The Virtual Reconstruction of an Archaeological Site - An Overview of the MURALE Project *

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Abstract. This paper gives an overview on the recently granted EU project 3D MURALE which stands for 3D Measurement & Virtual Reconstruction of Ancient Lost Worlds of Europe, Project Number: IST-1999-20273. This project aims to virtually reconstruct a complete archaeological site including landscape, buildings, and artifacts in 4 dimensions, where the 4th dimension stands for the time component. It should be possible to see also the history of the site from its beginnings to its destruction in order to understand the historic significance of the site. Finally this technique should be applicable to any archaeological site serving three purposes: for visitors at the site to see how the remains could have looked like in reality, for virtual tourists to see what can be seen on spot, and for archaeologist to ease their work in respect to reconstruction and classification of artifacts and buildings. Since the project recently started, no actual results can be presented, however, the main project goals and work already performed in this field are presented.

1 Introduction

New technologies are introduced to old research areas and provide new insights for both the researchers and people interested in this field. This statement can be proofed especially in the field of archaeology, since there are many researcher in that area who already use new technologies and there are many people interested in the field of archaeology since so-called archeo parks have an increasing number of visitors. Since we have some experience in applying technical knowledge to the field of archaeology, especially in the field of ceramic reconstruction and classification [MS96,KS99,KS00] and others in the reconstruction of archaeological buildings [GDH+00] a consortium was founded to virtually reconstruct a site in Turkey called Sagalassos [Wae93,WL00]. The MURALE consortium consists of 2 industrial and 5 academic partners, from 4 different European countries (Austria, Belgium, Switzerland, and the UK). MURALE is intended to add an additional technological layer to an extensive, ongoing excavation project.

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The advent of new multimedia technologies produces rich new ways of recording, cataloging, conserving, restoring and presenting archaeological artifacts, monuments and sites. The 3-D MURALE project wants to contribute to these developments and focuses on two aspects:

- By putting new technologies in the hands of the archaeologists themselves rather than creating multimedia content after the excavations. As an important consequence, a more complete record of the finds can be created and presented to the public
- By presenting the site not as a static entity from a long-gone past, but as a vibrant place that underwent a lot of changes throughout its existence. This includes the visualization of the situation in different eras and of the excavation as they proceeded through different time layers

Both these aspects of the project will help to produce records and visualizations that are more complete and scientifically precise. A first goal is to register in situ all stratigraphical evidence (an archaeological site is excavated layer by layer so-called stratas resulting in a sequence of strata), as archaeological fieldwork by its nature destroys this kind of information. The 3-D recording techniques should replace present techniques of 2-D recording which only offer a piecemeal representation and are both time consuming and labor intensive. Secondly, techniques need to be developed to build 3-D models of artifacts, mainly for cataloging and visualization, and of sculptures and buildings, mainly for restoration and visualization. Thirdly, the terrain of the site needs to be modeled in 3-D as such topographic data yield important information for the archaeologists and is vital for a realistic visualization. Finally, an integrated model must be built of the landscape, the buildings, and the artifacts and this for different eras, showing reconstructions for these periods or the current state. To summarize following main objectives can be identified:

- A currently excavated site, Sagalassos will be reconstructed for the different periods throughout the complete time of its occupation.
- Creating precise and realistically looking 3-D models of the natural environment (landscape with evolving vegetation) and the urban development of the site of the individual monuments, sculptures (statuary and reliefs), and of the ceramic.
- Easing the documentation and classification of pottery (sherds). Now this takes much time by numbering the finds, sorting them into different groups, measuring, drawing, describing the fragments in terms of shape, decoration, technology, and material, and through a final determination of shape and decoration according to literature (catalogues, corpora). These steps serve one final aim: the correct classification of the material to recognize types, to add labels for additional information as a measure of quantity, and to a limited extent for piecing together many fragmented artifacts. This is extremely time-consuming and except for real exhibition pieces scientifically unnecessary.

– To provide the archaeologists with tools to support the analysis and restoration of their finds; e.g. to outline the profiles of pottery or to prepare anastylosis by first virtually fitting together pieces of a building.

