Eurographics Italian Chapter Conference (2006)
G. Gallo and S. Battiato and F. Stanco (Editors)

From Skull to Face: an Improved Framework for Ethnically Faithful 3D Face Reconstruction

A.F. Abate, M. Nappi, S. Ricciardi, G. Sabatino

Dipartimento di Matematica ed Informatica, Università di Salerno, Italy

Abstract

3D imagery can be a useful tool for archaeologists and anthropologists committed to the study of ancient people, helping them to better visualize the results of their theories and findings. This paper presents a methodology to generate a tridimensional model of a compatible face from its skull, and is specifically aimed to archaeological/anthropological applications. The proposed approach to facial reconstruction, that relies on craniometrical analysis and content based image retrieval technology, has two main purposes: to achieve a more ethnically faithful reproduction of main facial features respect to other techniques based on statistical data, and to allow a plausible reproduction of important physiognomic features (such as eyes, nose, lips, ears and hairs) which 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 organic shapes has been dramatically improved [WT91], even anthropologists can benefit from 3D computer generated imaging, for example virtually reconstructing a face from its skull (Figure 1). But, though this technology can easily produce realistically looking images, the approach to the reconstruction is often an artistic one, mainly based on the anatomical knowledge of the modeller.

In fact, 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. It combines a craniometrical data driven reproduction of main facial features [G87]with an enhanced Context Based Image Retrieval (CBIR) search engine to integrate the first level of reconstruction with additional facial features (eye colour, hair, facial hair). These features, although aleatory, have fundamental relevance from a physiognomic point of view and are currently not enough addressed from non-artistic reconstructive methods such as those developed for forensic and facial surgery. The proposed methodology represent an improvement over a previously presented technique [ANRT03], now addressing female and even child face reconstruction, integrating genetic information coming from ancient DNA analysis of bone tissue and producing a more realistic rendering of facial details .

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.

Figure 1: S*kull partially overlaid on a face reconstructed by CG approach applied to radiological data*

2. Related works

Several facial reconstruction methodologies have been developed over more than a century [TECG97]. 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 reliable methods. 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.

While the simplest reconstructive techniques like *landmark based drawing* [G93] *photo overlay* [SVC*96] and can be useful to check identity of cadaver remains but are highly subjective, the more recent computer based methods typically starts from computer tomography data to obtain a 3D digital model of the skull [MLG*87] and then reproduce the skin surface using the aforementioned thickness statistics (see Figure 1). To the last category belong the so called *warping reconstructive techniques* which operate on a reference face mesh [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], mainly aimed to forensic and surgical applications, tough the warping method is flexible enough to be applied in other fields as well. On the other side the selection of a reference head mesh could be critical for the reliability of the reconstruction in all those facial regions not covered by the (usually small) set of soft tissue depth measurements. A method to overcome this limit is based on comparing 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 and the case study

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. and it has been tested on 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 several skulls belonged to a group of people who found death during the volcanic eruption of 79 a. C. While one of the male skulls has already been object of a face reconstruction research project, the most challenging remains are probably those belonging to a young woman and to kids. In fact most facial reconstruction techniques, hardly work on young subject, due to the limited range of ages considered for the soft tissue thickness statistics. The female skull present a new challenge because molecular biologists have found amplifiable traces of ancient DNA (aDNA) which could provide precious additional information. In fact, human remains from this site (and from Pompei as well) have an exceptional value as they represent a sample of human population randomly selected (due to the catastrophic events which suddenly caused its death) dated with absolute precision (the volcanic eruption). This unique characteristic allows to compare particular sequences of aDNA to corresponding sequences of DNA from modern population, hopefully providing information about ethnic composition in that region and about physiognomic similarities as well. While the methodology proposed below has been developed to address both teen/child facial reconstruction and facial feature integration by aDNA info, the focus of this case study is exclusively on the female subject.

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, chosen for their craniometrical relevance, each one with a unique name and number as in Figure 2. A complete list of the landmarks L_i used with $1 \le i \le 19$ is showed in Table 1 while their anatomic location is showed in Figure 2.

