Forensic Identification by Computer-Aided Craniofacial Superimposition: A Survey

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Craniofacial superimposition is a forensic process in which a photograph of a missing person is compared with a skull found to determine its identity. After one century of development, craniofacial superimposition has become an interdisciplinary research field where computer sciences have acquired a key role as a complement of forensic sciences. Moreover, the availability of new digital equipment (such as computers and 3D scanners) has resulted in a significant advance in the applicability of this forensic identification technique. The purpose of this contribution is twofold. On the one hand, we aim to clearly define the different stages involved in the computer-aided craniofacial superimposition process. Besides, we aim to clarify the role played by computers in the methods considered.

In order to accomplish these objectives, an up-to-date review of the recent works is presented along with a discussion of advantages and drawbacks of the existing approaches, with an emphasis on the automatic ones. Future case studies will be easily categorized by identifying which stage is tackled and which kind of computer-aided approach is chosen to face the identification problem. Remaining challenges are indicated and some directions for future research are given.

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1. INTRODUCTION

One of the main goals of forensic anthropology [Burns 2007] is to determine the identity of a person from the study of some skeletal remains. In the last few decades, anthropologists have focused their attention on improving those techniques that allow a more accurate identification.

Before making a decision on the identification, anthropologists follow different processes to assign sex, age, human group, and height to the human remains from the study of bones found. For these purposes, different methodologies have been proposed, according to the features of the different human groups of each region [Iscan 2005; Alemán et al. 1997; González-Colmenares et al. 2007].

Once the sample of candidates for identification is constrained by these preliminary studies, an identification technique is applied. Among them, *craniofacial superimposition* [Krogman and Iscan 1986; Iscan 1993] is a complex and uncertain forensic process where a photograph of a missing person is compared with the skull found. Such comparison is guided by the proper correspondence of a number of landmarks identified in both the skull (craniometric landmarks) and the photograph (cephalometric landmarks).

Before reviewing the basis of this forensic identification technique, one should note that different terms have been used to refer to it during its more than one century of development. This fact has been mainly due to the use of close synonyms and specially to the coining of new, more specific terms depending on the supporting technical devices considered through time. The following points justify our choice of "craniofacial superimposition" as the most general and currently extended name for this forensic identification method.

—Craniofacial superimposition is the term widely found in the literature to refer to all the tasks related to this forensic identification technique [Ubelaker et al. 1992; Yoshino et al. 1995; Cattaneo 2007]. In particular, the most recent studies confirm the suitability of this terminology [Stephan 2009a, 2009b; Stephan et al. 2009; Ranson 2009; Pickering and Bachman 2009].

—The term arises as a mean to differentiate between the forensic technique itself and the technical devices used to tackle the identification problem. Indeed, craniofacial superimpositons were initially conducted using tracings made from photographs [Webster 1955; Sen 1962] and authors refereed to the procedure as "photographic superimposition" [Dorion 1983; Brocklebank and Holmgren 1989; Maat 1989]. Because of the rapid developments in video technology, the term "video superimposition" was later used when this tool became common in forensic identification [Seta and Yoshino 1993; Pesce Delfino et al. 1993; Shahrom et al. 1996; Yoshino et al. 1997]. Finally, the use of computers to assist the anthropologists in the identification process involved the next generation of craniofacial superimposition systems.[1] The latter approaches are usually referred to as "computer-aided" or "computer-assisted craniofacial superimposition"[2] [Pesce Delfino et al. 1986; Ubelaker et al. 1992; Aulsebrook et al. 1995; Yoshino et al. 1997]. The current review will be devoted to these kinds of systems and specifically to the most advanced ones based on the use of computer vision, 3D modeling and machine learning-based automatic methods. These systems have not been carried a specific distinctive name till now despite the fact of being fundamental tools in current computer-aided procedures.

[1]Attempts to achieve high identification accuracy through the utilization of advanced computer technology has been a monumental task for experts in the field in the last two decades [Lan 1992].

[2]Notice that the terms "skull-face superimposition", "skull-photo superimposition", "photographic superimposition" or "video superimposition" have also been used in combination with the "computer-aided/assisted" adjective.

—Hence, when using the generic term "craniofacial superimposition" we are assuming neither a particular acquisition device nor a given data format as the inputs of our problem. We just consider that any craniofacial superimposition method will deal with a 2D image of the disappeared person (typically a photograph) and the skull found (maybe as a part of other skeletal remains).
—There are some sources that use the term "photographic supra-projection" [Bronkhorst 2006; Stratmann 1998] instead. We avoid its use because it does not explicitly indicate that a matching of a skull with a face is specifically involved.
—As we will show in Section 2, craniofacial superimposition should not be confused with the second stage of this forensic technique, that is, the skull-face overlay, since it refers to the whole identification process including the data acquisition and processing as well as the decision making stages.
—Finally, craniofacial superimposition should not be mislead by craniofacial identification either. Notice that the latter term is used as an umbrella including both craniofacial superimposition and facial approximation[3] [Clement and Ranson 1998; Stephan 2009b; Wilkinson 2009]. Both methods are underpinned by knowledge of human craniofacial anatomy. It is this principle that ties these two techniques together despite the use of different technical protocols for each of them.

Successful comparison of human skeletal remains with artistic or photographic replicas has been achieved many times using the craniofacial superimposition technique, ranging from the studies of the skeletal remains of the poet Dante Alighieri in the nineteenth century [Welcker 1867], to the identification of victims of the recent Indian Ocean tsunami [Al-Amad et al. 2006]. Among the huge number of case studies where craniofacial superimposition has been applied,[4] it is worth noting it was helpful in the identification of well-known criminals as John Demanjuk (known to Nazi concentration camp survivors as "Ivan the Terrible") and Adolf Hitler's chief medical officer Dr. Josef Mengele at Sao Paulo, Brazil in 1985 [Helmer 1986]. Furthermore, it is currently used in the identification of terrorists [Indriati 2009].

Important contributions during the first period of craniofacial superimposition are those devoted to study the correspondence of the cranial structures with the soft tissue covering them [Broca 1875]. Bertillon [1896] introduced the basis to collect physiognomic data of the accused of a crime at the end of the nineteenth century. Such data is still used nowadays. Much later, Martin and Saller [1966] proposed the basis to systematize this discipline. Following those premises, the usual procedure of the first identifications by means of craniofacial superimposition consisted of obtaining the negative of the original face photograph and marking the cephalometric landmarks on it. The same task was to be done with a skull photograph. Then, both negatives were overlapped and the positive was developed.

The technological support for the technique from these initial identifications involved a large number of very diverse approaches found in the literature. That could also be the reason for the current diversity of craniofacial superimposition methods and their terminology, as mentioned before. Instead of following a uniform methodology, every expert tends to apply his own approach to the problem based on the available technology and on his deep knowledge on human craniofacial anatomy, soft tissues,

[3]"In the past, facial approximation methods have been known by many other names. The most popular of these is *facial reconstruction*. This name is strongly misleading as it leaves the erroneous impression that the methods are exact, reliable and scientific" [Stephan 2009a].

[4]Although there is not a register to evaluate the exact number of cases in which craniofacial superimposition has been used and/or resulted in positive results, it would appear to be in the hundreds only in Australia [Stephan et al. 2008]. Besides, Lan et. al reported in 1992 that their system had been used to identify more than 300 cases in China by that time [Lan 1992].

and their relationships. Therefore, craniofacial superimposition approaches evolved as new technology was available although their foundations were previously laid.

Some of these approaches were classified in a review by Aulsebrook et al. [1995] according to the technology used to acquire the data and to support the skull-face overlay and identification processes, that is static photographic transparency, video technology, and computer graphics. Similar classification schemes have been reported also by other authors [Nickerson et al. 1991; Yoshino and Seta 2000], which describe how craniofacial superimposition has passed through three phases: photographic superimposition (developed in the mid 1930s), video superimposition (widely used since the second half of the 1970s), and computer-aided superimposition (introduced in the second half of the 1980s). Moreover, Yoshino et al. [1997] classified some of the computer-aided craniofacial superimposition methods into two categories from the viewpoint of the identification strategy. The first strategy is to digitalize the skull and facial photographs and then morphologically compare the two images by image processing. The second is to evaluate the fit between the skull and facial image by morphometric examination.

