

PHOTOREALISTIC VIRTUAL EXPLORATION OF AN ARCHAEOLOGICAL SITE

ANDREA F. ABATE,^a * FABIO NARDUCCI,^a AND STEFANO RICCIARDI ^a

(communicated by Liliana Restuccia)

ABSTRACT. This paper describes a case study concerning the virtual reconstruction and navigation of an archaeological site located in Moregine, near Pompeii as it appeared to archaeologists after the completion of the excavation and including the reconstruction of face and body appearance of a woman that found death there, during the eruption of 79 BC. The main challenges faced in this study concern the visual engine required to delivering possibly unlimited visual quality and the methodology for achieving an ethnically faithful face reconstruction from skull bones. The first objective is tackled by adopting a pre-rendering based visualization engine, through which environment navigation is achieved following pre-built paths and performing available actions through a context sensitive motion tracking based interface. Secondly, the plausible appearance of the woman's face is reconstructed exploiting an approach based on craniometrical analysis together with a pictorial physiognomic database and content-based image retrieval technology, to the aim of providing more faithful results compared to other methods in literature based solely on statistical data.

1. Introduction

Archaeology and, more in general, cultural heritage represent a perfect example of how Computer Generated Imagery (CGI) can bring back to their past appearance places, monuments, artefacts and even human beings. To this aim, two main components are typically involved, the digital restoring process usually referred to as "virtual reconstruction" and a content fruition technology, that can widely range in terms of visual quality and interaction level provided. A good example of an archaeological site suited to exploit the potential of CGI is represented by the site of Moregine, near Pompei, known for the beautiful paintings and jewels found within a very well preserved Roman villa and interesting also for the remains of a woman that found death there during the eruption of the Vesuvio on 79 BC that buried the whole site. This compound house was originally unveiled by a survey in the year 1880-81, then fully unearthed during local highway maintenance and finally buried again due to cost and convenience evaluations (Nappo 2012). Since there are still many unanswered questions that archaeologists can no more address through on-field research, this site is paradigmatic of how interactive CGI may help to further studying inaccessible

locations. To this regard, the approaches investigated in this case study concern, from the one side, the reconstruction methodology to be applied to the skull remains and, from the other side, the pre-rendering based visualization engine exploited for content fruition. More in detail, the face reconstruction method aims at achieving a greater physiognomic fidelity in the reconstructed character based on an ethnic hypothesis, while the approach behind the visual engine privileges highest quality content fruition over a greater freedom of interaction typically provided by real-time graphics engines. Consequently, it is important to remark that the focus and the contribution of this paper is not really on the CGI modelling, rendering and animation techniques involved in the various stages of virtual reconstruction, but rather on the whole reconstruction/fruition framework in which they have been used.

The rest of this paper is organized as follows. Section 2 reports previous works related to both archaeological site reconstruction and to face reconstruction. Section 3 briefly resumes how the site's reconstruction has been approached, while Section 4 provides a detailed description of the character's reconstruction methodology. Section 5 describes in detail the visualization engine exploited in this framework and finally Section 6 draws some conclusions about the work conducted.

2. Related works

Over the years, many approaches have been proposed in the field of 3D reconstruction for archaeological purposes. Among them there are methods based on the usage of laser scanners that enable to acquire objects faithfully. A variety of projects adopt laser scanners for documentation purposes (Allen *et al.* 2004; Ioannides and Wehr 2002; Marbs 2002). A method for large-scale reconstruction based on laser scanners was suggested by Ioannides and Wehr (2002). The main disadvantage of scanners is that they are not (or at least they have not been in the recent past) part of the standard documentation procedure in archaeology and serves only a very special purpose. Moreover, specifically trained personnel is required to operate the devices, data acquisition can be very time-consuming and they are not always applicable, as it is the case of underwater archaeology. Finally, their inherent technical complexity makes scanners still too expensive to be used widely.

An alternative to using scanners is represented by methods solely based on images sequences such as the work by Hartley and Zisserman (2003) and Pollefeys *et al.* (2004). ARC3D (Vergauwen and Van Gool 2006) is a web-based service computing 3D models for users that exploits image-based techniques. Although the resulting model is accurate it does not offer measuring capabilities so it is difficult to combine different excavation layers. Other existing systems focusing on archaeology or architecture are 3DMurale (Cosmas *et al.* 2001) and 3D-Arch (Remondino *et al.* 2009).

With regard to facial reconstruction, several methodologies have been developed over more than a century (Tyrrell *et al.* 1997), particularly for forensic applications. They are often based on the study of both facial anatomy and relationships between soft tissues and hard tissues, but in the last decades a growing amount of statistical data, coming from surveys on soft tissue thickness (Rhine, Moore, and Weston 1982), has led to the development of more believable methods. The measurement protocol, implemented for these surveys, consider a specific set of points located on the face surface to measure their

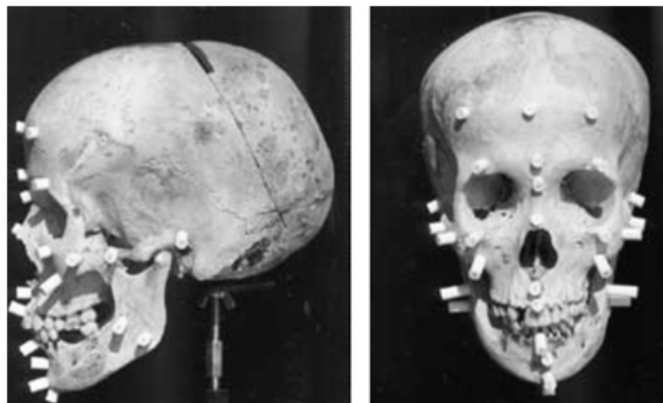


FIGURE 1. A skull with thickness landmarks applied

distance from cranial bones along a normal direction. The resulting statistics, grouped by race, build and gender provide a reference for the reconstruction.

