# Accepted Manuscript

Highlights

We use computer vision and soft computing as powerful tools to automate the skull-face overlay task.

We dramatically reduce the time taken by the expert and obtaining an unbiased overlay result.

We justify and analyze the use of soft computing and computer vision to properly model the skull-face overlay problem.

We consider and deal with the inherent uncertainty sources of the skull-face overlay problem.

1

# Technical Note: Computer Vision and Soft Computing for Automatic Skull-Face Overlay in Craniofacial Superimposition

B. Rosario Campomanes-Álvarez[1], O. Ibáñez[1], F. Navarro[2], I. Alemán[2], M. Botella[2], S. Damas[1*], O. Cordón[1,3,4]

*[1]European Centre for Soft Computing, 33600 Mieres, Asturias, Spain*

*[2]Physical Anthropology Laboratory, University of Granada, 18012, Granada, Spain*

*[3]Department of Computer Science and Artificial Intelligence, University of Granada, 18014, Granada, Spain*

*[4]Research Center on Information and Communication Technologies (CITIC-UGR), University of Granada, 18014, Granada, Spain*

**Abstract.** Craniofacial superimposition can provide evidence to support that some human skeletal remains belong or not to a missing person. It involves the process of overlaying a skull with a number of *ante mortem* images of an individual and the analysis of their morphological correspondence. Within the craniofacial superimposition process, the skull-face overlay stage just focuses on achieving the best possible overlay of the skull and a single *ante mortem* image of the suspect. Although craniofacial superimposition has been in use for over a century, skull-face overlay is still applied by means of a trial-and-error approach without an automatic method. Practitioners finish the process once they consider that a good enough overlay has been attained. Hence, skull-face overlay is a very challenging, subjective, error prone, and time consuming part of the whole process. Computer vision and soft computing arise as powerful tools to automate it, dramatically reducing the time taken by the expert and obtaining an unbiased overlay result. In this manuscript, we justify and analyze the use of these techniques to properly model the skull-face overlay problem. We also present the automatic technical procedure we have developed using these computational methods and show the four overlays obtained in two craniofacial superimposition cases. This automatic procedure can thus considered as a tool to aid forensic anthropologists to develop the skull-face overlay, automating and avoiding subjectivity of the most tedious task within craniofacial superimposition.

---

\* Corresponding author at: European Centre for Soft Computing, c/ Gonzalo Gutiérrez Quirós s/n, 33600, Mieres, Asturias, Spain. Tel.: +34 985 456545; fax: +34 985 456699. E-mail address: sergio.damas@softcomputing.es

2

# Technical Note: Computer Vision and Soft Computing for Automatic Skull-Face Overlay in Craniofacial Superimposition

Blinded manuscript (no authors details, as required).

**Abstract.** Craniofacial superimposition can provide evidence to support that some human skeletal remains belong or not to a missing person. It involves the process of overlaying a skull with a number of *ante mortem* images of an individual and the analysis of their morphological correspondence. Within the craniofacial superimposition process, the skull-face overlay stage just focuses on achieving the best possible overlay of the skull and a single *ante mortem* image of the suspect. Although craniofacial superimposition has been in use for over a century, skull-face overlay is still applied by means of a trial-and-error approach without an automatic method. Practitioners finish the process once they consider that a good enough overlay has been attained. Hence, skull-face overlay is a very challenging, subjective, error prone, and time consuming part of the whole process. Computer vision and soft computing arise as powerful tools to automate it, dramatically reducing the time taken by the expert and obtaining an unbiased overlay result. In this manuscript, we justify and analyze the use of these techniques to properly model the skull-face overlay problem. We also present the automatic technical procedure we have developed using these computational methods and show the four overlays obtained in two craniofacial superimposition cases. This automatic procedure can be thus considered as a tool to aid forensic anthropologists to develop the skull-face overlay, automating and avoiding subjectivity of the most tedious task within craniofacial superimposition.

3

## Acknowledgments

## 1. Introduction

Anthropologists have focused their attention on determining the identity of a missing person when skeletal information becomes the last resort for the forensic assessment [1, 2]. Craniofacial superimposition (CFS) [3], one of the approaches in craniofacial identification [4, 5], involves the superimposition of a skull (or a skull model) with a number of *ante mortem* images of an individual and the analysis of their morphological correspondence.

Since the first documented use of CFS for identification purposes [6] the technique has been under continuous improvement. Although the foundations of the CFS method were laid by the end of the ninetieth century [7, 8], the associated procedures evolved as new technology was available. Therefore, three main different approaches have been developed: photographic, video, and computer-aided superimposition [3, 9, 10].

The first superimpositions involved acquiring the negative of the original facial photograph and marking the landmarks on it. The same task was done with a photograph of the skull. Then, both negatives were overlapped and the positive was developed. This procedure was called photographic superimposition [3]. Many authors further developed photographic superimposition techniques to improve the scale and the orientation of the skull and the facial images [11, 12, 13].

Video superimposition was introduced in 1976 [14]. Instead of marking photographs, tracings or drawings in order to properly superimpose the skull and the face, video cameras provided a "live image" of the object (skull, photograph) focused. These systems presented an enormous advantage over the former photographic superimposition procedure by minimizing several problems associated to it. The video superimposition technique continued evolving [15, 16, 17] and it became the most broadly employed method.

