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3D Face Reconstruction from Skull Aimed to Archaeological Applications. The Site of Murecine: a Case Study

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Abstract

This paper presents a methodology to generate a 3D face model from its skull that is specifically aimed to archaeological/anthropological applications.

The proposed approach to facial reconstruction, starting from the well established "landmark based reconstruction technique", relies on craniometrical analysis and content based image retrieval technology to achieve a more ethnically faithful reproduction of main facial features respect to other methods based uniquely on very large scale statistical data. It also tries to address the problem of a plausible reproduction of important physiognomic features (such as eyes, nose, lips, ears and hairs) which simply can't be inferred from the skull. The facial reconstruction of a female subject found in the archaeological site of Murecine (Pompei) who found death during the volcanic eruption in 79 a. C. is presented as a case study.

Categories and Subject Descriptors (according to ACM CCS): J.2 [Computer Applications]: Archaeology

1. Introduction

Computer graphics and virtual reality have been often used in archaeology to visualize the original aspect of sites, buildings and objects found in excavations. This allows a better understanding and a broader dissemination of culture and lifestyle of ancient people like the Greeks, the Romans or the Egyptians, just to name a few.

As the modelling and rendering of human face has been dramatically improved [M*00] [D*00] [WT91], even anthropologists can benefit from 3D computer generated imaging, for example virtually reconstructing a face from its skull. But, though this technology can easily produce realistically looking images, the approach to the reconstruction is often artistic, mainly based on the anatomical knowledge of the modeller.

Unfortunately, there is no way to exactly reproduce a face simply from its skull because the relationship between the soft tissues (skin, fat, muscles) and the hard tissues (cranial bones) is not biunivocal. So, even if it is true that every skull affects the overall facial physiognomy, there are many ways in which soft tissues may cover the same skull leading to different final appearance.

This study presents a face reconstruction methodology optimized for archaeological/anthropological applications applied to one of the skulls found in the archaeological site of Murecine (in the Pompei surroundings). This site, originally discovered about fifty years ago, is known for the presence of an exceptionally well preserved roman villa including many bones belonged to a group of people who found death during the volcanic eruption of 79 a. C.

The idea behind the proposed method 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 [N82]. 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.

Therefore it is reasonable to develop a methodology to correlate ancient skull features to skull features of modern native Pompeians for facial reconstruction purposes.

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 thousands years ago.

This paper is organized as follows. In section 2 related works are presented. In section 3 the proposed methodology is presented in detail and applied to the case study. In section 4 the results of the proposed methodology are discussed and compared to other techniques. The paper concludes in section 5.

2. Related works

Several facial reconstruction methodologies have been developed over more than a century [TEC*97]. 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 [RM84] , has led to the development of more believable methods.

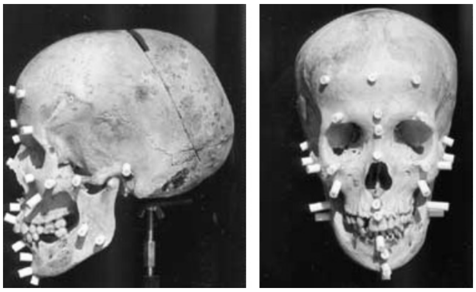

Figure 1: *A skull with thickness landmarks applied*

The measurement protocol, implemented for these surveys, consider a specific set of points located on the face surface to measure their 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* [G93] and *photo overlay* [SVC*96] can be useful to check identity of cadaver remains (see Figure 1), while the more recent computer based methods typically starts from computer tomography data to obtain a 3D digital model of the skull [V*00] [MLG*87] 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 [A97] [U97], 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 [MLG*88] [QCS*97] [KHS03], mainly aimed to forensic and surgical applications, though the basic warping method is flexible enough to be applied in other interesting applications as well [DMS98].

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. The proposed methodology

The proposed methodology can be briefly resumed 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 which is further improved by a landmark based warping. The resulting model is then enhanced integrating additional facial details selected from a pictorial database, and finally a photorealistic rendering is performed. The whole process is described in detail in the following subsections 3.1 to 3.4..