Notice that the latter contributions are previous to the image processing boom of the last decade. Indeed, important issues like 3D modeling and machine learning are neglected. In case it was used, the computer was usually considered just as a secondary support for the technique even when authors claim they followed a "computer-aided" approach [Ubelaker et al. 1992; Ricci et al. 2006].

The aim of this survey is to update previous reviews, both adding recent works and considering a new computing-based classification criterion. That criterion is more related to the use of computers in the different stages of the craniofacial superimposition process itself. The different stages involved in the craniofacial process will be thus clearly defined. In our opinion, to properly characterize any craniofacial superimposition system (and specifically computer-aided ones), the whole process should be considered as divided up into three consecutive stages, namely face enhancement and skull modeling, skull-face overlay, and decision making. We will point out advantages and disadvantages of different approaches, *with an emphasis on the computer-aided techniques that have been employed and on the tasks these techniques solve in a more automatic manner.* We are interested in the methods, not on the analysis of specific cases. Hence, papers reporting only case studies will be out of the scope of this survey.

We should emphasize that we will not judge the effectiveness of the methods due to the unavailability of datailed information about the tackled cases and used equipments, and therefore the impossibility to reproduce the experimental setup and to perform comparative experiments. As stated by Carl N. Stephan, "presently, it is not possible to draw firm statements concerning the overarching performance of superimposition methods because formal published studies on the accuracy and reliability of the methods have been infrequent, have used small samples, and have often not been replicated" [Stephan 2009a].

The current proposal is organized as follows. In Section 2, we will give an overview of the craniofacial superimposition process with a brief description of the stages that compose it. In Section 3, we will present the role performed by the computer to accomplish every craniofacial superimposition stage. We will review and categorize the existing contributions in Section 4. Some works partially related to the craniofacial superimposition process will be shortly listed in Section 5. Finally, Section 6 will be devoted to a discussion of solved and unsolved problems, trends, and challenges for future research.

2. THE CRANIOFACIAL SUPERIMPOSITION PROCESS

As said, *craniofacial superimposition* [Iscan 1993] is a forensic process where photographs or video shots of a missing person are compared with the skull that is found.

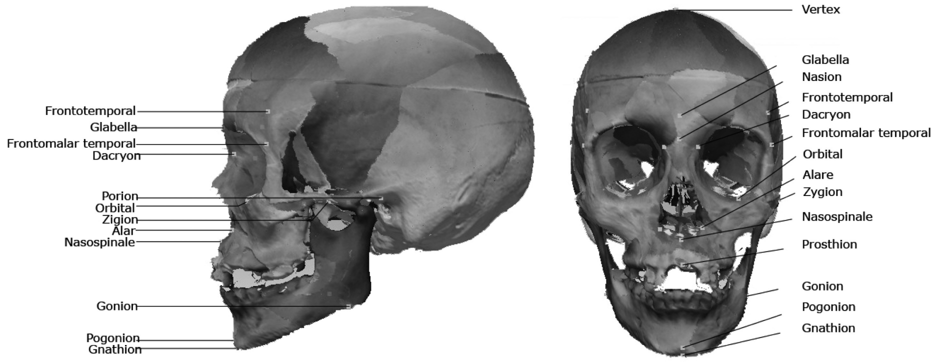

Fig. 1. From left to right, principal craniometric landmarks: lateral and frontal views.

By projecting both photographs on top of each other (or, even better, matching a scanned three-dimensional skull model against the face photo/series of video shots), the forensic anthropologist can try to establish whether that is the same person [Krogman and Iscan 1986].

This process is guided by a number of landmarks located in both the skull and the photograph of the missing person. The selected landmarks are located in those parts where the thickness of the soft tissue is low. The goal is to facilitate their location when the anthropologist must deal with changes in age, weight, and facial expressions.

The skull landmarks [George 1993] that are typically used (see Figure 1) follow.

Craniometric Landmarks

—*Dacryon (Da).* The point of junction of the frontal, maxillary, and lacrimal bones on the lateral wall of the orbit.
—*Frontomalar temporal (Fmt).* The most lateral point of junction of the frontal and zygomatic bones.
—*Glabella (G).* The most prominent point between the supraorbital ridges in the midsagittal plane.
—*Gnathion (Gn).* A constructed point midway between the most anterior (Pog) and most inferior (Me) points on the chin.
—*Gonion (Go).* A constructed point, the intersection of the lines tangent to the posterior margin of the ascending ramus and the mandibular base, or the most lateral point at the mandibular angle.
—*Nasion (N).* The midpoint of the suture between the frontal and the two nasal bones.
—*Nasospinale (Ns).* The point where a line drawn between the lower margins of the right and left nasal apertures is intersected by the midsagittal plane (MSP).
—*Pogonion (Pog).* The most anterior point in the midline on the mental protuberance.
—*Prosthion (Pr).* The apex of the alveolus in the midline between the maxillary central incisor.
—*Zygion (Zy).* The most lateral point on the zygomatic arch.

Meanwhile, the most usual face landmarks (see Figure 2) are:

Cephalometric Landmarks

—*Alare (al).* The most lateral point on the alar contour.
—*Ectocanthion (Ec).* The point at the outer commissure (lateral canthus) of the palpebral fissure just medial to the malar tubercle (of Whitnall) to which the lateral palpebral ligaments are attached.

Fig. 2. From left to right, principal facial landmarks: lateral and frontal views.

—*Endocanthion (En).* The point at the inner commissure (medial canthus) of the palpebral fissure.
—*Glabella (g').* In the midline, the most prominent point between the eyebrows.
—*Gnathion (gn').* The point on the soft tissue chin midway between Pog and Me.
—*Gonion (go').* The most lateral point of the jawline at the mandibular angle.
—*Menton (Me).* The lowest point on the MSP of the soft tissue chin.
—*Nasion (n).* In the midline, the point of maximum concavity between the nose and forehead. Frontally, this point is located at the midpoint of a tangent between the right and left superior palpebral folds.
—*Pogonion (pog').* The most anterior point of the soft tissue chin.
—*Labiale inferius (Li).* The midpoint on the vermilion line of the lower lip.
—*Labiale superius (Ls).* The midpoint on the vermilion line of the upper lip.
—*Subnasale (sn).* The midpoint of the columella base at the angle where the lower border of the nasal septum meets the upper lip.
—*Tragion (t).* Point in the notch just above the *tragus* of the ear; it lies 1 to 2 mm below the spine of the helix, which can be palpated.
—*Zygion (Zy').* The most lateral point of the check (zygomaticomalar) region.

Therefore, in every system for skull identification by craniofacial superimposition two objects are involved: a skull and the image of the face. The latter is typically a photograph although it can be sometimes replaced by a series of video shots or, in few cases, a portrait of the missing person. The final goal, common to every system, is to assess the anatomical consistency between the skull and the face. Different technologies and methods are used to achieve such goal, starting from the acquisition of the input data, that could be either to take a photograph of the skull in the same orientation of the face, to acquire a video of both skull and face with the help of a mixing device, or to acquire a 3D model of the skull and a digital photograph. Then, the methods to superimpose the acquired data range from the use of slides to the application of computer graphics techniques. Likewise, several methods of identification can be employed, sometimes related to the technology used to acquire the data, and other times independently chosen.

Readers interested in details about photographic and video superimposition systems can refer to Yoshino and Seta [2000]. In this survey, we will focus on computer-aided techniques, that we believe to be faster and more objective compared with manual and visual ones. However, there is some confusion in the forensic literature concerning the definition of a "computer-based" system and an "automatic" method. We will try to clarify that issue in Section 3.