The popularization, huge development and larger amount of possibilities offered by computers turned them into the next generation of CFS systems. Two different system categories arise within this group [10]. Non-automatic computer-aided methods use the computer for storing and/or visualizing the data [9, 18, 19, 20] but they do not consider the computational capacity to automate human tasks. Automatic computer-aided methods employ a computer program to accomplish any CFS sub-task itself [21, 22].

Regardless the technological means considered, we distinguished three different stages for the whole CFS process in [10]: 1) The first stage involves the acquisition and processing of the skull (or skull 3D model) and the *ante mortem* facial photographs together with the anatomical landmarks placed in the skull and the face; 2) The second stage is the skull-face overlay (SFO), which focuses on achieving the best possible superimposition of the skull and a single *ante mortem* image of the missing person. This process is repeated for each available photograph, obtaining different overlays. Skull-face overlay thus corresponds to what traditionally has been known as the adjustment of the skull size and its orientation with respect to the facial photograph [3]; 3) The third stage accomplishes decision making. Based on the superimpositions achieved in the latter SFO stage, the degree of support of being the same person or not (exclusion) is determined by considering the different factors studying the relationship between the skull and the face: the morphological correlation, the matching between the corresponding landmarks according to the soft tissue depth, and the consistency between asymmetries.

An important limitation of the CFS technique is the absence of a common methodology accepted worldwide[1]. Experts try to solve the CFS problem by applying a specific approach considering their knowledge and the

---

[1] There is an ongoing European project, entitled "New Methodologies and Protocols of Forensic Identification by Craniofacial Superimposition" (MEPROCS), aiming to develop a common methodology for the application of CFS. The interested reader is referred to http://www.meprocs.eu/

available technologies. During the SFO stage, most forensic anthropologists follow a trial-and-error method until they attain a good enough superimposition. The adjustment of the skull size and its orientation with respect to the facial photograph is a very challenging and time-consuming part of the CFS technique. That task can take hours to arrive at the best fit possible [15, 23]. In addition, an inherent uncertainty is introduced because of overlaying two different "objects" (a skull and a face) [24]. Hence, a systematic and automatic SFO method is a real need in forensic anthropology [23]. In the current contribution, we will specifically focus on the second task of CFS, i.e. SFO, with the aim to take a step ahead in the development of such automatic procedure.

Computational methods as computer vision (CV) and soft computing (SC) can be extremely useful for the latter aim. Computer vision includes techniques for processing, analyzing, segmenting, and registering image data in an automatic way [25]. Within CV, image registration (IR) aims to find a geometric transformation that overlays two images taken under different conditions (at different times, from different viewpoints, and/or by different sensors) [26]. Meanwhile, SC is aimed for the design of intelligent systems to process uncertain, imprecise, and incomplete information [27]. SC methods applied to real-world problems often offer more robust and tractable solutions than those obtained by more conventional mathematical techniques. Two of the main SC techniques are fuzzy logic (FL) and fuzzy set theory, which extend classical logic to provide a conceptual framework for knowledge representation under imprecision and the consequent uncertainty [28], and evolutionary algorithms (EAs), which are powerful bio-inspired search and optimization tools to automate problems solving in areas such as modeling, simulation, or global optimization [29].

From the CV point of view, a clear relationship arises between the SFO task and the IR problem. Skull-face overlay can be formulated following an IR approach aiming to superimpose the skull over the face in the photograph. However, this approach involves a complex optimization process. Since robust and precise results are demanded, IR methods based on EAs are a promising solution for facing this challenging optimization problem as they have already demonstrated in the clinical field [30].

Therefore, SFO shows many characteristics which make EAs and FL powerful tools to automate it applying:

- The manual procedure of SFO is a time-consuming task. The correct orientation of the skull with respect to the face in the photograph and the adjustment of its size can take several hours to complete [15].

- The underlying task is an extremely complex IR optimization problem (see Section 2.1), so SFO can be naturally modeled as a 3D-2D IR problem to be solved in an automatic way using EAs.

- Some landmarks present an imprecise definition [31]. The poor quality of some photographs, the pose of the face and other elements that originate the occlusion of some landmarks cause an inaccurate identification of the facial landmarks. Fuzzy sets can also be used to deal with these uncertainty sources in automatic procedures [24].

- Every forensic expert is prone to identify each specific landmark in a slightly different position, regardless of the means that are used to represent the involved objects (a skull and a face) [32, 33].

- The facial soft tissue, whose thickness differs for each corresponding pair of landmarks and varies among individuals, produces a mismatch among landmarks of the skull and the face, which can also be modeled using fuzzy sets [21, 24].

In fact, several successful applications of CV and SC in forensic anthropology have been developed so far, such as age estimation [34], skull 3D modeling [35], facial soft thickness prediction [36], or facial identification [37]. In general, the application of computational methods to forensic sciences is known as computational forensics [38]. The aim of this work is to justify and analyze the use of CV and SC techniques to model and solve the SFO problem. We also present the automatic SFO technical procedure that we have developed using these computational methods and show four skull-face overlays obtained using it.