The simplest reconstructive techniques like landmark based drawing or sculpting (Wilkinson 2010) and photo overlay (Shahrom *et al.* 1996) can be useful to check identity of cadaver remains (see Fig. 1), while the more recent computer based methods typically starts from computer tomography data to obtain a 3D digital model of the skull (Moss *et al.* 1987; Vanezis *et al.* 2000) and then reproduce the skin surface using the aforementioned thickness statistics. To the latter category belong the so called warping reconstructive techniques which operate on a reference face mesh (Archer 1997; Ulgen 1997), usually obtained as an average of different basic facial physiognomies, and deform it trying to best fit the skin thickness landmarks previously positioned on to the skull mesh. Many variations to this method are reported in literature (Kähler, Haber, and Seidel 2003; Moss *et al.* 1988; Quatrehomme *et al.* 1997), mainly aimed to forensic and surgical applications, though the basic warping method is flexible enough to be applied in other interesting applications as well (DeCarlo, Metaxas, and Stone 1998). On the other side the use of a "neutral" reference head mesh could lead to an ethnically unrealistic reconstruction of all those facial regions eventually not covered by the set of soft tissue depth measurements. To address this problem, the presented method compares craniometrical features of the skull to be reconstructed to those coming from a specifically built database of anthropologically affine living individuals. If the reference database is consistently built, then the more similar record is eligible as a better reference to the warping process than an averaged mesh.

3. Site reconstruction

For this case study, we selected for the virtual reconstruction the "building B" of the Moregine archaeological area (Mastroroberto 2004), more precisely the "house D" which is part of a wider block made of "cauponae" located on the northern side of the ancient Sarno river bed (Stefani and Di Maio 2003). Overall, the excavation considered for the virtual reconstruction covered an area 20×10 meters wide with a floor level positioned three

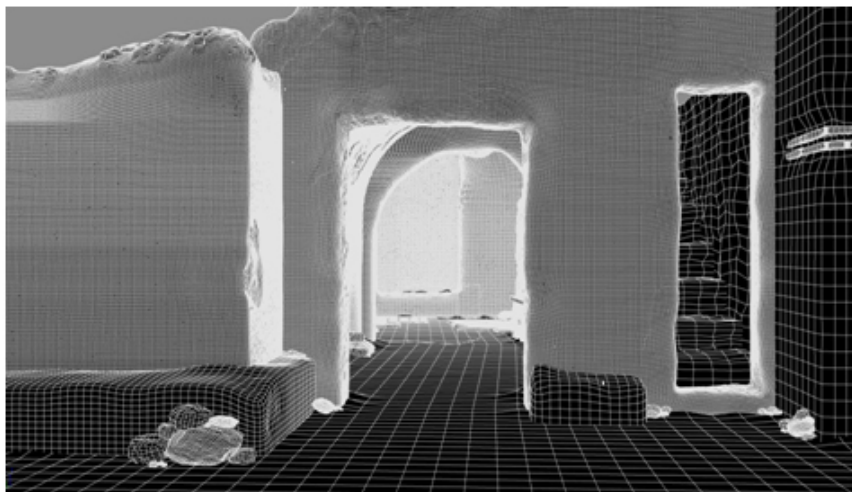


FIGURE 2. Wireframe representation of the "B Building" highlighting multiple level of detail

meters below the present-day street level and exposed to a waterbed whose infiltrations are among the main reasons behind the decision to bury the site again. The main goal here was to creating a 3D model of the inaccessible building as it appeared after the excavation campaign was completed. In this sense this study is more focused on the archaeologists' point of view than most of the digital reconstruction typically aimed at cultural heritage dissemination for non-expert audiences. This is particularly relevant since, at the time of the excavation, 3D scanning techniques were not available and, consequently, the entire building has been modelled exploiting the original survey's results, such as drawings, measurements, photographic material and video footage, accurately associating these data to the various model views. By this technique a reference grid of feature points is increasingly refined adding details retrieved from multiple sources (Debevec, Taylor, and Malik 1996). Digital sculpting by means of tools like Pixologic's *ZBrush* (2014) has also been extensively exploited under the supervision of archaeologists to increase the fidelity of the virtual reconstruction according to the existing photographic documentation and video footage (see Fig. 2 below and also Fig. 7 in Sec. 5). To the same purpose, high-resolution displacement mapping have been extensively exploited to render the aspect of most surface typologies, not how they originally appeared but again respecting the status in which they were found. Finally, the models have been refined and previewed to check them for active stereoscopic visualization (Sawhney *et al.* 2001). We remark again that, since the whole reconstruction/fruiting approach presented here is targeted to non real-time rendering, any kind of lighting and rendering techniques, even the most computing intensive, could possibly be adopted. So, the renderings provided throughout this paper just represent a sample of what could be achieved by means of modern CGI tools.

4. Character reconstruction

The character reconstruction method described hereafter is based on the work by G. Nicolucci who was the author in 1882 of one of the more detailed surveys ever conducted on ancient Pompeian skulls (Nicolucci 1882). In his classification of ethnic features deduced from skull shapes he suggests that the basic facial morphology of ancient native Pompeians, as it is shown in contemporary paintings and sculptures, belongs to a main ethnic group known as the Oscii-Campanii and it is still present in many living native Pompeians. The presented methodology, while shares some common techniques for face reconstruction like the landmark based mesh deformation, combines a craniometrical data driven reproduction of main facial features with a Context Based Image Retrieval (CBIR) search engine to integrate the first level of reconstruction with additional facial features (eye colour, hair).

