4.1 Environment Comparison

Scientific visualization applications using virtual reality have to help scientists get to new discoveries and hypotheses in a way at least comparable to what they are accustomed to using workstations [10]. Because of the current cost of some VR installations, such applications need to create a significant advantage to be able to compete with classic scientific tools.

Following on this idea, we first attempted to create a test case that would compare the performance of our system in several VR environments: a Cave, an Immersadesk, a Head Mounted Display (HMD) and a desktop [21] (Figure 3). The main difference among these is the level of immersion, which was an important point we wanted to evaluate. We also planned to compare those results with the use of a classic database approach to studying the excavation information.

Creating a comparable task that would allow us to validate our hypothesis was very difficult. Each environment needed a specific interface design and implementation, and this fact was orthogonal to our main goal, which is to test the application to perform valid archaeological research. Therefore, we concentrated in creating a test case that would allow us to validate the system from an archaeological point of view, first using our cave facility, and then comparing virtual environments and their performance.

4.2 Artifact Data Visualization

The first specific task archaeologists wanted to perform in our system was exploration of concentrations of artifacts throughout the site, having access to information about the geometry of the excavation trenches and their layers or *loci*. A first prototype of the system was built. It provided users with a full reconstruction of the temple building and a representation of the trenches and loci. On these, the concentration of pottery fragments was visualized by coloring the surface of the loci. The color range indicated the concentration at each level.

We also implemented a first multivariate visualization scheme in which concentration of a second artifact type could be plotted as a texture, the density of the texture being the indicator of the concentration.

For all these different aspects, the necessary user tests should be designed and performed. We went through several designs for a user study, but getting to a situation in which we could safely test our system and get statistically valid results was a difficult task. To create a meaningful study, from which we could extract valid conclusions, we needed a very simple set of tasks that users had to perform. Following this condition, we would lose all archaeological relevance for the tasks, therefore not testing our initial hypothesis. We could not get to a compromise between this two conditions.

Also, users commented that, with this system, only two variables could be visualized at any time, and that they needed more to be able to do real analysis. Moreover, the interface design to interact with the system in VR was not at all finished, since we concentrated our efforts on understanding the problem to be solved.

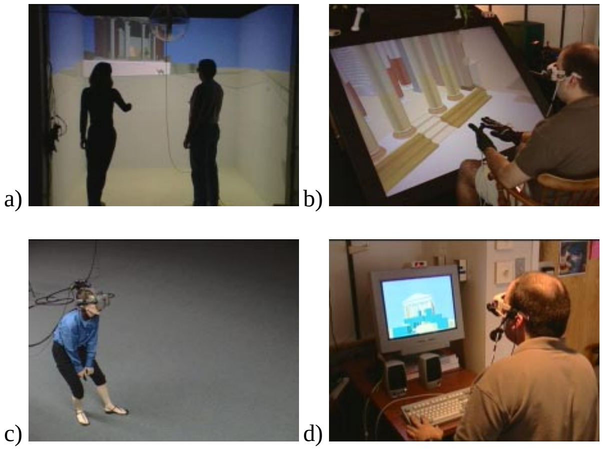

Figure 3: We tested ARCHAVE in different virtual environments: a) Cave, b) Immersadesk, c) Head-mounted display and d) Desktop

4.3 Lessons from the First Prototype

From creating the first prototype and trying to design a user study, we learned some important lessons:

- Researchers recognized the data being visualized, but could not perform any real analysis with it because of the limitations of the system in terms of both amount and type of data modeled.
- Users had a hard time navigating the site and understanding its size. They usually got lost in the virtual site.
- The complexity of the model makes the frame-rate of the system drop dramatically. Although this fact is understood by users during the demonstrations, it renders the application unusable for real research work.
- The experiment with multivariate visualization was unsuccessful. The perception of the data that archaeologists had was very limited by our decision of colors and textures for both data and underlying temple model (see Figure 4).
- We used a complete reconstruction of the Temple, as hypothesized by the chief archaeologist of the excavation, Martha Joukowsky. However we found that a fully textured reconstruction of the edifice was very distracting when trying to focus on the excavation data. In addition, archaeologists felt that using a reconstruction did not provide the valid clues present in an *in situ* model of the real unearthed remains.