MURALE will also provide tools for the virtual and real restoration of artifacts, sculptures, and buildings. Today, undecorated, heavy building elements or fragments can only be joined/pieced together by time-consuming trials with the help of heavy hoisting equipment. By creating the means to easily create 3-D models of the parts, it becomes possible to virtually puzzle them together first and to save a substantial amount of time. Today, the completion of large sections of buildings by means of newly carved or cast elements is avoided as much as possible. Rebuilding a ruined structure should only be decided, when more than 90% of the original building elements are preserved so that their anastylosis becomes possible. In this case, the new 3-D technology will check in virtual reality the level of completeness first. In most cases, however, anastylosis is no longer possible, so that the look and/or function of a ruined structure remain beyond reach of non-specialized audiences.

The paper describes the partners involved and their contribution to the project in Section 2. The main topic of the paper, the virtual and physical reconstruction of the archaeological remains is covered in Section 3. The paper concludes with an outlook of the work to be performed within the project.

2 Partners and Main Objectives

To give a short overview on the project we introduce the partners in more detail and show the dependency of the inputs to the project as a whole. The 7 partners are:

– **University of Brunel**: the University of Brunel is the coordinator and will design and build a text, image and 3-D database system that can be optionally accessed through annotations on a visualization system.
– **Eidgenossische Technische Hochschule Zürich**: The Eidgenössische Technische Hochschule at Zürich develop texture synthesis software that will be refined [vWvGKP99]. They will synthesize textures of materials and vegetation that are to be mapped onto the surfaces of the terrain and the buildings.
– **Eyetronics NV**: The company sells 3D acquisition tools. Their patented ShapeSnatcher technology only requires a single slide projection, a single camera, and a special slide [PvGO96]. The pattern on the slide is projected onto the scene and what are visible to the camera can be reconstructed in 3D from a single image. Also the texture is extracted from the same image.
– **Graz University of Technology**: The graphics team of the University of Graz are experts in the 3D modeling of architectural structures [May00]. They will provide the virtual restoration and modeling of the buildings at Sagalassos, for the different time periods, starting from drawings that the archaeologists will provide and from 3D models of existing pieces and their original or current textures provided by the other partners.

- **Imagination Computer Services GesmbH**: This company will develop a virtual reality visualization tool that can also be applied to museums, which will make it possible for users to get more information on exhibits, or to see exhibits that can not be seen in the museum (due to lack of space, or current restauration), or too see original archeological sites in the case of archeological museums [SG97].
- **Katholieke Universiteit Leuven**: The University of Leuven is represented with two groups. On the one hand they deliver the archaeological background for the project. The department of archaeology of that university leads the excavations at the Sagalassos site [WL00]. The electrotechnical department (ESAT) contributes passive 3D reconstruction technology from uncalibrated image sequences [PKVG99,PKV$^+$00]. This will be used to model the landscape, the buildings and large finds. This team will also supply the technology to build the 3D reconstructions of the excavation strata.
- **Vienna University of Technology**: Reconstruction and classification are of major concern of the PRIP group in the ongoing project. Engaged results comprise the recording of complete vessels in respect to archaeological needs and the virtual reconstruction of complete objects out of fragments [SM96].

An overview of the 3-D MURALE project can be seen in 1. As can be seen from the diagram, there are five clearly defined activities to the project organised into five workpackages, namely:

- User Requirements and Technology Assessment
- Recording
- Virtual and Physical Reconstruction
- Visualization
- Database Storage and Retrieval

Archaeological and Visitor User Requirements provide the specifications for Recording, Virtual and Physical Reconstruction, Visualization and a Database for storage and retrieval parts of the project. The results from all parts of the project are fed to a database for storage and queries of conventional text, images and 3-D objects and will enable all three part of the project to access content.

User Requirements and Technology Assessment defines the goals to be achieved, the requirements and specification of the new measurement technology, specifying service scenarios, user technical specification and demonstrating and is evaluating the MURALE system. Multimedia Database is responsible for storage and retrieval of conventional text information as well as storage and retrieval of images and 3-D content. The Recording workpackage obtains 3-D records of archaeological layers from simple photos (Stratigraphy) and measures pottery, statues, friezes, buildings and landscape. Virtual and Physical Reconstruction merges individual objects found at each stratographical layer and reconstructs virtually and physically pottery, statues, friezes and buildings. Visualization is virtually sequencing through the stratigraphic layers, adding representative sample of objects found at each layer and annotating the object with links to the database. It also constructs a complete scene visualization from landscape and reconstructs buildings and artifacts found on the site.