These features indeed, although aleatory, have great relevance from a physiognomic point of view and could help to better visualize the typical likeness of common Pompeians of two thousand years ago. Finally, the most uncertain features, like build and cloths, have been modelled under the direct supervision of expert archaeologists.

The reconstructive approach adopted can be summarized as follow: starting from a radiological analysis of the found skull, craniometrical features are extracted and compared to corresponding features of living subjects (records) contained in a craniometrical database. The most similar record is used for a first reconstruction that is further improved by a landmark-based deformation. The resulting model is then enhanced integrating additional facial details selected from a pictorial database, and finally a photorealistic rendering is performed.

The skull acquisition process requires three radiological images of the skull from three orthogonal planes (front, side and bottom). CT scanning can be used as well, but is not necessary. In this case study only radiological images were used, as the radiologists suggested they are particularly clear to read and reliable when the purpose is to take a set of distance and angular measurements like the ones required by the method to work.

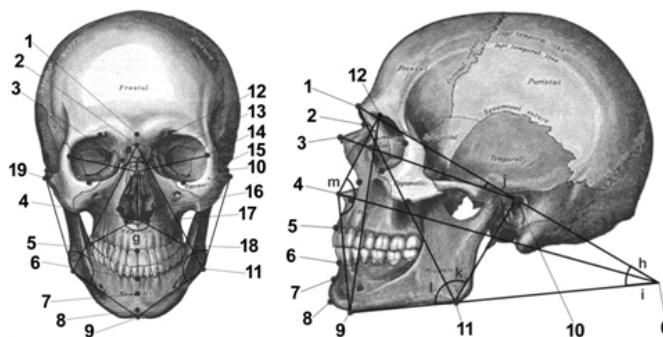


FIGURE 3. Front and side view of landmarks (black spots), and craniometrical tracing

The next step is to assign to each radiological image a corresponding set of anatomic landmarks, each one with a unique name and number as in Fig. 3. This set of landmarks is related to the aforementioned study by Rhine, Moore, and Weston (1982) about spatial

TABLE 1. List of landmarks referenced in Fig. 3.

Landmark nr.	Location (front view)	Landmark nr.	Location (side view)
1	Glabellas	11	Onion
2	Nasion	12	Supraorbital (left, right)
3	End of Nasals	13	Inner orbital (left, right)
4	Mid-philtrum	14	Outer orbital (left, right)
5	Upper lip margin	15	Suborbital (left, right)
6	Lower lip margin	16	Outer nasals (left, right)
7	Chin-Lip fold	17	Beneath nasals (left, right)
8	Mental eminence	18	Occlusal line (left, right)
9	Beneath chin	19	Supraglenoid (left, right)
10	Acoustic meatus	•	•

TABLE 2. List of features relative to landmarks and angles referenced in Fig. 3

Feature	Angle	Distance	Feature	Angle	Distance
1	a	•	17	h	•
2	•	2-11sx	18	•	0-1
3	•	2-11dx	19	•	0-4
4	b+c	•	20	i	•
5	•	11sx-19dx	21	•	0-9
6	•	11sx-9	22	j	•
7	d+e	•	23	•	10-1
8	•	11dx-19dx	24	•	10-3
9	•	11dx-9	25	k+l	•
10	•	3-4	26	•	1-11
11	f	•	27	•	9-11
12	•	4-18sx	28	m	•
13	•	4-18dx	29	•	12-9
14	g	•	•	•	•
15	•	3-14sx	•	•	•
16	•	3-14dx	•	•	•

relationships between soft and hard tissues in human head, but, after experiments, not all of the original landmarks have been considered, whereas others new ones have been added.

A complete list of the landmarks used with $1 \leq i \leq 19$ is shown in Table 1 while their anatomic location is shown in Fig. 3. After landmarks are assigned, the craniometrical tracing of the skull is performed. It consists in angular and linear measurements between landmarks, on front or side plane and it is based on standard craniographic techniques (George 1987). This set of measures, peculiar to this particular skull, allows to define the n-tuple of features $(F_1^*, F_2^*, \dots, F_n^*)$.

A complete list of features is shown in Table 2, where the suffix *sx* or *dx* after a numbered landmark means left or right for symmetrical points. As each craniometrical feature has a

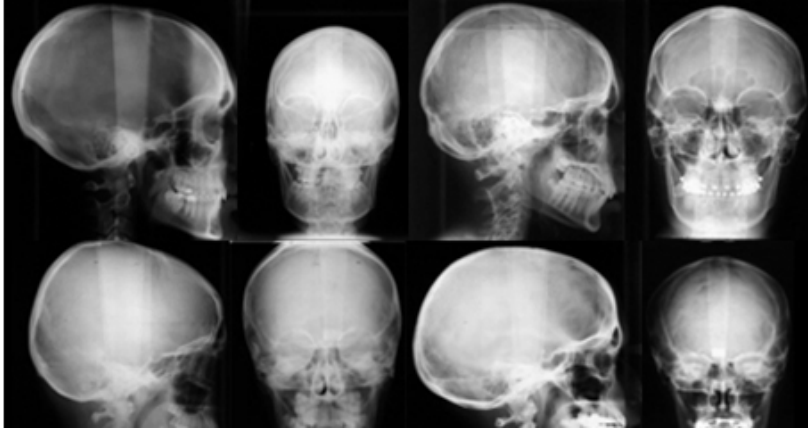


FIGURE 4. Samples of radiological images used to build the CD

different physiognomic relevance to the overall face aspect, we could assign to each one a different weight. The resulting n-tuples, (w_1, w_2, \dots, w_n) with $0 \leq w_j \leq 1$ and $1 \leq j \leq n$, contains the weights relative to $(F_1^*, F_2^*, \dots, F_n^*)$, and if $F_j = 0$ then $w_j = 0$. The extracted features can be compared to corresponding features of every record available in a previously built Craniometrical Database (CD). This database is a collection of craniometrical data gathered during a radiological survey (see Fig. 4) conducted by the Diagnostic Imaging, Emergency Radiology and Radiotherapy Department of the Second University of Naples. The survey collected in almost three years approximately 1.500 subjects of different sex and age ranging from 10 to 40 years, all native to the same geographic area in which the remains were found: Pompei and its surroundings. The CD is indexed by key data (gender, age, etc.) to speed up the search. Each individual is represented by a record in the database, and each craniometrical feature, extracted with the same procedure shown before, is stored in a numeric field, as well as the 3D coordinates $(L_{x_i}, L_{y_i}, L_{z_i})$ of each landmark L_i .