## 2. Materials and Methods

Our study involves two SFO cases composed of a skull 3D model acquired with a Konica-Minolta$^{TM}$ 3D VI-910 laser scanner and two facial photographs of the same person (per case) obtained at different moments and in different poses. The skull 3D models and the facial photographs are stored using the Face2Skull$^{TM}$ software [39], which has been developed by our team. This tool allows forensic experts to precisely mark the cranial landmarks. The facial landmarks can be positioned in a precise and/or imprecise way. Face2Skull$^{TM}$ also

5

integrates and runs the proposed automatic SFO algorithm to adjust the skull to position it in the most appropriate orientation that can be later refined manually by the user. All the experiments have been performed on an Intel Core[TM] 2 Quad CPU Q8400 2.66 GHz, with 4GB RAM, running Windows 7 Professional[TM].

### 2.1 Skull-face overlay as a computer vision problem

Skull-face overlay requires positioning the skull in the same pose as the face of the photograph. From a pure CV point of view, the *ante mortem* photograph is the result of the 2D projection of a real (3D) scene that was acquired by a particular (unknown) camera [40]. In such a scene, the living was somewhere inside the camera field of view with a given pose.

The right way to face the SFO problem is to replicate the latter original scenario. To do so, a 3D model of the skull must be considered. Current 3D scanners allow the forensic anthropologist to get skull 3D models with a precision lower than one millimeter in a reasonable time [41]. Those models can be properly handled using the computer, making the automation of the SFO task easier. Once the skull 3D model has been obtained, the goal is to adjust its size and its orientation with respect to the head in the photograph. In addition, the specific characteristics of the camera must also be replicated to reproduce the original as far as possible.

First, the skull 3D model is positioned in the camera coordinate system through geometric transformations, i.e. translation, rotation, and scaling, which corresponds to the adjustment of the skull size and its orientation in the same angle as the face in the photograph [3, 15]. Then a perspective projection of the skull 3D model is performed onto the facial photograph. Thus, the described SFO approach involves a 3D-2D IR task, which applies a geometric transformation $f$ to the skull 3D model reproducing the face pose in the snapshot moment.

Figure 1 illustrates the different moments and elements that have to be considered to model the SFO problem. Figure 1a shows the moment of the photograph acquisition with the real scene enclosed by the 3D polygon in red (dark grey in the black and white version). The skull 3D model is obtained by using a range scanner as depicted in Fig. 1b. The replication of the original scenario by means of a 3D-2D IR task is shown in Fig. 1c.
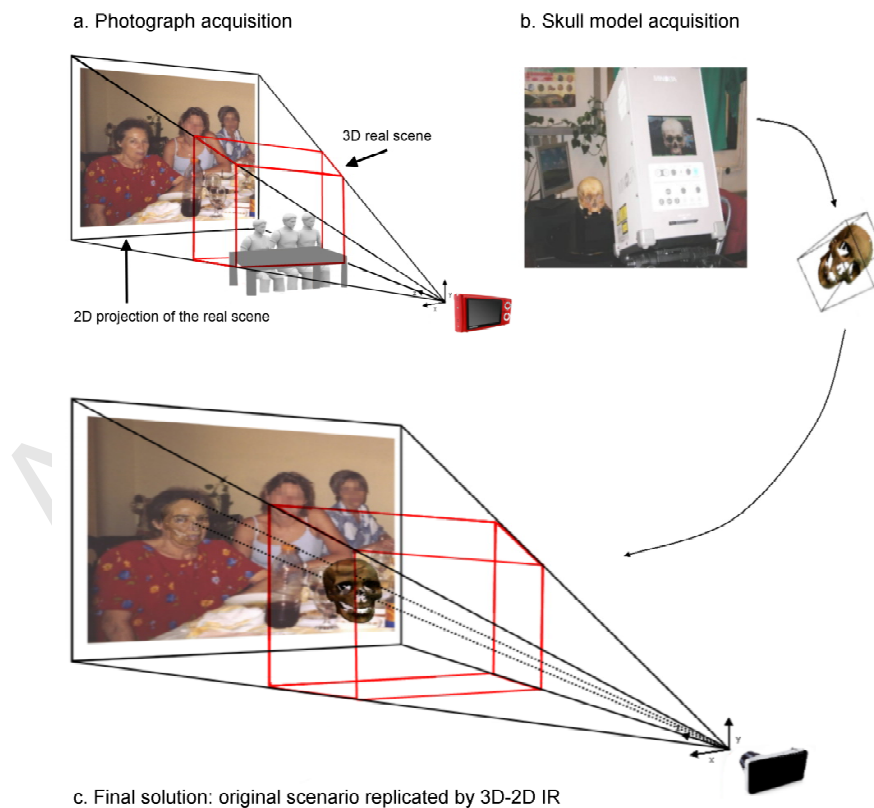


a. Photograph acquisition    b. Skull model acquisition

c. Final solution: original scenario replicated by 3D-2D IR

6

**Fig.1** Moment of the photograph acquisition (a) and skull 3D modeling (b). Orientation of the skull 3D model in the photograph by a location, scaling and perspective projection (c)

The 3D-2D IR task tries to reproduce the original scenario with several unknowns coming from two sources [42]:

- The camera configuration at the moment of the acquisition: the camera parameters have an influence in the SFO problem. Some of them are directly reflected on the photograph as the specific area of interest for the observer or the lightning conditions. However, other parameters cannot be easily derived from the photograph as the distance from the camera to the missing person or the focal length, which will determine what is finally projected into the picture.