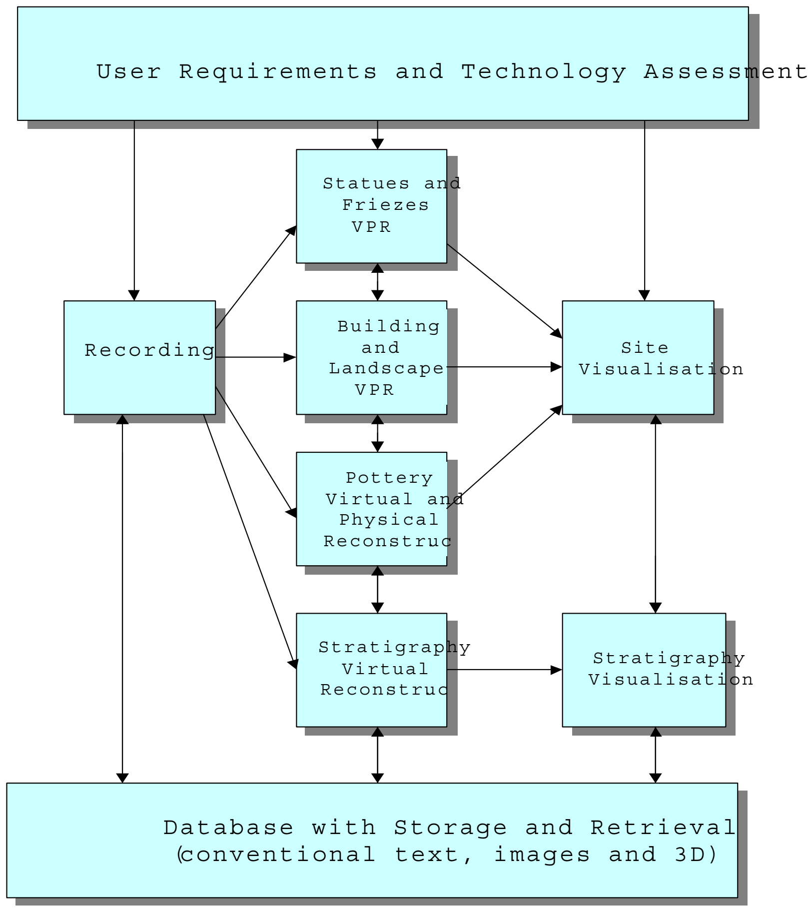

Fig. 1. Structure of the MURALE Project

3 Virtual and Physical Reconstruction

The Virtual and Physical Reconstruction is concerned with taking the 3-D models and completing them in a number of ways. First, there is the integration of information from different excavation layers into a single representation. Secondly, pieces of objects and buildings are combined into more complete 3-D models. The 3-D reconstructions of the separate excavation strata will be combined to build a 3-D record of the excavations. This will include segmenting the strata into bare soil and the different finds and building structures. A tool will be developed that performs a first segmentation on the basis of color and height. Loose pieces will be modeled separately, and then matched to the 3-D data of the upper layers where they become visible.

3.1 Data Acquisition

Archaeological excavations are carried out very carefully, scraping off layer by layer. After a layer has been removed, the layout of finds within that layer is recorded. For the recording in 3D of the different excavation strata MURALE uses reconstruction from multiple images, without calibration data. Neither the camera motion between the images nor the internal camera parameters themselves are assumed to be known. No a priori information about the scene is required. The calibration of the camera is automatically retrieved during the reconstruction process [PG00]. Even zoom and focus can be adapted during the acquisition of the images [PKVG99]. Although the initial steps are based on the matching of discrete features in the images, the final result are dense 3D surface representations on which the texture of the original images is mapped.

The 3-D shapes of selected sherds are recorded with the active system developed for this project [PvGO96]. As this system will be a handheld device, the shapes can be recorded in situ. The outer and inner surface are both recorded and brought into registration by matching the rims [RM99]. The thickness of the sherd (the distance between the outer and inner surfaces) will be measured as the minimal distance from a plane on which the pieces lie for recording. Letting rest the sherd at different points by manipulating it and taking a few images is a way to deal with variable thickness. The use of jigs will be avoided, as special positioning of the sherds would take time.