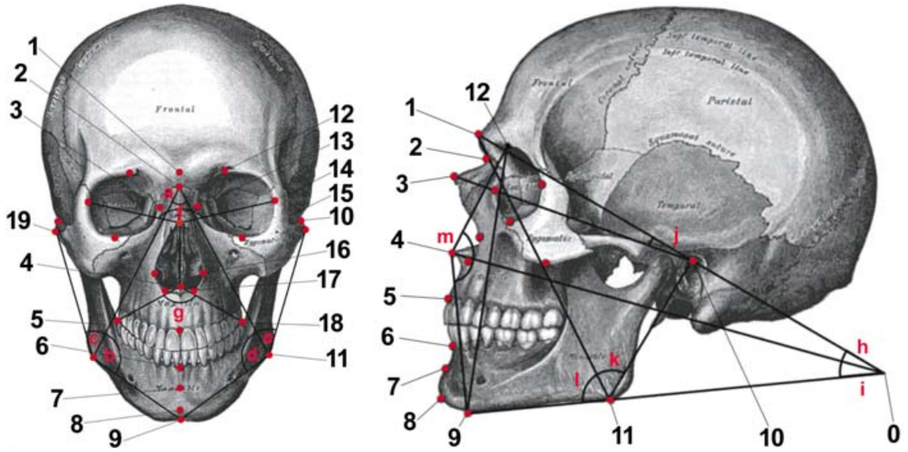

Figure 2: *Front and side view of landmarks (red spots), and craniometrical tracing.*

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.*

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. 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. Because each feature has a different relevance from a physiognomic and craniometrical point of view, each one has a different weight. The resulting n-tuples, $(w_1, w_2, \ldots, w_n)$ 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 on thousands of subjects of different ages and sex but all native to the same geographic area in which the remains were found: Pompei and its surroundings. It now includes even child craniometrical data to allow teen/child face reconstruction. The *CD* is indexed by key data such us gender and age to speed up the research.

Figure 3: *Samples of radiological images from CD.*

Each individual represent a record in the database, and each craniometrical feature, extracted with the same procedure showed 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:

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

In (1) F_{ij} is the j component of the n-tuple of features $(F_{i1}, F_{i2}, \ldots, F_{in})$, relative to record i, w_j represent its weight and D_j is the j component of an array $(D_1, D_2, \ldots, D_n)$ containing the max allowed difference between F_{ij} and F^*_j for each j. 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. Ideally *ST*, which is in the range [0, 1], should be no less than 80% for optimal results.

3.3. Face reconstruction

The most accurate way to generate a 3d model of the selected head would be to associate a 3D face laser scan to each record in *CD*, but this could not be an available option. A much simpler, though not as much accurate alternative is to use an efficient mesh generation method based on feature points detection on head pictures [LM00].

It requires two images shot from front and side view (the two image fields of each record in *CD*). 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 showed in Figure 4. We refine the previous "rough" reconstruction of the best match record through a landmark based mesh deformation.

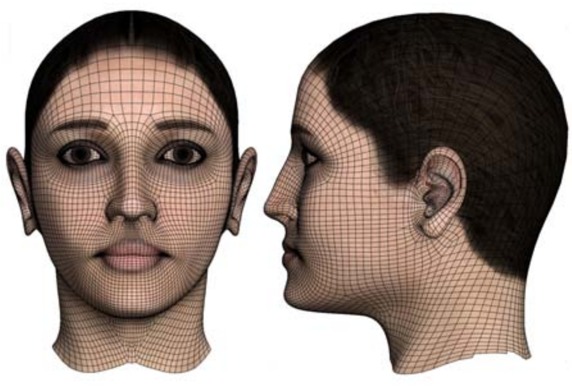

Figure 4: *Rough face reconstruction*

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 $(L_{x_i}, L_{y_i}, L_{z_i})$ differs from the coordinates of L^*_j (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^*_j) the surface is deformed accordingly.