- The skull 3D model: this skull model will have a specific orientation, resolution, and size given by the technical features of the considered scanner as well as by the skull modeling process. Notice that, the skull model size usually corresponds to the size of the real skull.

Hence, a 3D-2D IR process where all these unknown parameters have to be estimated seems to be the most appropriate formulation to automate SFO as it directly replicates the original scenario where the photograph was taken. Using the sets of cranial and facial landmarks, an automatic method will look for the geometric transformation (a translation, a rotation, a scaling, and a perspective projection) that minimizes the distances among the corresponding landmark pairs by properly overlaying the skull 3D model over the face in the 2D image (see Fig. 1c). Notice that, most of the software packages employed for performing SFO lack of specific tools to properly deal with the perspective effect.

The interested reader is referred to Appendix A (supplementary material), which provides a detailed description of the equations used to model the geometric transformations and the perspective projection.

### 2.2 Automatic skull-face overlay procedure

We present an automatic SFO technical procedure based on the use of CV and SC. The algorithm performs a 3D-2D IR approach considering a skull 3D model, obtained in a previous stage, and a facial photograph of a missing person as described in the latter subsection [24]. Cranial and facial landmarks have been previously assigned by a forensic anthropologist in the skull 3D model and the *ante mortem* photograph, respectively.

Thanks to the use of fuzzy sets, the proposed procedure faces many of the drawbacks associated with the inherent SFO uncertainty. In particular, the location of anthropometric landmarks is still a challenge when photographs become a key element of the forensic procedure [32, 33]. Our approach considers the way to invariantly locate anthropometric landmarks despite the photograph conditions [24, 43]. This method allows forensic anthropologists to mark facial landmarks by using ellipses. In this way, the experts can enclose a region where the landmark is placed without any doubt. The number of anatomical points located by the forensic expert can thus increase when those fuzzy landmarks are considered (see Appendix B-Fuzzy Landmarks in the supplementary material for detailed information). This is really useful for the proposed formulation of the SFO problem as a 3D-2D IR task.

The latter formulation depends on the position of the cranial and facial landmarks. It is necessary to define at least four non-coplanar facial landmarks to properly determine the geometric transformation $f$ (see Section 2.1). Otherwise, a wrong estimation of the perspective projection is always obtained, as in any 3D-2D IR or camera calibration problem [44, 45, 46]. Geometric objects lying in a common plane are said to be coplanar. Hence, we define as non-coplanar landmarks those points that lie in different planes of the skull or the face.
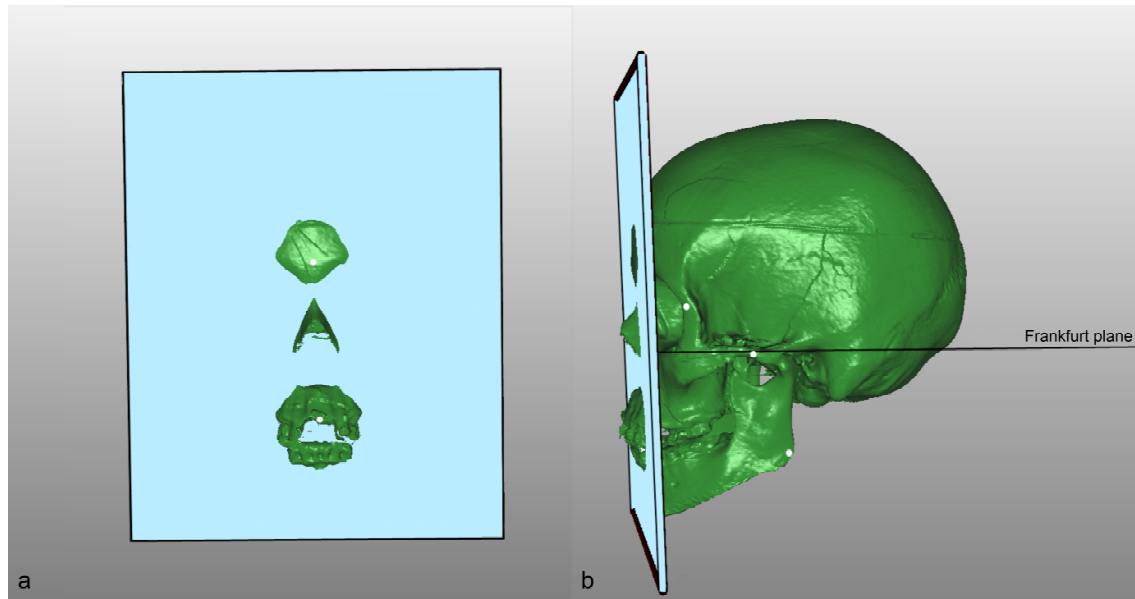
7