After this initial test, we had a large amount of feedback from archaeologists about how to improve the system. Also, one of the initial goals was almost realized: the fact that archaeologists were beginning to accept the system as a new research tool and were understanding the possibilities it had beyond the techniques they use now. Therefore, we decided to iteratively create a specific analysis task that researchers could perform using our application, and get real results.

4.4 Second Prototype Task Definition

During the excavations at the Great Temple of Petra, an enormous effort has been made to accurately record the three-dimensional features of relevant artifacts, their relative locations in excavation trenches, and all relevant associated attributes such as material, Munsell color, shape, date and other distinguishing characteristics.

Figure 4: Initial attempt to visualize multiple variables. Layer color indicates pottery concentration and texture density indicates bone concentration. Image shows the first prototype of ARCHAVE being used on the Immersadesk

In our task, we focused on a specific methodological problem posed by several archaeologists involved with the Great Temple site excavations in Petra, Jordan [6]: the isolation and cross-comparison of lamp and coin finds in the various excavated regions of the site.

Lamps get a lot of attention from researchers. Through analysis of lamp find material content, occupational patterns can be understood. The lamps shape and decoration indicates its cultural origin, which can help researchers define trade routes with other parts of the world. Religious icons and other markings help indicate how a find area was used. Also, *in situ* (find) location and relationships with surrounding site features and artifacts can also provide valuable clues in establishing relative dates for the region of excavated material or a connection with other local artifacts. The last two points were highlighted by archaeologists using our system.

It is crucial that archaeologists find and describe *sealed* regions in the excavated material to establish confidence in dating objects and in defining the relative associations among objects in that region. Defining these regions is difficult using current analysis techniques.

To evaluate the second prototype, two experienced archaeologists were invited to use our system to analyze these data. Both are familiar with the site and have been studying different aspects of the excavation for several years, one of them specializes in ancient lamp analysis. They used the system together, which allowed them to have a dynamic discussion regarding observations about the site and the artifacts found through excavation. Having and expert in lamps together with a non expert would provide us with two different points of view for the data. This would enhance the results of the evaluation/

5 Features of the Second Prototype and its Evaluation

The ARCHAVE system is currently running in a 8x8x8 foot cave-like immersive environment with four display surfaces, three walls and the floor. Users wear a pair of LCD shutter glasses to perceive the scenes being projected as three-dimensional, and have the illusion of being immersed in the virtual model. The position of one of the users is tracked, and the computer renders the virtual scene appropriately from his or her point of view each frame.

We used a basic virtual model of the *in situ* architecture (ruins) of the Petra Great Temple as the context for our experiment. We also integrated models of the excavated trenches and trench layers as contrasting white geometries. These geometries represent the actual volumes of dirt removed in each section of the site.

This constitutes the context for the excavation data. In the first prototype we colored and textured the temple model as realistically as possible. This created a distraction for archaeologists, much like being immersed in the real building during excavation. To concentrate users in the study of the data, we removed all textures from the ruins model and colored it with a dark grey (low lightness). Then we chose the colors for the different data types to have high lightness values. Archaeologists appreciated the effect created, since, at the real site, the building architecture creates a very imposing presence that *hides* the artifacts.

As explained before, certain interaction was provided so users could adapt this context at any point during the analysis. Users can modify the transparency of the excavation layers so they would be just a frame of reference for the data being displayed. They could also make them totally disappear so they would not occlude important information at some point.