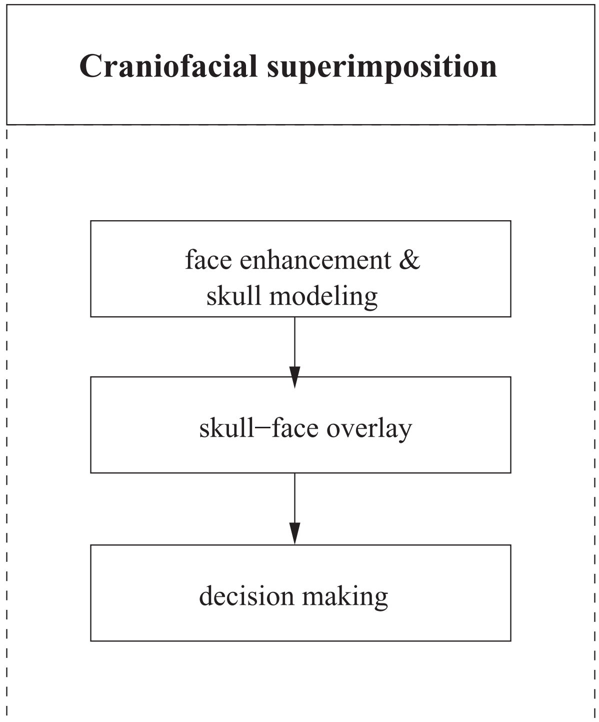

Fig. 3. The three stages involved the craniofacial superimposition process.

In our view, the whole craniofacial superimposition process is composed of three stages (see Figure 3).

(1) The first stage involves achieving a digital model of the skull and the enhancement of the image of the face. This stage is not present in all the systems. Indeed, the oldest systems and most of the recent ones still acquire a photograph and/or a series of video shots of the skull, instead of building a 3D model of it.[5] As we will explain in Section 6.1, obtaining an accurate 3D model of the skull has been considered a difficult task by forensic anthropologists in the past. However, it is nowadays an affordable and attainable activity using laser range scanners (Figure 4) like the one used by our team, available in the Physical Anthropology Lab at the University of Granada (Spain) (Santamaría et al. [2007a, 2007b, 2009a]). The subject of the identification process, that is, the skull, is a 3D object. Hence, the use of a 3D model of the skull instead of a 2D image of the skull should be preferred because it is definitively a more accurate representation. It has already been shown that 3D models are much more informative in other forensic identification tasks [De Angelis et al. 2009]. Concerning the image of the face, the most recent systems use a 2D digital image. This stage also involves the application of image processing techniques [Gonzalez and Woods 2008] to enhance the quality of the image of the face that was typically provided when the person disappeared.
(2) The second stage is the skull-face overlay. It consists of searching for the best overlay of either 2D images of the skull and face or 3D model of the skull and

[5]In that case, the first stage should be better called "face and skull data acquisition."

Fig. 4. Acquisition of a skull 3D partial view using a Konica-Minolta^{TM} laser range scanner.

the 2D image of the face achieved during the first stage. This is usually done by bringing to match some corresponding landmarks on the skull and the face.

(3) Finally, the third stage of the craniofacial superimposition process corresponds to the decision making. Based on the skull-face overlay achieved, the identification decision is made by either judging the matching between the corresponding landmarks in the skull and in the face, or by analyzing the respective profiles. Notice that the use of computers in this stage aims to support the final identification decision that will be always made by the forensic anthropologist.

As can be seen, the whole procedure is very time consuming. As said, there is not a systematic methodology but every expert usually applies a particular process. Hence, there is a strong interest in designing automatic methods to support the forensic anthropologist to put it into effect [Ubelaker 2000]. Moreover, the accuracy of each step of the process will influence the subsequent one. Thus, there is a need for optimizing each individual step properly.

3. COMPUTER-AIDED CRANIOFACIAL SUPERIMPOSITION

As said, the differentiation between methods that do not use computer technology and those that use it has already been proposed [Aulsebrook et al. 1995]. In the literature, photographic and video superimposition have been considered to belong to the former category. Meanwhile, methods defined as digital or computer-aided craniofacial superimposition techniques have been considered to belong to the latter. Thus, the distinction between computer-aided and non-computer-aided methods has been clearly guided by the use of computer-based technology along the craniofacial superimposition process up to now. Nevertheless, the role of the computer in that process is really important nowadays and it was not considered in previous reviews. Moreover, the analysis of previous contributions is especially difficult when some authors claim they propose a "computer-aided" or "'computer-assisted" system [Ricci et al. 2006] and the computer mainly plays the role of a simple visualization tool.

Hence, to fill that gap, we will expand the computer-aided category defined in previous reviews by distinguishing between nonautomatic and automatic methods. Computer-aided nonautomatic methods use some kind of digital infrastructure to support the craniofacial superimposition process, that is, computers are used for storing and/or visualizing the data. However, they are characterized by the fact that their computational capacity to automate human tasks is not considered. On the other hand, computer-aided automatic methods use computer programs to accomplish an identification sub-task itself. There are some remarks that should be made concerning the three stages of the process.

(1) Regarding the first stage, automatic methods may deal with either the 2D image of the face or the skull. On the one hand, when dealing with the 2D image of the face, automatic systems accomplish the restoration of the photograph by means of digital image processing techniques. On the other hand, the aim of automatic methods concerning the skull is the achievement of an accurate 3D model.
(2) Concerning the second stage, we will point out a clear division between computer-aided non-automatic and automatic skull-face overlay methods. The former ones use computers to support the overlay procedure and/or to visualize the skull, the face, and the obtained superimposition. Nevertheless, the size and orientation of the skull are changed manually to correctly match that one of the head in the photograph. This is achieved by either physically moving the skull, while computers are simply used to visualize it on the monitor, or (with the help of some commercial software) by moving its digital image on the screen until a good match is found. On the opposite, the automatic skull-face overlay methods find the optimal superimposition between the 3D model of the skull and the 2D image of the face using computer programs.
(3) Finally, regarding the decision making stage, automatic systems assist the forensic expert by applying decision support systems [Keen 1978]. Moreover, those computer programs must use objective and numerical data for evaluating the obtained matching between the skull and the face. Based on that evaluation, the system suggests an identification decision to the forensic expert. Thus, the decision support system is intended to help decision makers compile useful information from the analysis of the skull-face overlay outcomes. Of course, the final decision will be always made by the anthropologist according to both the support of the automatic system and his expertise. On the other hand, if the identification decision only relies on the human expert who visually evaluates the skull-face overlay obtained in the previous stage, then the method will be considered as a nonautomatic system, although it might use digital data as supporting means.

4. CLASSIFICATION AND DISCUSSION OF EXISTING WORKS

In this section, we will review and categorize the existing contributions of computer-aided craniofacial superimposition systems. They will be classified according to the stage of the process that is addressed using a computer-aided method. Information about the method used for the remaining stages will be given shortly together with a brief discussion.

Unfortunately, these stages are not so clearly distinguished in some of the existing craniofacial superimposition methods as we might expect. This fact causes some confusion as sometimes authors themselves define their own method as computer-aided craniofacial superimposition when they refer only to the decision making stage and others refer to identification method when they tackle the skull-face overlay stage. That is one of the reasons why our categorization is different from the previous ones that can be found in the literature.

Table I gives an overview of the papers describing computer-aided systems examined in the present survey. Studies are listed in chronological order. Additional information about the input data needed and/or the “classic” superimposition method used are included, when available.