**Fig.2** Plane showing some typical coplanar landmarks in the skull 3D model (frontal and lateral views)

Figure 2 shows two views of the intersection of a plane with the skull 3D model. The plane includes some typical landmarks used to guide the SFO process like glabella, nasion, subnasale or prosthion. These four landmarks are coplanar [47]. In other words, such landmarks share a rather similar depth value. If we guided the SFO procedure with the latter landmarks only, a number of undesired solutions could be automatically obtained. This is due to the fact that there are a number of possible orientations for the skull in which those cranial and facial landmarks coincide, once the skull 3D model is projected onto the 2D photograph. As long as we consider a more diverse set of landmarks (in terms of depth information), undesired solutions will be avoided and the resolution of the corresponding system of equations will lead to the appropriate solution. Unlike the facial landmarks in the photograph, the precise location of a complete set of cranial landmarks in the skull 3D model is usually an easy task. Therefore, it is crucial to facilitate the location of a significant number of facial landmarks. As previously said, fuzzy landmarks make easier the location of an increasing number of anatomical points, which at the same time allows the forensic anthropologists to locate a non-coplanar set of landmarks to run the automatic SFO technical procedure.

Meanwhile, we should also note that the correspondence of a particular landmark on the surface of the skull and on the surface of the skin may not be symmetrical and perpendicular [48]. In addition, the facial soft tissue depth varies for each landmark correspondence and for population groups. That variability has been widely studied regarding different age and gender subgroups [49, 50, 51, 52]. In SFO, these distances are also affected by the use of a 2D photograph of a real (3D) scene (face pose effect).These variations must be taken into account by the SFO procedure to obtain a good superimposition. In our case, the mean distance and the corresponding standard deviations (and orientations if available) associated to each population group have been modeled using fuzzy sets (what we named as cranial-facial landmark matching uncertainty) and incorporated to the automatic SFO procedure. In particular, we have considered three studies: one well-known for Caucasian population [49, 50] and another two specifically focused on Mediterranean population [53, 54]. We have selected those data because the cases we used to test our method were all Spanish. As a consequence, our approach overcomes the use of tissue depth markers [55] (Fig. 3) as it directly incorporates the handling of the corresponding landmark spatial relationships within the SFO procedure (see Appendix B-Landmark Matching Uncertainty in the supplementary information for a detailed explanation).
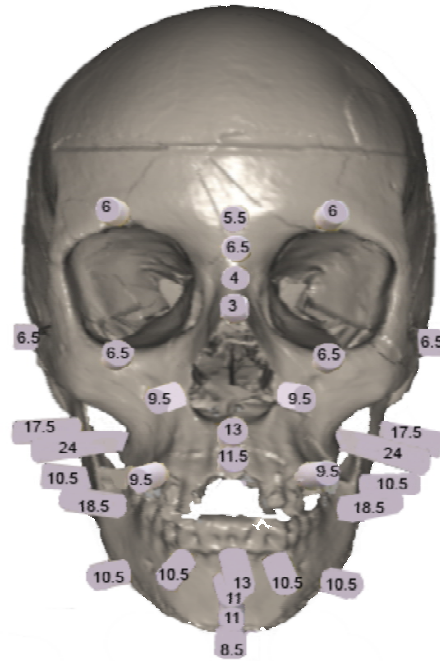
**Fig.3** Tissue depth markers using the distances (mm) of Stephan and Simpson [49, 50]