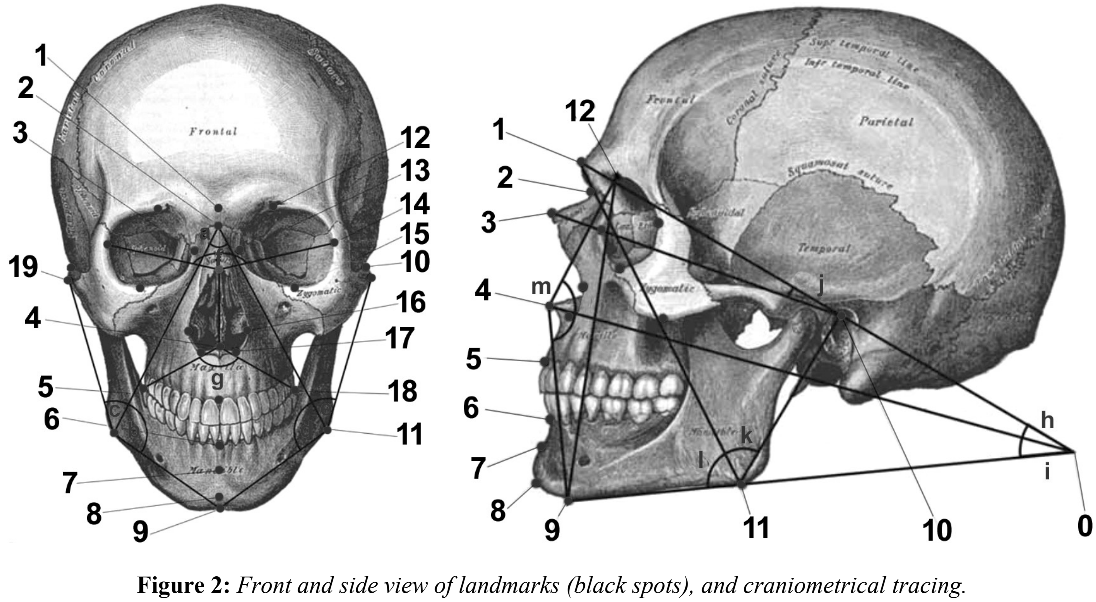

Figure 2: *Front and side view of landmarks (black spots), and craniometrical tracing.*

Landmark #	***Location (front view)***	***Landmark #***	***Location (side view)***
1	Glabellas	11	Onion
2	Nation	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 1. *List of landmarks referenced in Figure 2*

Features #	***Angles***	***Distance***	***Features #***	***Angles***	***Distance***
1	a		17	h	
2		2 -11sx	18		0-1
3		2-11dx	19		0-4
4	b+c		20	i	
5		11sx-19sx	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			

Table 2. *List of Features relative to landmarks and angles referenced in Figure 2.*

3.1. Skull acquisition and features extraction

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.

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 Figure 2. This set of landmarks is related to the aforementioned study by Rhine and Moore [RM84] about spatial 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 L_i used with 1<=i<=19 is shown in Table 1 while their anatomic location is shown in Figure 2. 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 [G87].

This set of measures, peculiar to this particular skull, allows to define the n-tuple of features $(F_1^*, F_2^*, ..., F_n^*)$.

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 different physiognomic relevance to the overall face aspect, we could assign to each one a different weight.

The resulting n-tuples, $(w_1, w_2, ..., w_n)$ with $0 \leq w_j \leq 1$ *and,* $1 \leq j \leq n$ contains the weights relative to $(F_1^*, F_2^*, ..., F_n^*)$, and if $F_j = 0$ then $w_j = 0$.

3.2. The Craniometrical Database

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 Figure 3) 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.