Table I. An Overview of the Literature on Computer-Aided Forensic Identification Systems by Craniofacial Superimposition

	SM	SF	DM	Remarks
[Lan and Cai 1985]		CN		uses “digital” superimposition
[Tao 1986; Lan et al. 1988, 1990, 1993]		CN	CA	uses “digital” superimposition
[PesceDelfino et al. 1986, 1993]			CA	manual positioning of the skull
[Nickerson et al. 1991]	CA	CA		binary-coded genetic algorithm
[Ubelaker et al. 1992]		CN	CA	uses “digital” superimposition
[Bajnóczky and Királyfalvi 1995]			CA	based on video superimposition
[Yoshino et al. 1995, 1997]		CN	CA	photo-video superimposition
[Shahrom et al. 1996]	CN			3D model in facial approximation
[Ghosh and Sinha 2001, 2005]		CA		works on 2D skull images
[Scully and Nambiar 2002]		CN		works on 2D skull images
[Bilge et al. 2003]		CN	NC	based on commercial software
[Biwasaka et al. 2005]	CA			based on optical techniques
[Al-Amad et al. 2006]		CN	NC	based on commercial software
[Galantucci et al. 2006]	CN			computed tomography vs. laser
[Ricci et al. 2006]		CN	CA	based on 2D skull radiographs
[Santamaría et al. 2007b, 2007a, 2009a]	CA			adjancent overlapping regions
[Ballerini et al. 2007]		CA		real-coded genetic algorithm
[Fantini et al. 2008]	CN			based on commercial software
[Ibáñez et al. 2008, 2011]		CA		uncertain landmark location
[Ibáñez et al. 2009]		CA		real-coded evolutionary algorithms
[Benazzi et al. 2009]	CN			based on commercial software
[Ballerini et al. 2009]	CA			use of heuristic features
[Santamaría et al. 2009b]		CA		coplanar landmarks avoidance

The stage of the process, i.e. skull modeling (SM), skull-face overlay (SF) and decision making (DM), that is addressed using a computer-aided method is indicated with CA (computer-aided automatic methods), or CN (computer-aided non-automatic methods). Notice that particular stages not tackled using computers are noted by NC.

4.1. Face Enhancement and Skull Modeling

Let us highlight the main differences between the image of the face and the model of the skull. The face image is typically a photograph. It was acquired under some conditions that are fixed and usually unknown at the moment of the forensic analysis. With a digital image, the only possibility is to attempt to enhance its quality. If it is not in digital format, it can be scanned and transformed into a 2D digital image. Then, it can be enhanced using digital image filters and/or processing algorithms. However, the skull is an available physical object and its model needs to be obtained to accomplish an automatic procedure.

We will detail both face enhancement and skull modeling procedures. Regarding the image of the face, good quality is needed [Nickerson et al. 1991]. Therefore enhancement techniques could be applied [Gonzalez and Woods 2008]. Such techniques depend on the available format (digital camera image or scanned photographic paper) and include frequency domain filters to fix artifacts due to aliasing and sampling problems present in scanned documents, as well as removal of nonuniform illumination effects and sharpening methods to deal with blurring and problems related to movements. Notice that the proper filter and its most suitable parameters are a choice that must be performed by the expert since they depend strongly on the acquisition conditions. In accordance with Section 3, approaches that use human operated commercial software for the 2D face image enhancement will be considered nonautomatic methods. Automatic methods perform such 2D image enhancement using computer programs with almost no human intervention.

Regarding the model of the skull, recent techniques for craniofacial superimposition need an accurate 3D model. In the biomedical field computed tomography, scanning images are the starting data to reconstruct the skull [Singare et al. 2009; Fantini et al. 2008]. However, the possibilities of recording 3D forensic objects are not so many considering the available resources of a typical forensic anthropology lab. Indeed, many forensic labs are exploiting the capabilities of laser range scanners nowadays. That is due to the fact that these devices present a greater availability and a lower cost. Thus, we will focus our skull modeling study on the contributions that use laser range scanners instead of other devices that have also been considered to obtain a 3D model of the skull in other application domains [Nakasima et al. 2005; Enciso et al. 2003]. Laser range scanners are based on the optical principle of triangulation and acquire a dense set of three-dimensional point data in a very rapid, noncontact way [Bernardini and Rushmeier 2002]. Some laser range scanners are equipped with an additional positioning device named rotary table and appropriate software that permits the 3D reconstruction. Nevertheless, there are situations where that software does not provide suitable 3D models. Moreover, there are scenarios where it is not even possible to use a rotary table.

Before going on with the 3D modeling process, every 3D view of the skull acquired by the laser range scanner must be preprocessed. This task involves the cleaning, smoothing, and filling of the view. Cleaning aims to remove those artifacts that were acquired by the scanner as part of the scene but which do not correspond to the skull. Meanwhile, smoothing is mainly concerned with the removal of some artificial vertices that could have been wrongly included by the scanner on the borders of the surface because of a perspective distortion. Fortunately, this task is not needed so often. Finally, filling is used to avoid small holes to appear in those parts of the skull that are not properly scanned because they are too dark for the scanner capabilities or because they are located in shadow regions.

In order to accomplish the 3D model, some anthropologists are skilled enough to deal with the set of 3D views and they supervise the procedure with a commercial software like RapidForm™. Sometimes, this software does not provide the expected outcomes and the anthropologists even have to *stitch up* manually every couple of adjacent views. Hence, 3D image reconstruction software is a real need to construct the 3D model by aligning the views in a common coordinate frame. Such process is usually referred as range image registration [Brown 1992; Ikeuchi and Sato 2001; Zitova and Flusser 2003]. It consists of finding the best 3D rigid transformation (composed of a rotation and a translation) to align the acquired views of the object. An example of three different views of a skull and the reconstructed 3D model is shown in Figure 5.

In this section, we will mainly focus on contributions that include an automatic 3D modeling procedure because the other methods do not consider this stage and directly acquire a 2D projection of the skull (i.e., a skull photo). In accordance with Section 3, all the approaches that use computers but do not consider the 3D skull model will be considered as nonautomatic methods [Yoshino et al. 1995; Ghosh and Sinha 2001; Pesce Delfino et al. 1986; Ricci et al. 2006].

To our knowledge, Nickerson et al. [1991] were the first researchers to propose the use of a 3D model to tackle the craniofacial superimposition problem. In their work, a range scanner and a digital camera were used for 3D digitalization of the skull surface mesh and the 2D antemortem facial photograph, respectively. Well known image processing algorithms were used for image enhancement (median filtering, histogram equalization, Wiener filtering) [Gonzalez and Woods 2008]. Rendering was done through computer graphics techniques. A feature-based algorithm to reduce the computational and memory complexities inherent in solid modeling was also described.

Shahrom et al. [1996] followed a similar approach based on the use of a 3D laser range scanner. The authors used a skull holder, which could be slowly rotated through 360° in a horizontal plane under computer control. The 3D model was later used in facial approximation.

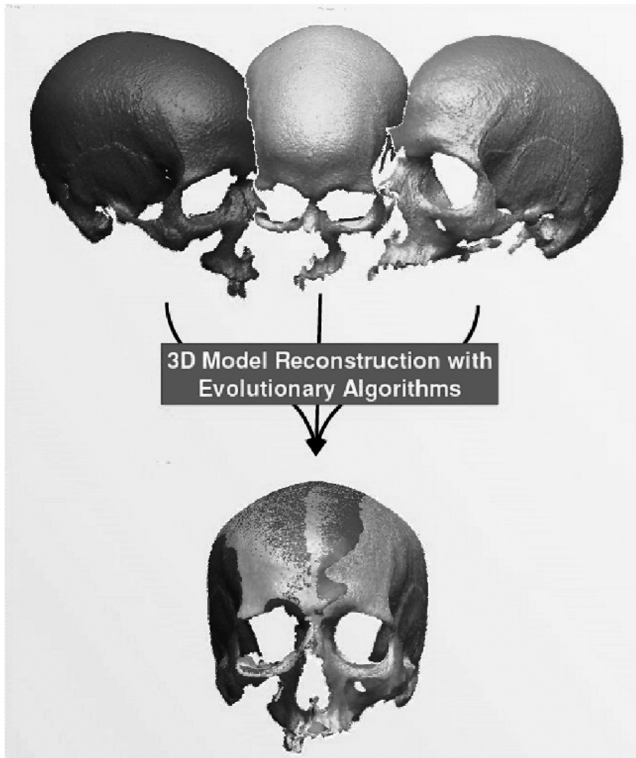

Fig. 5. Three different views of a skull and the reconstructed 3D model.

A completely different approach is presented in Biwasaka et al. [2005] where the authors examined the applicability of holography in the 3D recording of forensic objects. Holography is an optical technique capable of recording the 3D data of an object. Two types of images, real and virtual, can be recorded in a holographically exposed film or hologram. Two superimposition systems using holographic images were examined in order to evaluate the potential use of this recording method. The authors claim that the performance of holography is comparable to that of the computer graphics system, which consists of an image scanner, software, and a display unit. Moreover, they argue it can even be superior to the computer technique with respect to the 3D reconstruction of images. The suitability of this technique needs further studies. In particular, the use of an automatic superimposition method and a comparison with a reconstructed 3D range image could have objectively proved the actual utility of holography in this field.