The preliminary steps of our SFO process involve the location of the precise and the imprecise (fuzzy) facial landmarks in the facial photograph and their corresponding cranial points in the skull 3D model, as well as the incorporation of the soft tissue depth measurements of a specific study. Once all this information is collected, the automatic SFO procedure can start. The iterative optimization task, depicted in Fig. 4, will look for a good solution to the underlying 3D-2D IR problem by means of EAs. This solution is a registration transformation $f$ that minimizes an SFO error function measuring the distances between the corresponding landmarks. The interested reader is referred to Appendix B-Fuzzy Distances for a detailed formulation.
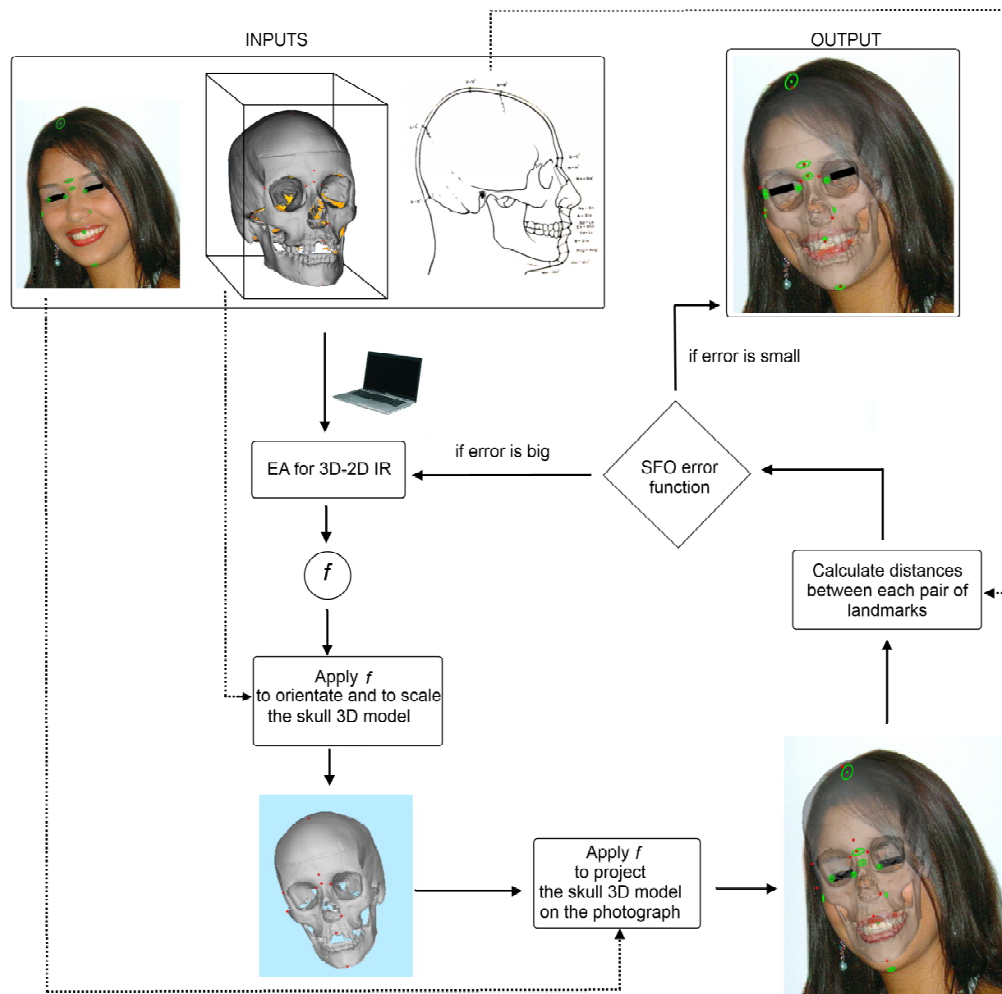
9

**Fig.4** Scheme of the SFO procedure as a 3D-2D IR problem

Figure 4 shows the EA-based process to obtain a skull-photograph superimposition. The algorithm takes the skull 3D model and the facial photograph with their respective landmarks placed by the forensic expert. Following a 3D-2D IR approach, our method automatically searches the geometric transformation $f$. This transformation orientates the skull, adjusts its size, and projects it onto the facial photograph leading to the best matching of the two sets of corresponding landmarks. The SFO quality is evaluated using a function based on fuzzy set theory. The evaluation function calculates the actual distance between each pair of anatomical landmarks in the current overlay considering the soft tissue thicknesses provided. The final solution corresponds to the superimposition that achieves the minimum error in the evaluation function after a given number of iterations.

## 3. Results

Some experiments have been accomplished to illustrate the behavior of our automatic SFO proposal. We should remark that every superimposition reported in the study has been directly obtained by our automatic method always taking less than four minutes. An additional manual refinement could be later performed by the expert if considered necessary.

Figures 5 – 6 show the superimpositions obtained for the two photographs of the first missing person (case 1). The outcomes achieved by our automatic procedure are reported in phantom mode (Figs. 5a and 6a). The resulting matching between pairs of cranial and facial landmarks is depicted in Figs. 5b and 6b. In particular, points in red color (in grey in the black and white version of this publication) correspond to the cranial landmarks after overlaying the skull 3D model on the photograph. Points colored in green (light grey in the black

and white version) are the facial landmarks marked by the expert in the photograph. We should remind that these facial points have been placed as either precise or imprecise (ellipses) landmarks. Each ellipse contains a green (light grey) point inside corresponding to its center.

The set of non-coplanar landmarks considered for the case 1 is detailed as follows:

Case 1, pose 1: The total number of landmarks identified by the experts was 10. Prosthion (pr) was placed in the photograph as a precise landmark. The remain landmarks were marked as imprecise landmarks in the photograph: vertex (v), glabella (g), nasion (n), exocanthion right (exr), endocanthion right and left (enr, enl), zygion right (zr), alare left (all), and gnathion (gn). The corresponding 10 cranial landmarks were placed as precise points in the skull 3D model.

Case 1, pose 2: The total number of landmarks considered was 15. All of them were identified in the photograph as imprecise landmarks: vertex (v), frontotemporale right and left (ftr, ftl), glabella (g), nasion (n), exocanthion right and left (exr, exl), endocanthion right and left (enr, enl), alare right (alr), subnasale (sn), zygion left (zyl), prosthion (pr), pogonion (pg), and gnathion (gn). The corresponding 15 cranial landmarks were placed as precise points in the skull 3D model.