We also store a front and side face images of each subject, usually shot during the same session of radiological images. Through a query in CD we evaluate for each record i the Craniometrical Similarity Score (CSS) that is calculated as:

$$CSS = \frac{w_1 \left(1 - \frac{|(F_{i1} - F_1^*)|}{D_1} \right) + w_2 \left(1 - \frac{|(F_{i2} - F_2^*)|}{D_2} \right) + \dots + w_n \left(1 - \frac{|(F_{in} - F_n^*)|}{D_n} \right)}{\sum_{j=1}^n w_j} \quad (1)$$

where F_{ij} is the j component of the n-tuple of features $(F_{i1}, F_{i2}, \dots, F_{in})$, relative to record i , w_j represents its weight and D_j is the component of an array (D_1, D_2, \dots, D_n) containing the max allowed difference between F_{ij} and F_j^* for each j . This array of values is not specific to each subject, nor is it specified by the user, but is based on human anatomical statistics. If any feature is not present in the input skull, due to missing anatomic element(s) for example, then the corresponding term(s) in the CSS formula becomes zero. CSS is a value in the range $[0, 1]$, where 1 means a perfect match. The result of the query is the record

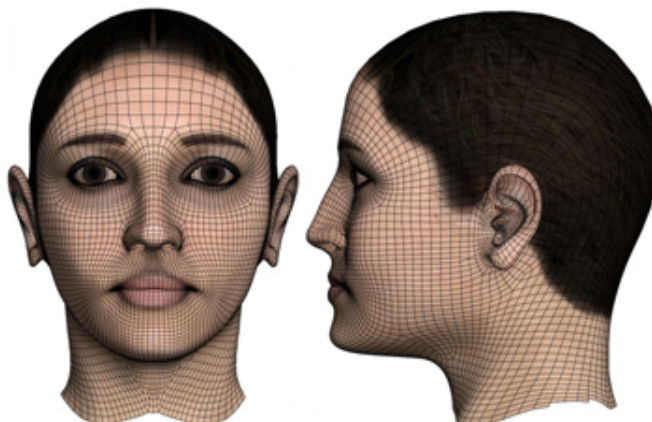


FIGURE 5. Rough face reconstruction.

with the highest CSS. If its CSS is above or equal to a Similarity Threshold (ST) then the record is eligible as a candidate to reconstruction.

We experimentally found that the ST, which is in the range $[0,1]$, should be no less than 80% to achieve optimal results. A first "rough" reconstruction of the best match record is therefore achieved by deforming a neutral head mesh (specifically built with an optimized polygonal tessellation) according to the features detected on the couple of front/side pictures of the candidate subject and exploiting the procedure proposed by Moccozet and Thalmann (1997) and based on the Dirichlet Free Form Deformation (DFFD). By this method, front/side face pictures are also exploited as the main head texture after that mapping coordinates have been projected on the head mesh vertices. The following step performs head refinement through a landmark based mesh deformation. In fact, except for the case in which $CSS=1$ (a practically impossible case), there will be one or more landmarks for which the 3D coordinates differs from the coordinates of the corresponding landmark on the found skull. To address this problem, we exploit a rig system in which each control bone (controlling the relative position of the mesh vertices surrounding it) is associated to each of the craniometrical landmarks previously defined, so that acting on the bone is possible to better approximate the original features by properly displacing the model's surface (see Fig. 5). The whole process described above has been mostly implemented by means of Autodesk *3DS Max* (2014) scripting language, except for the rough head reconstruction that is performed by an external procedure written in C++ whose output is exported back to *3DS Max*. We want now to complete this face by adding physiognomic details such as eye/hair colour, haircut, eyebrows/eyelashes, coming from the only sources we have: the paintings and sculptures made from artists contemporary to 79 a. C. eruption. In fact, anthropologists suppose these artists were inspired, in their works, from typical native subjects. So we introduce the Pictorial Physiognomic Database (PPD), built as a collection of images reproducing (in this case study) Pompeian portraits from classical arts (see Fig. 6). This database is based on the work by Abate *et al.* (2001) and on Content Based Image Retrieval (Gudivada and Raghavan 1995) technology to access and retrieve visual



FIGURE 6. Samples of PPD records

information. Through a query by pictorial example (the previously reconstructed face), we can retrieve images of ancient faces (Faloutsos *et al.* 1994) with a compatible physiognomy. The result of a search through PPD, is a set of physiognomic elements which guide the last refinement of the reconstruction. We used *3DS Max* built-in spline based hair system to achieve realistically rendered hair (and facial hair for male subjects as well). Since this kind of procedurally modelled geometry can be controlled in its shape by means of a set of parameters, an additional field pointing to a corresponding hair system preset is associated to every image in PPD to make possible transferring the hair appearance inferred by the PPD to the target model. Fig. 7 shows a photorealistic rendering of the reconstructed head. With regard to the reconstruction of the body including the clothes, there is no objective method to infer their real appearance from the remains found, apart estimating the overall build based on the long bones fragments available. Consequently, the modelling approach has been mostly driven by the specific knowledge of the archaeologists. The woman's body has been modelled by means of well known techniques such as polygonal modelling and subdivision surfaces, and then optimized for the subsequent rigging and skinning stages required to enable full character animation capabilities.