3.2 Stone Reconstruction

A monumental site produces hundreds of stone fragments, both sculptural and architectural. Many times they can be scattered over large surfaces as the result of seismic events, but also since they sometimes were reused as simple rubble stones in later constructions. Tools to check how pieces can be matched together are very helpful, such that virtual or even physical restorations can be made. A proper recording of broken surfaces and of all available parts of the complete artifact makes the matching possible. A virtual or physical restoration will not necessarily give a good idea of the original state of the piece. The weathered textures will be recorded, but it should be possible to replace them by similar, unweathered textures. The main aim of this task is to find pieces of broken stones or sculptures that match. Once such matches are found, the pieces can be put back together, virtually or physically. Given a limited number of fractured surfaces the computer can try to find potential matches. The virtual reconstruction also includes replacing weathered stone and material textures by synthesized textures as learned from similar materials in their original state. Again the seamless merging of textures will be necessary at places.

3.3 Ceramic Reconstruction

From the 3D sherd descriptions and their texture, the features have to be extracted to perform the classification as done by a human expert. The range- and pictorial information of a pottery fragment recorded by the acquisition system will serve as the basis for the further classification and reconstruction process.

The profile of a sherd has to be determined in the so-called orientation step. The term orientation describes the exact positioning of the fragment on the original vessel with the help of the axis of rotation. The main objective is to perform an automated classification and reconstruction of archaeological fragments by using the profile section of the oriented object and additional attributes (fabric, dimensions, type of vessel and the site) belonging to the fragment. To automate this process, the profile has to be determined in the same way as in the manual documentation. The generated profile is used to perform the reconstruction and retrieval of fragments of the same type. The reconstruction procedure works if the size of the fragment covers a large part of the original vessel in the vertical direction. The profile is rotated by the original axis of rotation, thus measurements like volume can be estimated. However, if only small fragments (with respect to the vertical size) are available, a reconstruction based on the fragment is not possible. In this case, the fragments have to be classified correctly in order to determine matching fragments. Figure 2 shows the automated archivation process schematically, giving an overview of the technical research aims.

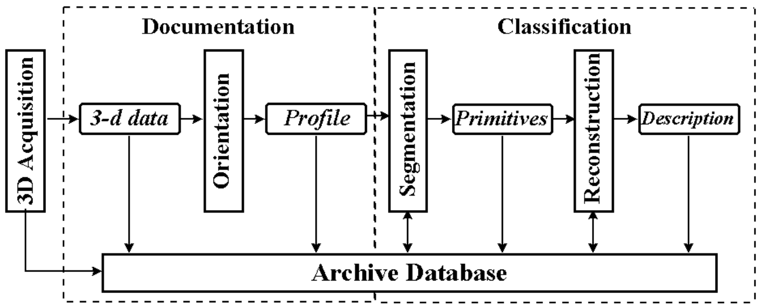

Fig. 2. Overview of the approach.

Using the $2\frac{1}{2}d$-model of the fragment's inner and outer surface, the axis of rotation has to be determined for both surfaces automatically. Once the axes are determined the profile section can be generated by registering the two surfaces on one another (Registration, that is used to refine the registration already performed by the 3D recording stage). Next, the longest intersection of a plane that is rotated within the rotational axis of the fragment with the surfaces of the fragment is determined (orientation). The profile section of the fragment is the result of this processing step. This profile is then segmented into its primitives (with certain properties like length and curvature) and relations among these primitives (like position and curvature of connecting points). In order to classify and reconstruct fragments, the profile is segmented into primitives like rim, wall, base and so on. This segmentation is based on mathematical properties of the profile like curvature and length and has to be determined in a classification scheme that uniquely relates primitives to shape properties.

All classified fragments are stored in an archive database as description, 3D-model, and intensity image. Each fragment will have a unique number when archived. The fragment is stored in the description together with all attributes.

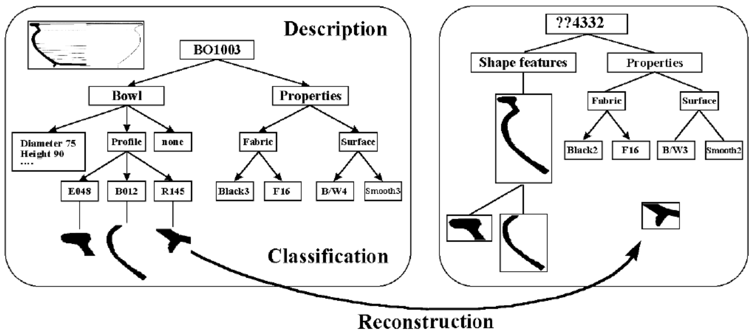

Fig. 3. Retrieval of similar fragments.