Notice that, each pair of corresponding landmarks is expected to have a partial matching according to the soft tissue depth and the effect of the projection on a 2D image (Figs. 5b and 6b). We have modeled both the projection and the soft tissue depth within our technical procedure. Nevertheless, we should remark that the evaluation of the degree of matching between the skull and the face corresponds to the forensic expert within the decision making stage.
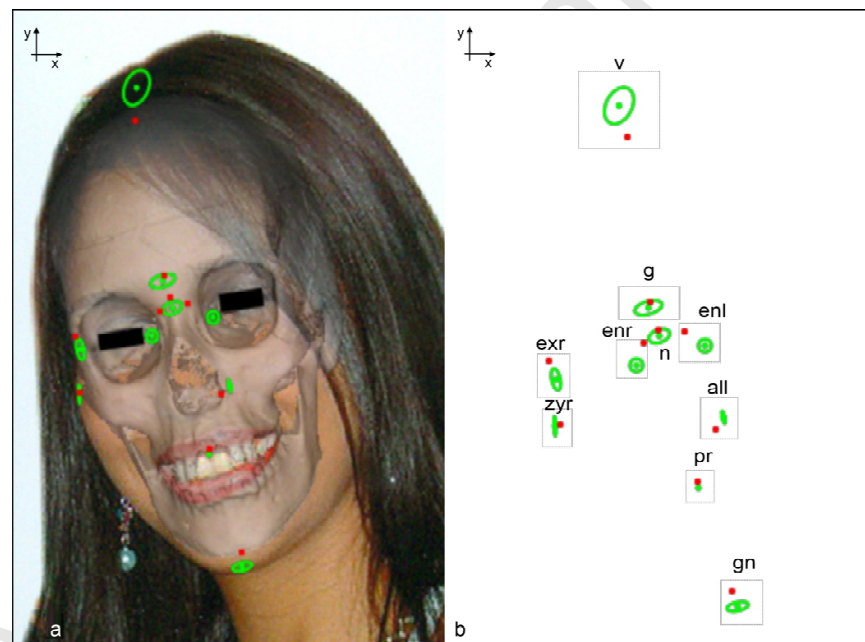


**Fig.5** (a) Automatically obtained superimposition for the left-side view photograph of the first case generated in phantom mode and (b) the resulting matching between pairs of cranial (red-dark grey) and facial landmarks (green-light grey)

**Fig.6** (a) Automatically obtained superimposition for the right-side view photograph of the first case generated in phantom mode and (b) the resulting matching between pairs of cranial (red-dark grey) and facial landmarks (green-light grey)
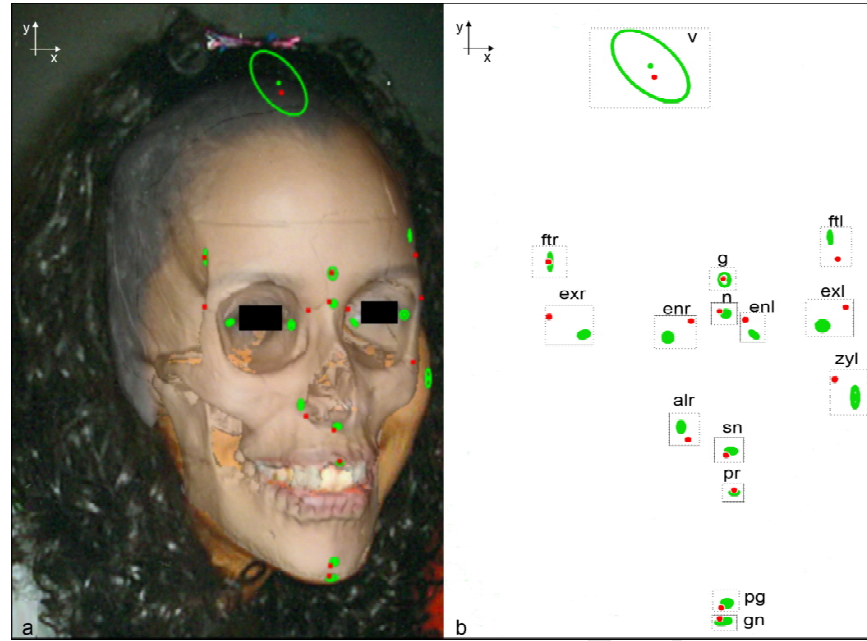
For illustrative purposes, Fig. 7 shows the superimposition obtained for the case 1 in the second pose using a set of coplanar landmarks to report the behavior of our procedure in these deceptive conditions. The number of landmarks considered for this experiment was nine: exocanthion left and right (exl, exr), endocanthion left and right (enl, enr), glabella (g), alare right (alr), subnasale (sn), pogonion (pg), and gnathion (gn). All of them were marked as imprecise landmarks using small ellipses in the photograph and as precise points in the skull 3D model. Although the technique manages to achieve a good matching between corresponding landmarks, Fig.7 clearly shows an unacceptable overlay. The projected skull is represented as a plane on the photograph that only overlaps part of the face, without the depth achieved in the non-coplanar case (Fig.6a). As said in Section 2.2 and showed in Fig. 2, the latter is a consequence of the wrong perspective projection estimation obtained when considering a set of coplanar landmarks. We should also remark that these kinds of outcomes are also obtained by software packages employed for performing SFO which lack of specific tools to properly deal with the perspective effect.
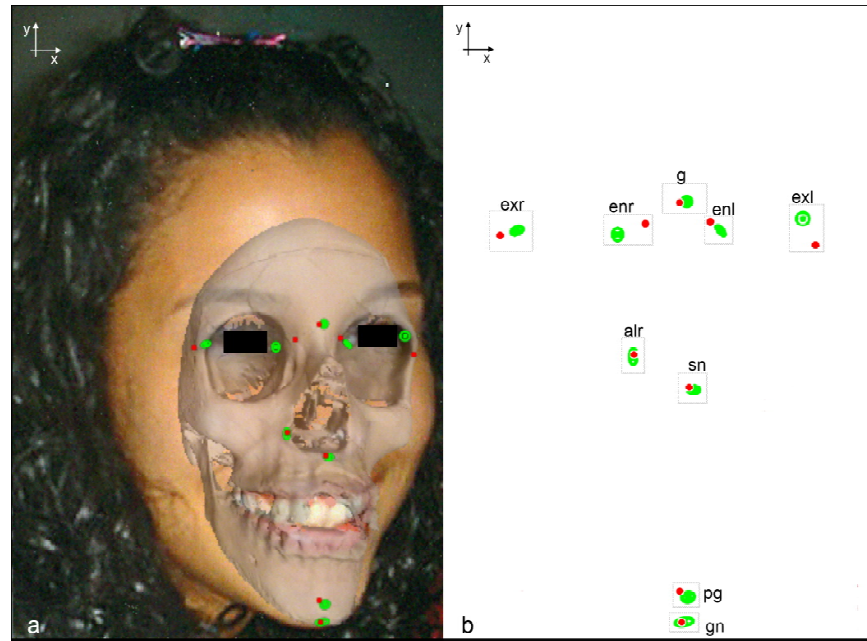
12