FIGURE 7. Final rendering of reconstructed face from the presented case study

Clothes have been modelled through specific *3DS Max* tools as a group of 2D patches cut and stitched together and then virtually worn by applying parametric constraints such



FIGURE 8. Final rendering of full-body reconstruction

as gravity, friction, elasticity, shape retention, polygon-to-polygon collision detection and repulsion forces, etc. to achieve a realistic folding effects and a dynamically correct motion. Finally a physically-based rendering of the reconstructed character is performed using ray-tracing and indirect illumination lighting (via the Mental Ray renderer embedded in *3DS Max*), and the result is shown in Fig. 8.

5. The pre-rendered virtual site navigator

The main aim of the proposed methodology is to allow the interactive fruition of a rich virtual reconstruction making content creators free to exploit even the most realistic (and

computing expensive) techniques for modelling, animation and rendering, without any constraints in terms of scene complexity. On the other hand, since a pre-rendering based approach limits interactivity, we want to reduce this disadvantage through effective system design and an intuitive interface, using smart techniques enabling on-the-fly assembling of visual content based on user's choice.

The foundation of this proposal is the development of a pre-rendered virtual world in which user can navigate following pre-built paths and performing available actions through a context sensitive motion tracking based interface. The entire virtual world, is a collection of video clips stored on a high performance server, including every scene, eventually viewed from any allowed angle, and every path from one scene to another. In other terms such a virtual world can be visualized as a graph whose nodes represents scenes and whose oriented arches represent available paths that take the user from scene to scene (see Fig. 9).

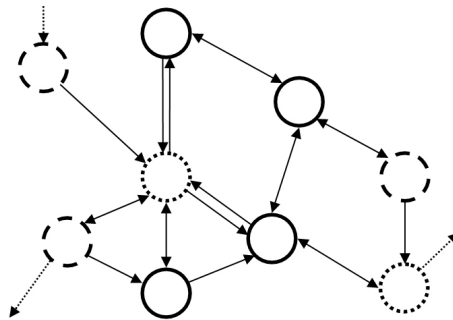


FIGURE 9. Sample graph fragment of a pre-rendered world. Solid nodes, represent scenes in which user's point of view is fixed, dashed nodes represent scenes in which the camera can rotate along one axis, while in scene corresponding to dotted nodes the camera can rotate along two axis (yaw and pitch)

Any node or arch is uniquely identified with a tag pointing to the start frame of the corresponding clip. There can be various types of scene-nodes and various types of path-arches. Every arch coming out from a scene-node equals to an action available to user at that precise point of the virtual experience. Mono-directional arches only allow to move from source node to destination node according to the direction of the arrow, bi-directional arches represent a single clip that can be played in both direction, whereas two parallel mono-directional arches represent that a path is reversible, but only through two different clips.

The heart of this system is the navigation engine, implementing a real time video editing application which, based on the virtual world design and on user's input plays the correct video clip for a given context (Kwatra *et al.* 2003). Thanks to the underlying hardware technology, available clips (previously rendered to be jointed at specific locations in time) are seamlessly played. In this way the navigation and interaction results in a pseudo real-time experience. For instance, since the hardware architecture is able to play a video sequence in both directions, user can smoothly change his viewpoint (on a given axis) simply playing a circular seamless pre-rendered animation if that option is available for

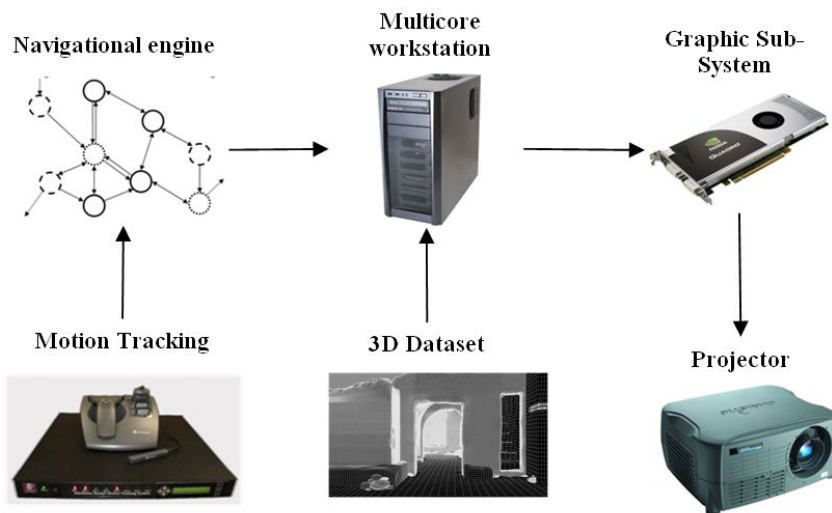


FIGURE 10. Schematic view of the proposed architecture

that particular scene-node. The hardware equipment necessary for this architecture to work effectively is tightly related to the requested image resolution (in this case 1600×1200) and to the number of clips present in the World-Graph (including all layers if any). A schematic representation of the overall system is provided in Fig. 10. Typical system configuration (for an output resolution up to 2K+ pixels) requires a RAID-0 server equipped with an array of SATA3 disks or, even better, one or more Solid State Disk (SSD) that, despite the greater cost, can easily provide a throughput of 600+ Mbytes/sec. A total of 5-10 TBytes of storage space is not unusual and enables to playing up to hours of high-resolution uncompressed content. The navigation software run on the video server as it has a very low computing load since images are stored uncompressed, therefore it does not need special hardware or powerful processors. The graphic subsystem is based on a workstation class graphic board that is not used for polygon processing but for its high pixel fill-rate, driving simultaneously two monitors or projectors in passive stereo, or just one in active stereo through a quad buffered output. User interaction is accomplished through a motion tracking system, which detects the hand and/or head position in 3D space, plus their rotation on three axes for up to 6 degrees of freedom (Papaioannou, Gaitatzes, and Christopoulos 2003).