To navigate in the environment, users carry a wand and wear a tracked pinch glove to perform queries to the database of information from the site. Archaeologists learned how to use these devices quite quickly, but more development and formal testing is necessary. The database was created at the beginning of the excavation in 1993, and it can be queried in real time from the virtual environment. Users can interactively select different data types to visualize in all or just specified trenches. Data types represented in the experiment are summarized here:

- *In situ* architecture: architectural evidence surviving from the remains of the Great Temple. It is represented with a dark gray color to contrast with trench and artifact evidence.
- Excavation trenches: volume of debris excavated in each area. Trenches are divided into layers.
- Excavation layers or loci: important to understand sediment patterns and for keeping track of where found artifacts are located inside a given trench.
- Bulk finds: objects that are eroded, damaged or otherwise indistinguishable as individual objects. We are currently visualizing four bulk find materials: pottery, bone, metal and stone. They are represented as small tetrahedra, colored depending upon the type of find.
- Special finds: they represent the most significant finds because they are usually in excellent condition and generally provide more specific evidence about their origin and use. Lamps are represented as large tetrahedra and coins as large hexagonal prisms. They are colored according to their presumed cultural origin, i.e., Nabatean, Roman, Byzantine or Unknown.

5.1 Visualization Tools

In previous tests we realized that archaeologists wanted an overview of the model (obtained by flying high up over the virtual model) so they could study how the different artifacts were distributed over the whole site. Therefore, we created a miniature version [9] of the full-scale model that users can bring up at any point. As shown in Figure 5 (a), this miniature is stationary relative to the walls of the cave and acts like a three-dimensional map. We also created a virtual room, by texture mapping the real walls of our cave. Since the main model with the data is not visible, we hoped this would provide a sense of enclosure for archaeologists to discuss different aspects of the site data while either looking at a 2D map displayed on the floor of the cave or the miniature ruins of the Temple with or without associated trenches and objects (Figure 5 (b)).

a) b)

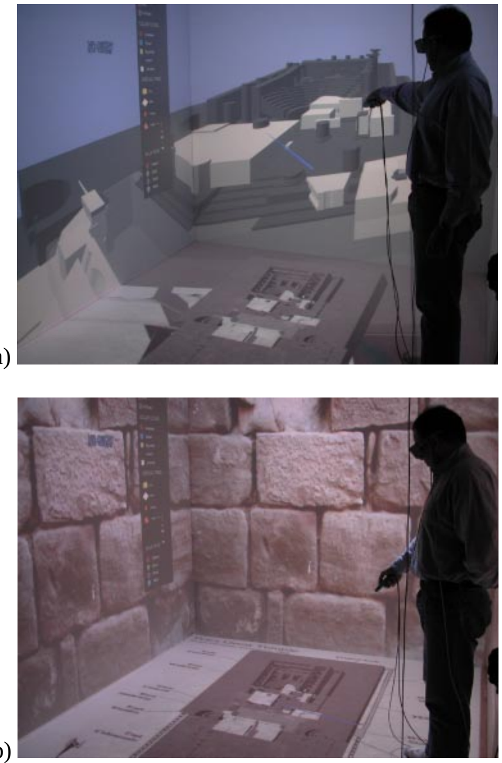

Figure 5: The ARCHAVE system in use, full scale model (a) and miniature model (b)

After users query the database, the results are displayed as a variety of 3D geometries. Special finds are represented as larger geometries such as: lamps (tetrahedrons) and coins (hexagonal prisms). These artifacts are color coded with their cultural origins (also stored in the database). Bulk finds are visualized as smaller geometries and are color-coded depending upon artifact type (pottery fragments, metal pieces, stones or bones). All artifact types are stored and retrieved from the database on a per-excavation-layer basis, see Figure 6.

Colors used on these artifacts and on the model of the architecture, greatly affect the perception of the researchers when trying to find anomalies or patterns on data being visualized. We spent a long time adjusting colors and shapes of objects that users would see. We considered alternatives like texture mapping, transparency and even motion [11], but technical limitations made it impossible to implement these techniques without lowering even more the frame-rate at which the application was running.