3.4. Augmenting the reconstruction through the Physiognomic Database

The 3D model generated so far is a bald head that come from 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 [ASDS01] and it is based on Content Based Image Retrieval [GR95] 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. At this point, genetic information from aDNA (if available) can be used to filter the search process, leading to a more congruent output. The result of a search through *PPD*, is a set of physiognomic elements which guide the last refinement of the reconstruction. We used a 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 manually, tough an automatic placement of hair strands based on image analysis is a subject we would like to investigate.

The colour of eye/hair is matched to genetic info where present, otherwise is retained from the texture produced in section 3.3. Finally a photorealistic rendering of the reconstructed head is performed using a global illumination algorithm, as showed in Figure 5.

4. Discussion

The presented methodology, while shares some of the techniques currently used in reconstructive methods listed in section 2, aims to maximize the results in archaeological and anthropological applications.

In fact, though the deformation (warping) of a reference face mesh is common to other presented methodologies, the proposed approach differs substantially from the other ones in many fundamental aspects.

Figure 5: *Final rendering of reconstructed face from the presented case study*

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 was 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 is 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.) often not addressed from other methods. These peculiarities lead to a precise applicative range for the proposed metodology, 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. Recently added child craniometrical data allows face reconstruction of young subjects, while soft tissue thickness statistic does not address this point. Most computer based reconstructive techniques do not reproduce facial details or adopt an artistic approach to address this problem. They mainly focus on those areas of the face for which a soft tissue thickness statistic is available [KHS03]. Outside this area the model surface is the same of the reference neutral mesh that, although chosen according to basic races (Caucasian, Afro, Asian, etc.), sex and build (fat, normal or thin) is often too generic to accurately reproduce the aspect of specific ethnic groups. On the other side, the use of *CD* and *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. We summarize the key points of various face reconstruction methodologies as follows: *Quick/Simple*, referring to a method that quickly leads to a result with simple or no technology; *3D Output*, referring to a method capable to generate a three dimensional reconstruction of the face; *Missing mandible*, referring to a method capable to work and to produce acceptable results even in the case of absence of the mandible; *aDNA Info*, referring to a method able to use genetic information coming from bone tissue analysis to refine the reconstruction; *Forensic applications*, referring to a method suitable for forensic purposes, such as reconstruction of identity from cadaver remains; *Archaeological applications*, referring to a method that leads to valid results for archaeological and anthropological studies; *Teen/child reconstructions*, referring to a method suitable for teen/child reconstruction. Table 3 shows a comparison between the presented method and main skull to face reconstruction methodologies.

5. Conclusions

We presented a face reconstruction framework that combines craniometrical data, physiognomic data and ancient DNA info to enhance both the fidelity 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 performed well on the case study, a female skull found in the Pompei surroundings, and showed significant advantages over other methods 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 this methodology to other fields.

	Landmark Based Drawing [G93]	Photo Overlay [SVC*96]	3D Reconstr. [VBL*89]	3D Warping [KHS03]	***Proposed Method***
Quick / Simple	*	*			
3D Output			*	*	*
Missing Mandible	*	*			*
aDNA Info					*
Forensic Applicat.		*	*	*	
Archaeol. Recon.			*	*	*
Teen/child Recon..				*	*

Table 3. *Summary of main facial reconstruction methodologies.*

6. References

[ANRT03] Abate A. F., Nappi M., Ricciardi S., Tortora G.: An Integrated Approach to 3D Facial Reconstruction from Ancient Skulls, In *Proc. of the First International Workshop on E-Learning, understanding, Information Retrieval and Medical*, Cagliari, (June 2003), World Scientific Publishing Co., vol. 15, pp. 46-59.

[ASDS01] Abate A. F., Sasso G., Donadio A. C., Sasso F.: The riddles of murecine: the role of anthropological research by images and visual computing, In *Proc. of MDIC 2001*, LNCS 2184, Springer-Verlag, (2001) , pp. 33-41.