In our experiments we used the IS 900 ultrasonic based motion tracking hardware from Intersense corp., able to precisely acquire and process motion data coming from each of two wireless devices the user can wear: a head tracker and a tracked joypad (see Fig. 11) both wireless. The joypad features programmable multi button interface and an analog joystick that can be used to trigger specific actions.

The experimental setup included an array of eight ceiling-mounted ultrasonic emitting bars, spaced about sixty centimetres from each other and providing a total sampling volume of approximately $5 \times 3 \times 2.5$ meters. The user is therefore able to freely moving while she/he is fully captured according to the origin of the reference system located at the center of



FIGURE 11. User wearing wireless trackers and stereoscopic goggles during navigation through the reconstructed environment

the floor. Based on various experiments aimed to improving the overall accuracy of the measurements while reducing their drift to a minimum, the sensitivity and the predictability of the IS900 processing station has been set to "medium" and 50ms respectively. Finally, communication speed of the RS422 serial interface has been set to 19200 bit/s, since this low value seemed to facilitating the connection to the host workstation.

In our implementation we also developed an iconic context dependent graphical interface showing either actions or camera options available at a given stage of navigation. These icons appear as an overlay drawn in real time over the video content, and allow the user to visualize not only which option is available (to change the viewpoint, to move forward or backward, to choose a new path, etc.) but even how to select it. In fact the user can select the desired action simply moving the head toward the corresponding icon and confirming the selection via the wireless keypad (a button-icon color based correspondence and an animated confirmation simplify this task). During the fruition of the system, additional info such as text, actual photos or drawings can be visualized onto the rendered scene augmenting it, if requested. It is worth noting that, while for the context of interest of this case study real-time VR approaches (Abate, Acampora, and Ricciardi 2011) could provide a greater level of interaction, in these solutions the visual quality is directly related to rapidly changing specialized hardware, and cost can be prohibitive for large screen productions. Moreover the obsolescence of required hardware and software is much faster resulting in a correspondent obsolescence of the content developed. With the proposed pre-rendered approach instead, content development is decoupled from hardware characteristics (except

for image resolution and clips duration) and can even be integrated later simply adding new clips (new nodes and arches to the world graph).

6. Final Remarks

We presented a case study concerning the virtual reconstruction and fruition of the archaeological site of Moregine and including the reconstruction of the appearance of the woman whose remains have been found there. The contribution of this paper is twofold. Firstly, we presented a face reconstruction framework that integrates craniometrical and physiognomic data to enhance both the ethnical correctness and the appearance of resulting model. The result achieved is a 3D head model that is not just a polygonal surface fitting a set of statistically located landmarks, but an anthropologically compatible reproduction of the plausible appearance of ancient individuals. Additionally a full body (subjective) reconstruction has been also performed to complete the character and to place it in the (virtually reconstructed) original environment.

Secondly, we showcase how pre-rendered VR, in which to navigating through the environment and to interacting with it is achieved by visiting a graph, can be a valid choice compared to real-time VR for particular contexts in which the need for a greater degree of interaction freedom is not prevalent.

From what we have learned by this case-study, we believe that pre-rendered VR can be effectively exploited in many contexts like virtual museums, or virtual reconstruction of historical characters, which not necessarily need the advanced interaction and fast feedback of pure entertainment simulations, but could greatly benefit from unparalleled visual realism. Adaptivity to user's age or interests might represent another advantage offered by the proposed architecture, as the whole graph can be layered to satisfy different preferences. The intrinsic limit of this approach, related to the pre-defined number of actions or viewpoints available in a given moment of the virtual experience, can be considered a well tolerable constraint in many applicative contexts and can be mitigated, adding new clips as, today, storage cost and space is not a bottleneck any more.

Since the facial reconstruction process described in this paper is currently performed off-line according to a supervised manual procedure, we plan to implement a real time reconstruction engine based on *Unity3D* (2015) and providing interactive control over all the craniometrical measurements driving the mesh warping to make the process more straightforward and to allow the experts to visually simulating the effect of changing the weights associated to facial features.

References

- 3DS Max* (2014). *3D modeling, animation, and rendering software*. URL: <http://www.autodesk.com/products/3ds-max/overview> (visited on 11/25/2014).
- Abate, A. F., Acampora, G., and Ricciardi, S. (2011). "An interactive virtual guide for the AR based visit of archaeological sites". *Journal of Visual Languages & Computing* **22**(6), 415–425. DOI: [10.1016/j.jvlc.2011.02.005](https://doi.org/10.1016/j.jvlc.2011.02.005).
- Abate, A. F., Sasso, G., Donadio, A. C., and Sasso, F. S. (2001). "The Riddles of Murecine: The Role of Anthropological Research by Images and Visual Computing". In: *Multimedia Databases and*