Figure 3. *Samples of radiological images used to built the CD.*

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 (Lx_i, Ly_i, Lz_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:

$$CSS = \frac{w_1\left(1-\frac{|(F_{i1}-F_1^*)|}{D_1}\right)+w_2\left(1-\frac{|(F_{i2}-F_2^*)|}{D_2}\right)+\cdots\cdots+w_n\left(1-\frac{|(F_{in}-F_n^*)|}{D_n}\right)}{\sum_1^n w_j} \quad (1)$$

In (1) F_{ij} is the *j* component of the n-tuple of features $(F_{i1}, F_{i2}, \ldots\ldots, F_{in})$, relative to record i, w_j represent its weight and D_j is the *j* component of an array $(D_1, D_2, \ldots\ldots, D_n)$ 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 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.

3.3. Face reconstruction

The most accurate way to generate the 3d model of the selected head would be probably to acquire it by a laser or structured light scanner during the radiological survey, and to associate it to a record in the *CD*.

Unfortunately this approach was not possible when the survey was conducted and the only data useful for 3D reconstruction were a couple of front and side pictures of each subject.

There are many works in CG which address the problem of generating a 3D model of a face from two or more pictures [BV99], so we adopted an efficient mesh generation method based on feature points detection on head pictures [LM00] that, though not accurate like a 3D scan, has produced interesting results from the available material. This technique also generates a facial texture from the two pictures and automatically map it onto mesh geometry.

We do not include hair shape in the mesh generation process at this time, because this feature will be addressed in a more realistic way later. The resulting mesh is shown in Figure 4.

We refine the previous "rough" reconstruction of the best match record through a landmark based mesh deformation.

In fact, except for the case in which *CSS*=1 (an almost impossible case), there will be one or more landmarks for which the 3D coordinates (Lx_i, Ly_i, Lz_i) differs from the

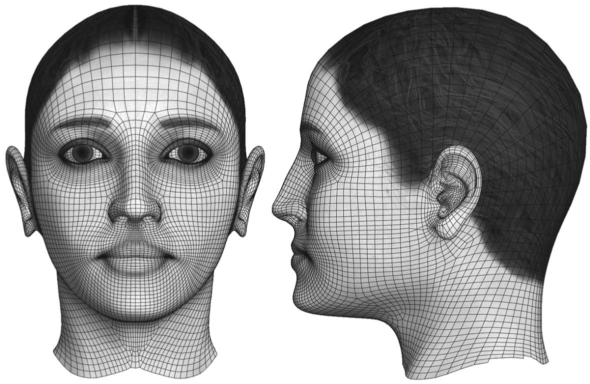

Figure 4. Rough f*ace reconstruction.*

coordinates of L_i^* (the corresponding landmark on the skull). Therefore we apply a Dirichlet Free Form [MM97] deformation (DFFD) to the rough mesh in which the control points correspond to the landmarks L_i, so that displacing the control points (to L_i^*) the surface is deformed accordingly .

3.4. Augmenting the reconstruction through the Physiognomic Database

The 3D model generated so far replicates the head of a living individual with craniometrical and anthropological features similar to the found skull.

We want now to complete this tridimensional identikit adding physiognomic details such as eye/hair colour, haircut, facial hair, 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 classical arts. This database is based on the work by [ASD*01] and on Content Based Image Retrieval [GRR95] technology to access and retrieve visual information. Through a query by pictorial example (the previously reconstructed face), we can retrieve images of ancient faces [FEF*94] with a compatible physiognomy (see Figure 5).

The result of a search through *PPD*, is a set of physiognomic elements which guide the last refinement of the reconstruction. We used a commercial spline based hair system to achieve realistically rendered hair and facial hair, so an additional field pointing to a corresponding hair system preset is associated to every image in *PPD*.

At the moment, the adaptation of the selected hair system to the specific topology of the reconstructed head is performed interactively, though an automatic placement of hair strands based on image analysis is an interesting subject we are currently working on. The color of eye/hair is retained from the texture produced in section 3.4.

Finally a photorealistic rendering of the reconstructed head is performed using a global illumination algorithm, as shown in Figure 6.

4. Discussion

The presented methodology, while shares some of the techniques currently used in reconstructive methods listed in section 2, aims to optimize the results for archaeological and anthropological applications. In fact, though the deformation (warping) of a reference face mesh is common to other presented works, the proposed approach differs substantially from the other ones in many aspects, as detailed below.