5.2 Testing the Second Prototype

Our experimental design was built to evaluate ARCHAVE in performing relevant archaeological research. The analysis of lamps throughout the site was a task specific enough to allow us to prepare a valid test to give us a good measurement of the validity of the system.

We brought in two archaeologists who had worked consistently at the site from the beginning of the excavations. One of them specializes in lamp analysis using lamps found at the Petra Great Temple site and some neighboring sites in Petra. She tried the system several times and eventually wanted to use the system to generate specific evidence to support some of her theories regarding lamps at the site. The second archaeologist specializes in analysis of glass finds. Although that data type was not supported in our current visualization, she wanted to see possibilities for correlating the visualized artifacts with her glass data. The experiment proceeded as follows:

1. We introduced both archaeologists to the cave environment and the navigation and visualization tools.

2. We asked both to state their current research hypotheses and what ideas they had to try to evaluate them.

3. We prompted them to query the database for lamp finds in all available trenches, analyze their distribution first on the miniature model (site-wide analysis), and then, attend to their vertical distribution per trench, on the full scale model.

4. We asked them to query the database for coin finds in all available trenches. Then analyze their distribution first on the miniature model (site-wide analysis), and then, attend to their vertical distribution per trench, on the full scale model.

5. We asked them to query the database for bulk finds (pottery, metal, bone and stone fragments) in all available trenches. Then analyze their distribution first on the miniature model (site-wide analysis), and then, attend to their vertical distribution per trench, on the full scale model.

6. We asked them some questions after having experienced the system. These were made while staying in the cave, in our *virtual room* with a map of the site or the miniature model as reference for discussion:

    - What do you want to take away from this experiment to help with your research?
    - If you found evidence today to support some theories you already had, what evidence, if any, did you have before to evaluate those theories?
    - Could you give an specific example of a research task that you would rather perform with ARCHAVE than with traditional methods?
    - Could you give an specific example of a research task that you would rather perform with traditional methods than with ARCHAVE in its current state?
    - Do you have new hypotheses about the data you have seen? How could you have developed these new ideas with traditional methods?

5.3 Evaluation Results

Archaeologists used the ability to visualize the data in three-dimensions in our immersive virtual environment in order to understand the site better [20]. They achieved this by touring around the site with existing architectural remains, by looking at the trenches and by looking at the trench loci and artifact types in various combinations. They attempted to synthesize their observations with earlier analysis of some features. For example, our lamp specialist was interested in seeing the objects in the central stair area (trench SP 4) and noticed a few things that did not agree with her memory from excavating the trench in 1996. Also, she was able to identify a few areas of mixed deposit that she had not formerly been able to identify. This is significant because it confirms some of their longstanding suspicions about the various levels and their ability to trust earlier findings. Areas of mixed deposit are areas where objects from different cultural origin are found together in the same stratigraphic level.

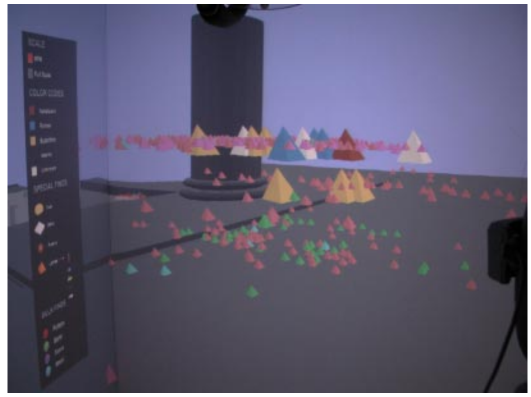

Figure 6: The artifacts are retrieved layer by layer, and visualized so that the loci hierarchy is maintained

She had specific questions about the lamps she had been attempting to analyze. Through a query of lamp finds with coin and bulk finds, she was able to isolate a cache of Byzantine lamps in a middle locus of the western aisle which indicated that there may have been habitation in that area during the Byzantine occupation. Because she had not personally excavated that trench, she was not familiar with the exact find location, a vital clue which could have been missed without this system. Also, along with this observation, she noticed a cache of metal above the lamp finds. She then posited that these were remains from door hardware or even the roof.