- Image Communication*. Ed. by M. Tucci. Vol. 2184. Lecture Notes in Computer Science. Springer Berlin Heidelberg, pp. 33–41. DOI: [10.1007/3-540-44819-5_3](https://doi.org/10.1007/3-540-44819-5_3).
- Allen, P., Feiner, S., Troccoli, A., Benko, H., Ishak, E., and Smith, B. (2004). “Seeing into the past: creating a 3D modeling pipeline for archaeological visualization”. In: *3D Data Processing, Visualization and Transmission, 2004. 3DPVT 2004. Proceedings. 2nd International Symposium on*, pp. 751–758. DOI: [10.1109/TDPVT.2004.1335391](https://doi.org/10.1109/TDPVT.2004.1335391).
- Archer, K. M. (1997). “Craniofacial reconstruction using hierarchical B-spline interpolation”. PhD thesis. University of British Columbia. URL: <http://www.cs.ubc.ca/labs/imager/th/1997/Archer1997/Archer1997.pdf>.
- Cosmas, J., Itegaki, T., Green, D., Grabczewski, E., Weimer, F., Van Gool, L., Zalesny, A., Vanrintel, D., Leberl, F., Grabner, M., *et al.* (2001). “3D MURALE: a multimedia system for archaeology”. In: *Proceedings of the 2001 conference on Virtual reality, archeology, and cultural heritage*. ACM, pp. 297–306. DOI: [10.1145/584993.585048](https://doi.org/10.1145/584993.585048).
- Debevec, P. E., Taylor, C. J., and Malik, J. (1996). “Modeling and rendering architecture from photographs: A hybrid geometry-and image-based approach”. In: *Proceedings of the 23rd annual conference on Computer graphics and interactive techniques*. ACM, pp. 11–20. DOI: [10.1145/237170.237191](https://doi.org/10.1145/237170.237191).
- DeCarlo, D., Metaxas, D., and Stone, M. (1998). “An Anthropometric Face Model Using Variational Techniques”. In: *Proceedings of the 25th Annual Conference on Computer Graphics and Interactive Techniques*. SIGGRAPH '98. New York, NY, USA: ACM, pp. 67–74. DOI: [10.1145/280814.280823](https://doi.org/10.1145/280814.280823).
- Faloutsos, C., Barber, R., Flickner, M., Hafner, J., Niblack, W., Petkovic, D., and Equitz, W. (1994). “Efficient and effective Querying by Image Content”. *Journal of Intelligent Information Systems* **3**(3-4), 231–262. DOI: [10.1007/BF00962238](https://doi.org/10.1007/BF00962238).
- George, R. M. (1987). “The lateral craniographic method of facial reconstruction”. *Journal of Forensic Sciences* **32**(5), 1305–30. DOI: [10.1520/JFS11181J](https://doi.org/10.1520/JFS11181J).
- Gudivada, V. N. and Raghavan, V. V. (1995). “Content-Based Image Retrieval Systems”. *Computer* **28**(9), 18–22. DOI: [10.1109/2.410145](https://doi.org/10.1109/2.410145).
- Hartley, R. and Zisserman, A. (2003). *Multiple view geometry in computer vision*. 2nd ed. Cambridge, UK: Cambridge University Press. URL: <https://cseweb.ucsd.edu/classes/sp13/cse252B-a/HZ2eCh2.pdf>.
- Ioannides, M. and Wehr, A. (2002). “3D-reconstruction & re-production in archaeology”. In: *Proceedings of the CIPA–ISPRS International Workshop on Scanning for Cultural Heritage Recording*, pp. 1–6. URL: http://www.nav.uni-stuttgart.de/navigation/publikationen/fachartikel/2002/wehr_korfu.pdf.
- Kähler, K., Haber, J., and Seidel, H.-P. (2003). “Reanimating the dead: reconstruction of expressive faces from skull data”. *ACM Transactions on Graphics* **22**(3), 554–561. DOI: [10.1145/882262.882307](https://doi.org/10.1145/882262.882307).
- Kwatra, V., Schödl, A., Essa, I., Turk, G., and Bobick, A. (2003). “Graphcut textures: image and video synthesis using graph cuts”. *ACM Transactions on Graphics* **22**(3), 277–286. DOI: [10.1145/882262.882264](https://doi.org/10.1145/882262.882264).
- Marbs, A. (2002). “Experiences with laser scanning at i3mainz”. In: *Proceedings of the CIPA WG 6 International Workshop on Scanning for Cultural Heritage Recording*, pp. 1–6. URL: https://143.93.114.105/sites/default/files/public/data/p20_Marbs.pdf.
- Mastroroberto, M. (2004). “Un caseggiato del quartiere sul Sarno (Edificio B)”. In: *Storie da un'eruzione. Pompei, Ercolano, Oplontis*. Ed. by P. G. Guzzo, M. Mastroroberto, and A. D'Ambrosio. Mondadori Electa, pp. 464–472. URL: http://www.electaweb.it/catalogo/scheda/978883703217/it?language=en_EN#.