Galantucci et al. [2006] compared two different acquisition techniques of images of a skull. In particular, computed tomography and laser range scanners performance were compared to ascertain which enabled more accurate reproductions of the original specimen. Comparison between the original and every model yielded satisfactory results for both techniques. However, computed tomography scanning demonstrated some advantages over the laser technique, as it provided a cleaner point cloud, enabling shorter preprocessing times, as well as data on the internal parts, which resulted in the reproduction of a more faithful model.

Santamaría et al. [2007b, 2007a, 2009a] proposed a method, based on evolutionary algorithms [Bäck et al. 1997], for the automatic alignment of skull range images. Different views of the skull to be modeled were acquired by using a laser range scanner.

A two step pairwise range image registration technique was successfully applied to such images. The method includes a pre-alignment stage that uses a scatter-search-based algorithm [Laguna and Martí 2003] and a refinement stage based on the classical iterative closest point algorithm [Besl and McKay 1992]. The method is very robust since it reconstructs the 3D model of the skull even if there is no turn table and the views are wrongly scanned.

Fantini et al. [2008] used a laser range scanner to create a 3D model of a medieval damaged skull. The large missing part of the skull allowed scanning both outer and inner surfaces of the object. Thirty-three partial views were needed to complete the acquisition of the whole surface by rotating the skull. Through post-processing of the data collected from the 3D scans, a triangular mesh was finally obtained. Those operations were performed by RapidForm 2006, RE™ commercial software.

A similar approach was followed in [Benazzi et al. 2009] in order to tackle the 3D skull reconstruction of Dante Alighieri (1265-1321) as part of a project to achieve the facial approximation of the famous poet. Based on the data provided by a laser range scanner, the model of Dante's skull was constructed using the utilities provided by the Rapidform XOS2™ commercial software. In particular, authors refer to operations as registration and merging of the point clouds, and simplification and editing of the digital model.

Ballerini et al. [2009] proposed the automatic reduction of the data provided by the laser range scanner used in the skull 3D model reconstruction task. The dense point cloud corresponding to every skull view is synthesized by considering heuristic features that are based on the curvature values of the skull surface. Those features guide the automatic 3D skull model reconstruction by means of an evolutionary algorithm.

4.2. Skull-Face Overlay

The success of the superimposition technique requires positioning the skull in the same pose of the face as seen in the given photograph. The orientation process is a very challenging and time-consuming part of the craniofacial superimposition technique [Fenton et al. 2008]. Most of the existing craniofacial superimposition methods are guided by a number of landmarks of the skull and the face (see Section 2). Once these landmarks are available, the skull-face overlay procedure is based on searching for the skull orientation leading to the best matching of the set of landmarks. Scientific methods for positioning the skull had already been proposed before computers became largely available [Chandra Sekharan 1993; Glaister and Brash 1937; Kumari and Chandra Sekharan 1992; Maat 1989].

These methods are not computer aided but are somehow closer to them than to trial and error procedures. In these approaches the skull is manually placed on a tripod. However, its pose is estimated using a mathematical procedure, instead of a trial and error routine. The researchers applying these methods calculate the head size and orientation in the photograph, so they can position the skull in the same posture. We briefly summarize those contributions as follows.

—In very early approaches [Glaister and Brash 1937], the enlargement factor is calculated based on linear measurements of items within the antemortem photograph, such as fabric, button, tie, and other objects of known geometry (doors, chairs, etc.) [Chandra Sekharan 1993]. Other scale correlation methodology has included measurement of the interpupillary distance and size of dentition [Austin-Smith and Maples 1994].

—Maat [1989] proposed to use a set of anthropometrical landmarks, along with relative reference lines, to calculate the three components of head rotation ("bending forward", "turning sideways", and "rolling sidewards") to position the skull. The principle of central projection and a minimum photographic distance of 1.5 m are important preconditions.

—Chandra Sekharan [1993] suggested using the vertical distance "d" between the *ectocanthions* and *tragion* as a measure for calculating the extent of flexion or extension of the head. The extent of the rotation of the face was calculated from the L/R ratio, where L and R denote the distances between the left and right *ectocanthion* from the midline of the face. Using these factors, the skull under examination was positioned on a tripod stand with the help of a remote control positioning device [Kumari and Chandra Sekharan 1992]. A practical suggestion for the camera distance was also given.

However, these methods are out of the scope of this proposal that is focused on computer-aided skull-face overlay contributions. Within this group of approaches, we will differentiate between nonautomatic and automatic works as follows.

4.2.1. Nonautomatic skull-face overlay methods. In this section, we describe skull-face overlay methods known as computer-aided methods in the literature. Nevertheless, we prefer to refer to them as computer-aided nonautomatic skull-face overlay methods. They are typical examples of the use of a digital infrastructure but without taking advantage of its potential utility as automatic support tools for the forensic anthropologists. Notice that they depend on good visualization and overlay mechanisms to aid human operators. Hence, processes following this approach are prone to be time-consuming, hard to be reproduced, and subjective.

—Lan and Cai [1985] developed a craniofacial superimposition apparatus called TLGA-1, based on the principles of dual projection. During the following years, these authors evolved this system resulting in new subsequent versions, TLGA-2 and finally TLGA-213 [Tao 1986; Lan and Cai 1988, 1993; Lan 1990]. The TLGA-213 system was mainly composed of a TV camera, a computer, an A/D and D/A converter, a mouse, and the 213 system software library. The system calculated the pitch angle of the photograph of the face by measuring the ratio between the distances in the vertical line segments *glabella* to *nasion* and *gnathion* to *nasion*. The natural head size was calculated from the distance between the *ectocanthions* and the deflection angle in the photograph. The latter parameters were iteratively computed and considered as a guide for the manually performed skull-face overlay.

—Ubelaker et al. [1992] solved a huge number of cases submitted to the Smithsonian Institute by the FBI. Their software allows any desired combination of skeletal-photograph comparison, including the chance to remove the soft tissue to view the underlying skeletal structure. It works on digitalized images of both face and skull and offers the possibility to assess the consistency between them. The identification procedure usually requires less than one hour. It is not specified if this time includes the acquisition and skull-face overlay steps or only the decision making stage. However for the acquisition of the digital images, the authors visualize the facial photograph and trace anatomical landmarks on a plastic slide taped on the monitor. Then, they visualize the skull and manually manipulate it to match the marked landmarks. The quality of the photograph and the proper orientation of the skull are claimed to highly influence the success of the technique.

—Yoshino et al.'s skull identification system [Yoshino et al. 1997] consists of two main units, namely a video skull-face overlay system and a computer-aided decision making system. In the former, the determination of the orientation and size of the skull to those of the facial photograph is done by a pulse motor-driven mechanism, through the help of the fade-out or wipe mode of the video image mixing device.

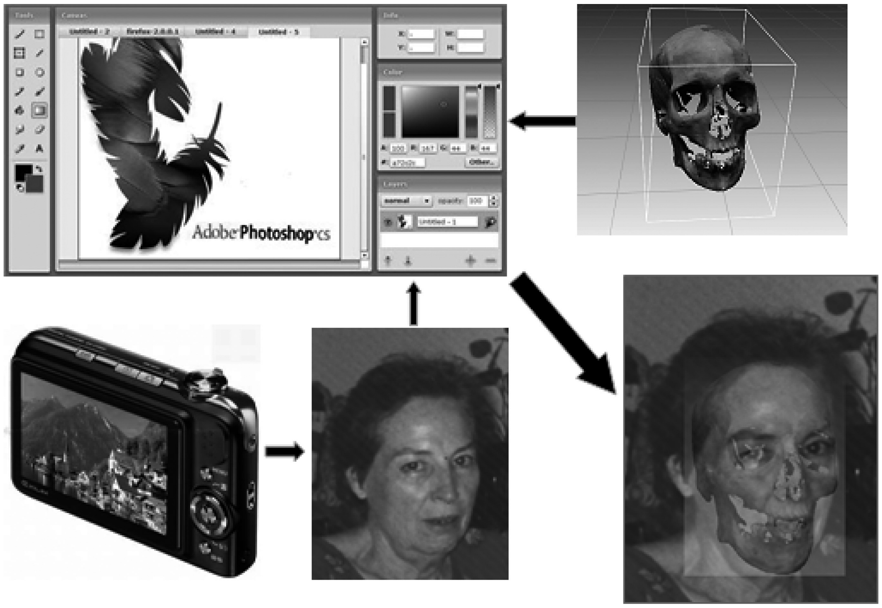

Fig. 6. Non-automatic skull-face overlay based on Photoshop^{TM}.