It is based on the anthropological hypothesis that individuals with similar physiognomic and craniometrical features can still be present in the same area in which the remaining were found.

It selects a reference candidate through a search for craniometrical similarities in the *CD* and not just a neutral male or female mesh.

The face mesh could be obtained by actual (photo, CT or 3D scan) data of the selected (living) reference candidate, and not by average soft tissue depths coming from statistics.

The warping is applied to the face mesh only to improve the reconstruction, instead of using it as the main tool to conform a generic facial mesh to the found skull.

It uses *PPD* data to refine the reconstruction adding compatible physiognomic elements (hair/eye colour, haircut, etc.).

These peculiarities lead to a precise applicative range for the proposed methodology, with advantages and limits respect to other methods presented.

It works best on a complete skull, but even in the case of missing mandible it can still produce interesting results, using the remaining craniometrical measurements to search a similar subject in the *CD*, thus replacing lost information with compatible data.

Most landmark based methods, depending on soft tissues statistics to reconstruct the facial surface, inherit the physiognomic features typical to the basic races (Caucasian, Afro, Asian, etc.) considered in the statistic itself. So even if the result is feasible in terms of human likeness it could be too generic to accurately reproduce the aspect of specific ethnic groups. On the other side, the use of the *CD* and the *PPD* could be a limit to the application of this technique or to the reliability of its results, if an appropriate radiological/photographic survey on a population anthropologically similar to the subject to be reconstructed could not be available.

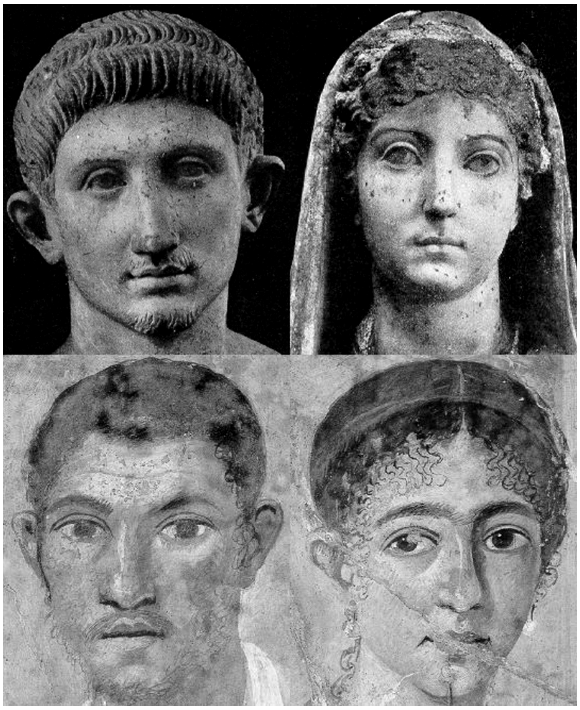

Figure 5. *Samples of PPD records.*

Figure 6: *Final rendering of reconstructed face from the presented case study*

5. Conclusions

We presented a face reconstruction framework that integrates craniometrical and physiognomic data to enhance both the ethnical correctness and the appearance of resulting model.

Our aim is to gather different kind of data to produce a 3D head model that is not just a polygonal surface fitting a set of statistically located landmarks, but an anthropologically compatible and visually detailed reproduction of the plausible appearance of ancient individuals. The standard warping approach to face reconstruction has been improved selecting the reference mesh by a craniometrical similarity criterion.

The proposed methodology produced interesting results on the case study, a female skull found in the Pompei surroundings, and proved to be promising when applied to an archaeological context.

Its strength and weakness come from the use of two specifically built databases (CD and PPD) which, while enhancing the reconstruction, could limit the application of the methodology to other fields.

As the range of ages covered by the local radiological survey conducted includes kids and adolescents we are in the process to apply this method to some ancient skull of Pompeian children, a challenging task often not addressed by classic methods.

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