[FEF*94] Faloutsos C., Equitz W., Flickner M., Niblack W., Petkovic D., Barber R.: Efficient and effective querying by image content, *Journal of Intell. Inf. Systems 3* (3/4) (1994), pp. 231-262.

[G93] George R.M.: Anatomical and artistic guidelines for forensic facial reconstruction, *Forensic Analysis of the Skull*, M.H. Iscan, R.P. Helmer (Eds.), Wiley-Liss, New York, (1993), pp. 215–227.

[G87] George R.M.: The lateral craniographic method of facial reconstruction, *J. Forensic Sci. 32* (1987), pp. 1305–1330.

[GF98] Gonzalez, Figueroa, An Evaluation of the Optical Laser Scanning System for Facial Reconstruction, *Ph.D. thesis*, University of Glasgow, (1998).

[GR95] Gudivada, V. N., Raghavan V. V.: Finding the Right Image, *Content-Based Image Retrieval Systems, Computer*, (Sept. 1995), IEEE Computer Society, pp. 18-62.

[KHS03] Kalher K., Haber J., Seidel H. P.: Reanimating the Dead, in *ACM Transactions on Graphics Volume 22* , ACM Press, Issue 3 (July 2003) , pp. 554-561

[LM00] Won-Sook Lee, Magnenat-Thalmann N.: Fast Head Modeling for Animation, in *Journal Image and Vision Computing*, (March, 2000), Elsevier, Volume 18, Number 4, pp. 355-364.

[MLG*88] Moss J.P., Linney A.D., Grinrod S.R., Arridge S.R., James D.: A computer system for the interactive planning and prediction of maxillo-facial surgery, *Am. J. Orthodont. Dental-facial Orthopaed.* 94 (1988), pp. 469–474.

[MLG*87] Moss J.P., Linney A.D., Grinrod S.R., Arridge S.R., Clifton J.S.: Three dimensional visualization of the face and skull using computerized tomography and laser scanning techniques, *Eur. J. Orthodont. 9* (1987), pp. 247–253.

[MM97] Moccozet L., Magnenat-Thalmann N.: "Dirichlet Free-Form Deformations and their Application to Hand Simulation", In *Proc. Computer Animation'97*, (1997), IEEE Computer Society, pp. 93-102.

[QCS*97] Quatrehomme G., Cotin S., Subsol G., Delingette H., Garidel Y., Grevin G., Fidrich M., Bailet P., Ollier A.: A fully three-dimensional method for facial reconstruction based on deformable models, *J. Forensic Sci. 42* (1997), pp. 649–652.

[RM84] Rhine J.S., Moore C.E.: Facial reproduction tables of facial tissue thickness of American caucasoids in forensic anthropology, *Maxwell Museum Technical Series 1*, Maxwell Museum, Albuquerque, New Mexico, (1984).

[SVC*96] Sharom A.W., Vanezis P., Chapman R.C., Gonzales A., Blenkinsop C., Rossi M.L., Techniques in facial identification: computer-aided facial reconstruction using a laser scanner and video superimposition, *Int.J. Legal Med. 108* (1996), pp. 194–200.

[TECG97] A.J. Tyrell, M.P. Evison, A.T. Chamberlain, M.A. Green.: Forensic three-dimensional facial reconstruction: historical review and contemporary developments, *J. Forensic Sci. 42* (1997), pp. 653–661.

[U97] Ulgen F.: "A Step Toward Universal Facial Animation via Volume Morphing". In 6th IEEE *Int'l Workshop on Robot and Human Communication*, 1997, pp. 358-363.

[VBL*89] Vanezis P., Blowes R.W., Linney A.D., Tan A.C., Richards R., Neave R.: Application of 3-D computer graphics for facial reconstruction and comparison with sculpting techniques, *Forensic Sci. Int. 42* (1989), pp. 69–84.

[WT91] Waters K., Terzopoulos D.: Modelling and animating faces using scanned data, *Journal of Visualization and Computer Animation*, (1991),Vol. 2, No. 4, pp.123-128.