The system allowed our two test subjects to widen their view of the excavation, since they were able to easily explore areas they were not familiar with. They commented that ARCHAVE allowed them to be curious about areas with possible connections to the data they were studying. This is something they simply cannot afford to do with current techniques. With current methodology, if researchers suspect there might be an area of interest somewhere in the site, they must spend a lot of time and resources digging through trench notebooks and excavation reports they are not familiar with, to finally find out there is no correlation between that area and the one they are experts on. This limits the analysis process [23] and leaves under-studied a lot of possibly interesting links, within a site or among different excavation sites.

6 Summary and Discussion

6.1 The Archaeological Problem

Archaeological analysis is a process of generating and evaluating hypotheses about a site based on evidence obtained during the excavation process. In this process, researchers try to answer specific questions about how the excavated edifice (The Great Temple of Petra) was used, who lived there and when the various areas of the site were built. The objects unearthed provide valuable clues for a better understanding of the site. The analysis process is a broad effort to evaluate the clues and generate valid hypotheses with the highest degree of confidence possible.

Unfortunately, there are many factors that cannot be represented well with a traditional database approach and in reports generated from it. Specifically, these methods cannot integrate important spatial information from the maps and plans and specific attribute data, location and relational data between artifacts and site features.

Also, an obvious and marked problem with these methods is the basic inability a researcher has to get a complete picture of the physical information recovered and to visually process its characteristics in a comprehensive way.

6.2 Our Solution

Our system presents the excavation data in three dimensions in the context of a virtual model of the site. This model represents either a reconstruction of how the building looked like when it was in use, or the actual state of the building (*in situ* architecture) almost two thousand years after it was abandoned. This *real* background for the data is one of the characteristics our system has, trying to answer researchers request for an adequate context to analyze the information. A number of requests were made by archaeologists during the development process of ARCHAVE, they being more specific as users got more familiar with the technology and its possibilities. This wish-list lead our work.

ARCHAVE provides users with a way of understanding the data in a way at least comparable, if not better, to how current tools allow them to do now. Having an adequate data representation, in conjunction with the virtual model, facilitated the understanding of the data and enhanced researchers visual search for anomalies and areas of interest.

6.3 Research Results

The fact that we combined important research issues from several different areas of study complicated the system's development and testing processes, but provided a unique opportunity to develop methodology and techniques intended to solve a practical problem in archaeology.

We introduced a new language to represent multivariate data, combining color, shape, size and context to create the appropriate perceptual effect. We created and developed novel techniques for multi-scale navigation in virtual environments.

One of the most relevant results in this area is [9], in which we describe a set of techniques for navigating and exploring virtual environments at different scales. That work was inspired, among other motivations, by results obtained during the first tests with ARCHAVE. The system itself could not be tested with our research environment because of technical problems, but techniques from it, such us the miniature model of the temple, were incorporated in our test case. The multi-scale approach to analyzing excavation data proved to be one of the most successful and extensively used techniques of the final system. This new tool, combined with the use of our virtual room (Figure 5 (b)), improved the sense of orientation of users in the virtual environment, but further testing is required to study the reasons and of this behavior.

7 Conclusion

The final system addresses some of the issues described in the motivation section of this report. Most of them still require more development and testing, but after creating these two versions of ARCHAVE and getting users to test the latest one, described above, we have the confirmation we needed to confidently advance towards novel techniques yet to be defined and evaluated. We successfully evaluated the ARCHAVE system in performing a relevant scientific research task. This result is now the basis for future advances in the system, since researchers who have tried ARCHAVE have realized its potential, and will continue to adapt their analysis methodology to use this new research environment.

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