Then, the skull and facial images are digitalized, stored in the computer, and superimposed on the monitor.

—Ricci et al. [2006] presented an algorithm to compare a facial image with a skull radiograph. Thus they work with pairs of 2D images and the superimposition is done by the human operator that manually marks anatomical points and brings them to match. Their software seems to account only for translation and scaling, while the algorithm is able to compensate for up to 10^o of head rotation. However, the algorithm only calculates distances and threshold in an automatic way, while the skull-face overlay is done manually.

—The use of commercial software as Adobe Photoshop^{TM} has been reported by Bilge et al. [2003] and Al-Amad et al. [2006]. They use the "free transform" tool to adjust the scale of the photograph of the face, superimposed over the skull photo. The "semi-transparent" utility allows the operator to see both images while moving, rotating, and resizing the overlaid image (see Figure 6). A similar approach was also used in both Scully and Nambiar [2002] and Ricci et al. [2006] to validate a classical method and to superimpose skull radiographs, respectively.

4.2.2. Automatic Skull-Face Overlay Methods. We have found only few really interesting works to perform skull-face overlay in a fully automatic way. They are based on the use of machine learning algorithms [Mitchell 1997] from artificial intelligence, as artificial neural networks [Rumelhart and McClelland 1986], evolutionary algorithms [Bäck et al. 1997], and fuzzy logic [Zadeh 1965]. The automation provided by these approaches represents an added value since they are typically faster than non-automatic methods. Moreover, they rely on quantitative measures and they can be easily reproduced. However, this sort of works often involve technical concepts that are usually unknown by most of the forensic anthropologists. Thus, a multidisciplinary research team is required. A brief description of the methods in this group is provided as follows.

—The method proposed by Ghosh and Sinha [2001] is an adaptation of their previous work for face recognition problems [Sinha 1998] and it was recently applied to an unusual case [Ghosh and Sinha 2005]. The Extended Symmetry Perceiving Adaptive Neuronet (ESPAN) consists of two neural networks to be applied to two different parts of the overlaying and allows to select fuzzy facial features to account for ambiguities due to soft tissue thickness. More in details, the system can implement an objective assessment of the symmetry between two nearly front 2D images: the cranial image and the facial image that are the inputs as the source and the target images, respectively. The output is the mapped cranial image suitable for superimposition. Two neural networks need to be trained separately because each of them can correctly map only a part of the cranial image. Two limitations are pointed out by the authors: (i) a part of the cranial image will not be properly mapped, and (ii) a front view image is needed. Moreover, this method is not fully applicable because of two reasons. First, its long computation time is an important drawback. Second, the need of separately applying two different networks is a relevant flaw. Each network must deal with the upper skull contour and the front view cranial features, respectively. The superimposition found by the first network can be disrupted by that one achieved by the second network.

—On the other hand, Nickerson et al. [1991] proposed a novel methodology to find the optimal fit between a 3D skull model and a 2D digital facial photograph. The most important novelty of this technique was the automatic calculation of the overlay of the skull surface mesh on the digital facial photograph. This mapping was achieved from the matching of four landmarks previously identified both in the face and the skull. The landmarks used in their work were: either the *glabella* or *nasion* landmarks, the two *ectocanthion* points, and an upper mandibular dentition point, if present, or the *subnasal* point. The mappings were developed from sets of similarity transformations and a perspective projection. The parameters of the transformations and the projection that overlay the 3D skull on the 2D photograph are optimized with three different methods: a heuristic, a classic nonlinear optimization, and a binary-coded genetic algorithm, with the latter achieving the best results.

—Ballerini et al. [2007] proposed an improvement of Nickerson et al.'s approach. The forensic experts extract different landmarks on the skull 3D model obtained in the first stage (see Section 4.1) and on the face photograph. Then, a genetic algorithm is used to find the optimal transformation to match them. The main differences between this approach and the previous one are the use of a real coding scheme and a better design of the genetic algorithm components. The method for the superimposition of the 3D skull model on the 2D face photograph is fully automatic.

—Ibáñez et al. [2009] extended the initial results in Ballerini et al. [2007] to accomplish a broader study in order to demonstrate that real-coded evolutionary algorithms are suitable approaches for craniofacial superimposition. In particular, the authors highlight the good performance and high robustness of the state of the art covariance matrix adaptation evolution strategy (CMA-ES) [Hansen and Ostermeier 2001]. Moreover, CMA-ES computation time is less than 15 seconds, in the six real-world identification cases considered. It is an impressive improvement with respect to the manual superimposition performed by a forensic expert which took 24 hours. An example of the manual and computer-based craniofacial superimposition results is shown in Figure 7. This is a real case that has been previously solved by the staff of the Physical Anthropology Lab at the University of Granada in collaboration with the Spanish scientific police.

—Ibáñez et al. [2008, 2011] extended the approach in Ballerini et al. [2007] considering the uncertainty involved in the location of the cephalometric landmarks. In particular, authors use fuzzy logic to model the extremely difficult task of locating

Fig. 7. From left to right, manual and computer-aided craniofacial superimposition.

the landmarks [Richtsmeier et al. 1995] in a invariable place, with the accuracy needed by craniofacial superimposition.

—Santamaría et al. [2009b] avoid the coplanarity problem that is typical in computer vision by using an extended set of cephalometric landmarks including fuzzy landmarks. Those fuzzy landmarks are regions in the face image that are provided by the forensic anthropologists when it is not possible to determine an accurate location for the cephalometric landmarks.

4.3. Decision Making

Once the skull-face overlay is achieved, the decision making stage can be tackled. The straightforward approach would involve measuring the distances between every pair of landmarks in the face and in the skull. Nevertheless, this is not advisable because errors are prone to be accumulated during the process of calibrating the size of the images. Instead, studies based on proportions among landmarks are preferred. Geometric figures like triangles or squares are good choices. It is also important to consider as many landmarks as possible, and different proportions among them [George 1993].

Although the methods described in the following are usually called in the literature as computer-aided craniofacial superimposition, we prefer to refer to them as decision making methods since we think the authors fail on specifying the right craniofacial superimposition stage where their works are included. Indeed, the proposed automatic techniques mainly focus on the decision making strategy as they are actually decision support systems assisting the anthropologist to take the final identification decision.[6] These algorithms are applied on the digitalized images stored on the computer, after the determination of the orientation and size of the skull by “routine” skull-face overlay techniques.

Tao [1986] developed the first procedure in which a computer was used for the decision making stage. That decision support system aimed to replace the previously used

[6]We should remark that, although the reviewed systems are labeled as automatic in the sense that they are able to provide an identification decision without the intervention of the forensic expert, the supervision and final validation of the latter is always required as in any computer-aided medical diagnosis system [Berner 2007].

methods based on range estimation and subjective judgment. The system provided an identification conclusion by using distances between landmarks from the superimposed images. Later, Lan [1990] and Lan and Cai [1988, 1993] proposed the use of 52 different superimposition identification indexes for that aim in the TLGA-213 system. Those indexes were based on anthropometrical measures of Chinese adults, male and females, and were used together with proportion and distances between superimposed landmarks lines to automatically compute the final identification decision.