Figure 3 describes an example of the retrieval. Each fragment has a unique number when archived. Together with all attributes the fragment is stored in the description. The left side of Figure 3 shows the profile classified as bowl. The primitives are the basis for the classification and reconstruction process. On the right hand side of Figure 3 a fragment that is not yet classified is depicted, thus the type of vessel is not yet known. Its profile is to be matched against those in the database. The type of fragment can be classified as bowl. Furthermore, missing parts of the fragment (like the base in this case) can be reconstructed based on the already stored information.

3.4 Virtual Reconstruction

The virtually reconstructed vessel may then be visualized as part model, parts that are existing are visualized with their proper texture, and missing parts on the vessel are visualized with a unique color. Furthermore, to relate the vessel within a building to its approximate finding place, those parts that where found on the entire spot may be colored differently from other parts. To guide the physical reconstruction different fragments that form the vessel could be visualized in different color together with the number of the fragment. To actually glue together the vessel, it is only necessary to collect the fragments displayed on the screen and put them together as proposed by the system. Only pieces that have a specific value and would be worthwhile to be exhibited will be physically reconstructed by the conservation team. For the others, storing the virtual reconstruction image will be enough for scientific purposes. To sum up, following sub-goals can be identified for pottery:

- **Automatic orientation**: Determination of the axis of rotation, Registration, Profile generation
- **Automatic profile-segmentation**: Determination of shape characteristics and description, curvature-based segmentation, generation of primitives and description
- **Automatic reconstruction**: Automatic classification, Reconstruction of missing parts of profile, Reconstruction of vessel, Search for already archived fragments of the same vessel

Once when all objects are reconstructed and inserted into the database, the LOD will be generated for all objects, and the whole scene will be composed. Since there are a lot of commercially available scene composition software, one of these packages will be used. As temporal "dimension" is needed as well, a package that supports animation will be used. The final goal is the visualization of the reconstructed parts which can be summarized as:

- **CAD modeling of buildings in their original state**: Based on the drawings supplied by the archaeological team 3-D models of the buildings will be constructed for several of the major buildings that have existed at the archaeological site.
- **Matching building parts**: Based on the 3-D models of different parts of buildings such as separate stones or ornaments, virtual restorations of the buildings are to be made. The problem is like piecing together cross-sections of e.g. separate stones to fill the outlines without gaps. The user is supposed to help the system, as blindly trying combinations of e.g. stones that might fit quickly becomes prohibitive. But the archaeologists can assist in reducing the number of possibilities, based on where pieces have been found, based on the material they are made of, based on knowledge of the architectural styles, etc.
- **Integrating the different models**: The different 3-D entities also have to be combined into a general site model. As mentioned, the database will indicate where objects should be placed and for which eras they have to be included. It is e.g. necessary to adapt the LOD at the intersections of different entities. For instance, if buildings are included into the landscape, the latter should be modeled precisely enough near such intersections in order to ensure realistic transitions.
- **Texture Synthesis**: An innovating aspect of the texture synthesis used to mimic the vegetation and terrain of the landscape will be that it will take account of the strong 3D nature of such textures. The Gibbs texture synthesis approach will be extended to generate textures that depend on the viewing angle. This will allow to mimic occlusions and other 3D effects. Again, the models will be generated from example images which will now have to be taken under a series of viewing angles.

4 Conclusion and Outlook

Archaeologists will continuously play the role of critical users, who make suggestions for improvements from their perspective. Through a direct collaboration with the whole team of archaeologists behind the MURALE project, the archaeologists will have an important influence on the objects, buildings, and sites on which the techniques will be tested. The whole MURALE technology and set of tools will be demonstrated both to specialized audiences and to non specialized visitors. The task will be responsible for the set-up and operation of service demonstrations and the performance of the new tools. These results will be progressively collected and presented in demonstrations both on the site and elsewhere for larger European and other audiences. At the end of the project an overall service package will be delivered. It is intended that the experience and results of the project could also be reproduced in trials at other European sites and in other European collections.

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