- Moccozet, L. and Thalmann, N. M. (1997). "Dirichlet free-form deformations and their application to hand simulation". In: *Computer Animation '97*, pp. 93–102. DOI: [10.1109/CA.1997.601047](https://doi.org/10.1109/CA.1997.601047).
- Moss, J. P., Grindrod, S. R., Linney, A. D., Arridge, S. R., and James, D. (1988). "A computer system for the interactive planning and prediction of maxillofacial surgery". *American Journal of Orthodontics and Dentofacial Orthopedics* **94**(6), 469–475. DOI: [10.1016/0889-5406\(88\)90004-2](https://doi.org/10.1016/0889-5406(88)90004-2).
- Moss, J. P., Linney, A. D., Grindrod, S. R., Arridge, S. R., and Clifton, J. S. (1987). "Three-dimensional visualization of the face and skull using computerized tomography and laser scanning techniques". *The European Journal of Orthodontics* **9**(1), 247–253. DOI: [10.1093/ejo/9.1.247](https://doi.org/10.1093/ejo/9.1.247).
- Nappo, S. C. (2012). "L'edificio di Murecine a Pompei: un esempio di architettura ricettiva alla foce del Sarno". *Rivista di Studi Pompeiani* **23**, 89–102. URL: <http://www.lerma.it/index.php?pg=SchedaTitolo&key=00012860>.
- Nicolucci, G. (1882). "Crania Pompeiana ovvero descrizione dei crani umani rinvenuti nelle ruine dell'antica Pompei". In: *Atti della Reale Accademia delle Scienze Fisiche e Matematiche*. Vol. IX. URL: http://pompei.sns.it/prado_front_end/index.php?page=Home&id=3136.
- Papaioannou, G., Gaitatzes, A., and Christopoulos, D. (2003). "Enhancing Virtual Reality Walk-throughs of Archaeological Sites". In: *The 4th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage*. Ed. by D. Arnold, A. Chalmers, and F. Niccolucci. The Eurographics Association. DOI: [10.2312/VAST/VAST03/175-184](https://doi.org/10.2312/VAST/VAST03/175-184).
- Pollefeys, M., Van Gool, L., Vergauwen, M., Verbiest, F., Cornelis, K., Tops, J., and Koch, R. (2004). "Visual Modeling with a Hand-Held Camera". *International Journal of Computer Vision* **59**(3), 207–232. DOI: [10.1023/B:VISI.0000025798.50602.3a](https://doi.org/10.1023/B:VISI.0000025798.50602.3a).
- Quatrehomme, G., Cotin, S., Subsol, G., Delingette, H., Garidel, Y., Grévin, G., Fidrich, M., Baillet, P., and Ollier, A. (1997). "A fully three-dimensional method for facial reconstruction based on deformable models". *Journal of Forensic Sciences* **42**(4), 649–652. URL: <https://hal.inria.fr/inria-00615074>.
- Remondino, F., El-Hakim, S., Girardi, S., Rizzi, A., Benedetti, S., and Gonzo, L. (2009). "3D Virtual Reconstruction and Visualization of Complex Architectures-The" 3D-ARCH" Project". In: *Proceedings of the ISPRS Working Group V/4 Workshop 3D-ARCH" Virtual Reconstruction and Visualization of Complex Architectures"*, 2009. URL: <http://nparc.cisti-icist.nrc-cnrc.gc.ca/npsi/ctrl?action=rtdoc&an=15188886>.
- Rhine, J. S., Moore, C. E., and Weston, J. T. (1982). *Facial Reproduction: Tables of Facial Tissue Thicknesses of American Caucasoids in Forensic Anthropology*. Maxwell Museum of Anthropology, The University of New Mexico.
- Sawhney, H. S., Guo, Y., Hanna, K., Kumar, R., Adkins, S., and Zhou, S. (2001). "Hybrid Stereo Camera: An IBR Approach for Synthesis of Very High Resolution Stereoscopic Image Sequences". In: *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques*. SIGGRAPH '01. New York, NY, USA: ACM, pp. 451–460. DOI: [10.1145/383259.383312](https://doi.org/10.1145/383259.383312).
- Shahrom, A. W., Vanezis, P., Chapman, R. C., Gonzales, A., Blenkinsop, C., and Rossi, M. L. (1996). "Techniques in facial identification: Computer-aided facial reconstruction using a laser scanner and video superimposition". *International Journal of Legal Medicine* **108**(4), 194–200. DOI: [10.1007/BF01369791](https://doi.org/10.1007/BF01369791).
- Stefani, G. and Di Maio, G. (2003). "Considerazioni sulla linea di costa del 79 d.C. e sul porto dell'antica Pompei". *Rivista di studi Pompeiani* **14**(14), 141–195. URL: <http://www.lerma.it/index.php?pg=SchedaTitolo&key=00011004>.
- Tyrrell, A. J., Evison, M. P., Chamberlain, A. T., and Green, M. A. (1997). "Forensic three-dimensional facial reconstruction: historical review and contemporary developments". *Journal of Forensic Sciences* **42**(4), 653–661. URL: <http://europepmc.org/abstract/MED/9243827>.

- Ulgen, F. (1997). "A step towards universal facial animation via volume morphing". In: *Robot and Human Communication, 1997. RO-MAN '97. Proceedings., 6th IEEE International Workshop on*, pp. 358–363. DOI: [10.1109/ROMAN.1997.647012](https://doi.org/10.1109/ROMAN.1997.647012).
- Unity3D (2015). *Create and connect with Unity 5*. URL: <http://www.unity3d.com/> (visited on 10/08/2015).
- Vanezis, P., Vanezis, M., McCombe, G., and Niblett, T. (2000). "Facial reconstruction using 3-D computer graphics". *Forensic Science International* **108**(2), 81–95. DOI: [10.1016/S0379-0738\(99\)00026-2](https://doi.org/10.1016/S0379-0738(99)00026-2).
- Vergauwen, M. and Van Gool, L. (2006). "Web-based 3D Reconstruction Service". *Machine Vision and Applications* **17**(6), 411–426. DOI: [10.1007/s00138-006-0027-1](https://doi.org/10.1007/s00138-006-0027-1).
- Wilkinson, C. (2010). "Facial reconstruction – anatomical art or artistic anatomy?" *Journal of Anatomy* **216**(2), 235–250. DOI: [10.1111/j.1469-7580.2009.01182.x](https://doi.org/10.1111/j.1469-7580.2009.01182.x).
- ZBrush (2014). *An Introduction to ZBrush with Kurt Papstein*. URL: <http://www.pixologic.com/zbrush/> (visited on 10/22/2014).

^a Università degli Studi di Salerno
Dipartimento di Informatica
Via Giovanni Paolo II, 84084 Fisciano (SA), Italy

* To whom correspondence should be addressed | Email: abate@unisa.it

Communicated 30 May 2013; manuscript received 10 May 2014; published online 28 January 2016



© 2016 by the author(s); licensee *Accademia Peloritana dei Pericolanti* (Messina, Italy). This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/) (<https://creativecommons.org/licenses/by/4.0/>).