Pesce Delfino et al. [1986, 1993] applied kth-order polynomial functions and Fourier harmonic analysis to assess the fit between the outline of the skull and the face. Ten cases including positive and negative identifications were investigated. The polynomial function was used to smooth the curve representing the investigated profile. The square root of the mean square error is taken to calculate the distance between polynomial function curves obtained for the skull and the face profile. The Fourier analysis considered the profile as an irregular periodic function whose sinusoidal contributors are found. Low-order harmonics (the first three or four) represented the basic profile shape and the high order harmonics corresponded to details. The sum of the amplitude differences of the sinusoidal contributors between profiles of the skull and the face represented the second independent parameter for numerical comparison. A Janus procedure (so called by the authors because of the double-headed Latin god Janus, the bi-front) was used to evaluate the symmetry differences between the two profiles. This procedure takes into account the relationship between the total arc and the chord length and the area they delimit in the two faced profiles. All these parameters are calculated by a computer software package called Shape Analytic Morphometry. However, this method would be only applicable when lateral or oblique photographs are available. Furthermore, their contribution requires manual repositioning of the skull for the correct superimposition.

Bajnóczky and Királyfalvi [1995] used the difference between the coordinate values of the pair of anatomical and/or anthropometrical points in both skull and face for judging the match between the skull and facial image obtained by the superimposition technique. Eight to twelve pairs of points were recorded and expressed as pixel units. Then, the final matrix, containing coordinates of measured points and calculated values, was established by computer-aided processing. Lacking the appropriate information, their model assumed that all data in that matrix were independent and followed a normal distribution with the same variance. A part of that variance was σ^2, which was the square of the measurement error and was itself assumed to be the same for all the data. The model of the authors was based on assumptions that. The components of the error term are independent and distributed according to $N(0, 2\,\sigma^2)$.

The authors used a presupposed value of σ as part of the model assumptions. Under the assumption that the null hypothesis (Eq. (1)) is valid, it was statistically tested using two values for σ. The authors claimed that, when a given case is evaluated, it is crucial to know what value can be considered as measurement error. One skull and two photographs were used to test the method. Both frontal and lateral face photographs are considered. They noted that their method is suitable for filtering out false positive identifications. Although the results obtained from this method are objective and easily interpreted for lay people, the anatomical and anthropometrical consistency between the skull and the face should be assessed by forensic examiners who are well versed in the anatomy of the skull and face. The authors conclude that their method should be used only in combination with classic video superimposition and could be regarded as an independent check.

In Yoshino et al.'s skull identification system [Yoshino et al. 1997] the distance between the landmarks and the thickness of the soft tissue of the anthropometrical points are semi-automatically measured on the monitor for the assessment of the anatomical consistency between the digitalized skull and face. The consistency is based on 13 criteria they previously defined using 52 skulls [Yoshino et al. 1995]. The software includes polynomial functions and Fourier harmonic analysis for evaluating the match of the outline such as the forehead and mandibular line in both digitized images. To extract the outline, gradient and threshold operations are used. Five case studies are carried out. However, they noted that these analysis could not always be applied because of the difficulties in extracting the facial contour from small and poor facial photographs offered from the victim's family.

The skull-face overlay in Ricci et al. [2006] was guided by different crosses that were manually marked by the human operator in both the face and the skull radiograph photographs. Once that stage was performed, the algorithm calculated the distance of each cross moved and the respective mean in pixels. The algorithm considered a 7-pixel distance a negligible move. The mean value of the total distance in crosses moved represented the index of similarity between the given face and skull: the smaller the index value, the greater the similarity. The algorithm suggested an identification decision based on that index of similarity. The authors claim 100% of correct identification over 196 cross-comparisons and report that the minimal number of needed landmarks is 4.

5. RELATED WORKS

Nearly all the methods described in the previous section use anthropological landmarks to compute and/or to assess the fit between the skull and the face, but we found only one paper that addresses their automatic extraction in the skull [Parzianello et al. 1996]. The authors proposed a method based on simple image processing algorithms for the detection of craniometric points in video-based skull images. Their method works on 2D digitalized images of undamaged skulls and assumes they are in frontal view. The authors claimed that their method produces good results and it is potentially useful for the craniofacial superimposition process. However, we did not find any paper describing a system using the automatically extracted landmarks.

The literature on facial feature extraction is huge. Douglas [2004] reviews a number of image processing algorithms for the automatic extraction of landmarks in photograms and cephalograms. Interesting algorithms combining artificial intelligence techniques have been successfully developed and applied. However, they are out of the scope of this survey as well, as they are related to studies on craniofacial surgery or on face recognition and not to forensic skull identification.

Readers interested in 3D cranial landmark categorization can refer to Brown et al. [2004]. The accurate placement of anatomical features for craniofacial superimposition is nowadays a real need [Stephan et al. 2009]. However, to the best of our knowledge, no method for their automatic localization is found in the literature.

The area of 3D face processing [Zhen and Huang 2004; Zhao and Chellapa 2005] could also seem to have some relation with craniofacial superimposition, specifically the face modeling topic. 3D face processing methods deal with the very complex task of properly turning a 3D object (the subject face) into a 2D image. Obtaining a skull 3D model is feasible – as well as very useful to improve the identification process – due to the availability of the physical object in the forensic anthropology lab (see Section 4.1). Nevertheless, the existing powerful methods in 3D face modeling (such as Shan et al. [2001]) are not applied since craniofacial superimposition deals with the identification of deceased people. Hence, it is usually difficult for the anthropologist to get significant data in real conditions to apply the latter techniques. The availability of photographs and videos of the sample of candidates is low. This is one of the reasons why the currently established fundamentals of the forensic technique are based either on a 2D skull photo-2D face photo or on a 3D skull model-2D face photo comparison. The use of 3D models of the face is not considered by forensic anthropologists nowadays.

Nevertheless, it could become an interesting area in the future when the massive use of video and imaging devices the world is experiencing will solve the problem of the lack of subject data.

There are some other approaches apart from craniofacial superimposition that put into correspondence 3D face models and 2D face photographs. On the one hand, there is the well-known area of face recognition [Zhao et al. 2003] that includes several multimodal 3D-2D approaches [Bowyer et al. 2006]. One of the most representative works in this subarea is that by Blanz and Vetter [2003]. On the other hand, we can find techniques tackling 3D face model-2D face photograph superimposition for personal identification [Goos et al. 2006; De Angelis et al. 2009]. The opposite problem, the registration of 2D face photos to a 3D facial model, is considered in Clarkson et al. [2001]. Of course, all the latter approaches are out of the scope of this survey as they deal with completely different problems and data (3D face models instead of 3D skull models).

Besides, recent literature has considerably developed the potential of another technique related to craniofacial superimposition: craniofacial reconstruction preferably referred to as facial approximation [Vanezis et al. 2000; Claes et al. 2006; Wilkinson 2010]. The 3D facial image may be reconstructed by either building muscle and soft tissue using clay, or by means of computer graphics. Data concerning the reliability of these methods for forensic anthropology and the lack of relationship between facial approximation and resemblance rating have been reported [Stephan and Arthur 2006]. An interesting review of current systems for computer-aided forensic facial reconstruction can be found in Wilkinson [2005].

6. DISCUSSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

In this final section, we summarize the results by reporting a number of solved and unsolved problems in craniofacial superimposition as well as possibilities for forensic applications by identifying some trends in the field. We also provide a list of recommendations for future research. Finally, we discuss the need of public forensic data and we present a web site we have created for this purpose.

6.1. Solved and Unsolved Problems

To date, no fully automatic method is used in practical applications despite the high number of cases examined [Ubelaker 2000] and the large amount of time the forensic experts need to spend in performing such examination.

All the researchers agree that a key problem of craniofacial superimposition is the size and orientation of the skull to correctly match the head in the photo. In fact, it would be most of the times impossible to obtain the technical specifications used to take the antemortem photograph.

The need of a sophisticated procedure or an expensive hardware configuration to implement a digitalized 3D cranial image reconstruction has been stated to be the reason why computer-aided automatic craniofacial superimposition methods did not gain much popularity [Ghosh and Sinha 2001]. Nevertheless, the acquisition of a 3D model of the skull should not be a hinder nowadays. Indeed, such model could be reconstructed either by the scanner's software when the rotary device is available or by range image registration algorithms (Santamaría et al. [2007a, 2009a]).

Regardless the automatic or nonautomatic nature of the approach to tackle craniofacial superimposition problems, some authors [Cattaneo 2007; Yoshino et al. 1997; Jayaprakash et al. 2001; Shahrom et al. 1996] agree that this technique should be used only for excluding identity, rather than for positive identification. [Seta and Yoshino 1993] state the general rule that superimposition is of greater value in ruling out a match, because it can be definitely stated that the skull and photograph are not those of the same person. If they do align, it can only be stated that the skull might possibly be that of the person in the photograph. However, a research carried out on very large number of comparisons indicates that there is a 9% chance of misidentification if just one photograph is used for the comparison, and this probability of false identification diminishes to less than 1% if multiple photographs from widely different angles to the camera are used [Austin-Smith and Maples 1994].

Skull identification by craniofacial superimposition peaked in the 1990-1994 period and subsequently declined, with last use of the technique occurring in 1996 [Ubelaker 2000]. According to Ubelaker, these frequencies appear to reflect the availability of the necessary equipment and expertise in 1990, coupled with awareness of the value of this approach in the forensic science and law enforcement communities. The decline in use likely reflects both the increased awareness of the limitations of this technique and the greater availability of more precise methods of identification, especially the molecular approaches [Ubelaker 2000].

We have to stress that these statements were valid when the equipments were either very expensive or not very accurate. Nowadays, the limitations pointed out by some researchers, like the poor quality of the antemortem photographs [Ubelaker et al. 1992; Nickerson et al. 1991] or the curved surface of the monitor [Shahrom et al. 1996], which were claimed to influence a correct superimposition, should not be a problem.

We believe that most of the claimed difficulties in finding an accurate magnification and orientation of skull can be currently overcome by computer-aided automatic craniofacial superimposition methods. Meanwhile, other reasons adduced for a low reliability in such methods are definitively solved nowadays. In particular, the high computation time spent by methods proposed more than a decade ago (e.g., Nickerson et al. [1991] required several days to achieve an automatic craniofacial superimposition) is not a problem anymore.

Plenty of research has also focused on supporting the anthropologist in the decision making stage [Pesce Delfino et al. 1986; Yoshino et al. 1995; Ricci et al. 2006] and/or the validity of "routine" superimposition methods [Bajnóczky and Királyfalvi 1995; Scully and Nambiar 2002]. At the same time, Jayaprakash et al. [2001] affirmed that visual assessment is more effective than metrical studies. Indeed, the method they propose, called "craniofacial morphoanalysis" is based on the visual evaluation of a number of attributes. This is the reason why this method is not included in the computer-aided approaches described in this survey.

6.2. Trends

Video superimposition has been preferred to photographic superimposition since the former is simpler and quicker [Jayaprakash et al. 2001]. Video superimposition overcomes the protracted time involved with photographic superimposition, where many photographs of the skull had to be taken in varying orientations [Nickerson et al. 1991]. Moreover, the fade and wipe facility in video superimposition allows the expert to analyze the congruence in every sector of the superimposed images, thereby rendering this method more popular [Jayaprakash et al. 2001]. However, it has been indicated that craniofacial superimposition based on the use of photographs is better than using video in terms of resolution of details [Yoshino et al. 1995]. Furthermore, video superimposition is still quite subjective, relying on the skill and dexterity of the operator [Nickerson et al. 1991].

Recent papers confirm that some authors think the most advanced method is based on computer-aided craniofacial superimposition through the use of the imaging tools provided by Adobe Photoshop^{TM} and Corel Draw^{TM} software packages [Al-Amad et al. 2006; Bilge et al. 2003; Ross 2004]. We agree with these authors that working with digital images is definitively simpler and cheaper than with photographic or video superimposition equipments. However, we should note that the methods they use are not automatic as they manually resize, shift and rotate the images by trial and error. Thus, they deal with a very time consuming and error affected process.[7]

There seems to be an increasing interest in facial reconstruction or approximation. Besides the advantages and disadvantages described in Wilkinson's review [Wilkinson 2005], and the undoubted attractiveness of these techniques, we believe that they still need extensive research before being fully accepted in forensic investigations. Indeed, researchers involved in facial approximation think that craniofacial superimposition may be preferred to reconstruction in cases where some clues can limit the identity to a few candidates [Turner et al. 2005].

6.3. Recommendations

It would be worthwhile to investigate how all the manual steps of the routine methods described in Section 4, from the skull modeling to the decision making, can be automated.

Automatic localization of anthropological landmarks on both 3D models of the skull and 2D images of the face are few examples of useful potential applications of image processing techniques to forensic sciences. Computer graphics techniques can provide accurate and automatic registration methods for 3D model building and for superimposition of 3D models on 2D images, which are a real need.

The use of 3D models of skulls should be preferred to their 2D representation (like photographs [Ghosh and Sinha 2001] or radiographs [Ricci et al. 2006]) due to the inherent problems of representing a 3D object with a 2D image.

Besides, we can explain the underlying uncertainty involved in the craniofacial superimposition process. The correspondence between facial and cranial anthropometric landmarks is not always symmetrical and perpendicular: some landmarks are located in a higher position in the face of the alive person than in the skull, and some others have not a directly related landmark in the other set. The identification decision is to be expressed according several confidence levels ("absolute matching," "absolute mismatching," "relative matching," "relative mismatching", and "lack of information"). Hence, we again find the uncertainty and partial truth involved in the identification process. In conclusion, fuzzy logic could be an interesting tool to be applied. However, we have only found few proposals considering this artificial intelligence tool [Ghosh and Sinha 2001; Ibáñez et al. 2008, 2009b].

It is recommended to use recent photographs or not to consider age-related features; otherwise, algorithms for predicting what an adult head and face at one point in time might look like several years later will be necessary [Albert et al. 2007].

The distortions that may arise during the craniofacial superimposition process could influence the reliability of the identification. It is advised to use central projections or to apply a mathematical model to eliminate the distortions [Eliášová and Krsek 2007].

In computer-aided diagnosis, the general agreement is that the focus should be on making useful computer-generated information available to physicians for decision support rather than trying to make a computer act like a diagnostician [Berner 2007]. Following the same track, the final goal of computer-aided automatic craniofacial identification systems should be to provide the forensic anthropologists with identification decisions they will have to supervise and validate.

[7] It is worth ro remind that the forensic expert employed approximately 24 hours to manually superimpose the skull and the face shown in Figure 7 (left) following a computer-aided procedure similar to those proposals.

6.4. The Craniofacial Superimposition Challenge

Science evolves thanks to the knowledge exchange and the chance to either improve existing approaches or propose new methods for the problems that are tackled. Therefore, it is essential to guarantee objective procedures to evaluate the performance of those proposals.

Unlike other related research fields like face recognition or machine learning, it is not possible to compare the performance of the developed craniofacial superimposition methods since there is not a common forensic dataset available comprised by 3D partial views of skulls, the corresponding reconstructed 3D model, photographs of the person the skull belongs to, landmarks, superimposition results detailing the used techniques together with the identification decision and, so on. This fact has already been mentioned by some experts on the area, such as Carl N. Stephan (see [Stephan 2009a] and his sentence quoted in the Introduction section).

We think this is the main reason for finding few practical applications of computer-aided automatic methods. In our opinion, having forensic material available is a keystone for the advance of the craniofacial superimposition research field.

Large, publicly available databases of known case studies should be collected. Those databases will encourage the development and testing of new methods. They will also allow the validation of the methods by applying them to solved cases and by comparing the results with the identification previously determined by forensic anthropologists.

Assuming this challenge, we have created a website[8] with the aim to provide forensic data to the research community and to join forces by the collaboration with other forensic labs.

As said, there are different issues in craniofacial superimposition that can be tackled by means of advanced artificial intelligence approaches. Evolutionary algorithms, fuzzy logic, and neural networks have demonstrated their suitability for tackling different craniofacial superimposition tasks. Moreover, the application of these techniques to the craniofacial superimposition problem has been presented in this survey as an emerging trend. Thus, public craniofacial superimposition datasets will be interesting for the artificial intelligence research community. Indeed, different authors have recently claimed that a multidisciplinary research team is a real need in forensic identification by craniofacial superimposition nowadays [Ricci et al. 2006; Benazzi et al. 2009].

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