**Fig.7** (a) Automatically obtained superimposition for the right-side view photograph of the first case (using coplanar landmarks) generated in phantom mode and (b) the resulting matching between pairs of cranial (dark grey) and facial landmarks (light grey)

Figures 8 and 9 present the superimpositions for the case 2, considering two photographs in frontal (pose 1) and lateral-left (pose 2) views. The non-coplanar anatomical landmarks placed by the forensic expert for the case 2 are detailed below:

Case 2, pose 1: The experts identified 17 landmarks in the skull and the photograph. The number of precise landmarks marked by the expert in the photograph was 12: exocanthion left and right (exl, exr), endocanthion left and right (enl, enr), glabella (g), nasion (n), alare left and right (all, alr), subnasale (sn), prosthion (pr), pogonion (pg), and gnathion (gn). Five imprecise landmarks placed in the image: vertex (v), zygion left and right (zyl, zyr), and gonion left and right (gol, gor). The corresponding 17 landmarks were placed as precise points in the skull 3D model.

Case 2, pose 2: The total number of landmarks identified by the experts was seven. All of them were marked both in the skull 3D model and the photograph as precise landmarks: glabella (g), nasion (n), exocanthion left (exl), tragion left (tl), alare left (all), pogonion (pg), and gnathion (gn).
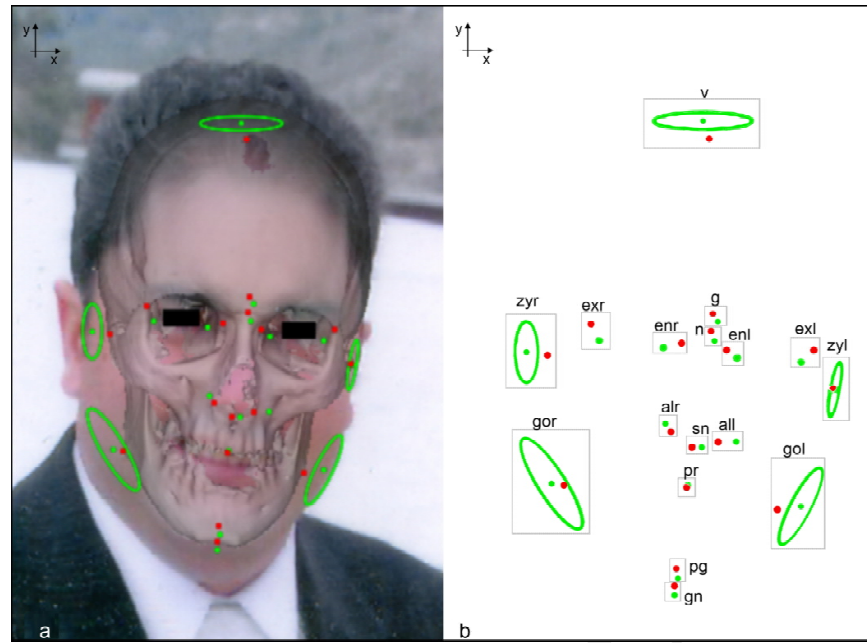
13

**Fig.8** (a) Automatically obtained superimposition for the front view photograph of the second case generated in phantom mode and (b) the resulting matching between pairs of cranial (red-dark grey) and facial landmarks (green-light grey)



**Fig.9** (a) Automatically obtained superimposition for the lateral left view photograph of the second case generated in phantom mode and (b) the resulting matching between pairs of cranial (red-dark grey) and facial landmarks (green-light grey)

## 4. Discussion and Conclusions

The SFO process is known to be a tedious and slow task [15] within CFS. In usual real-world situations, the overlay of the skull found on a single facial photograph can take up to several hours. Hence, there is a strong interest in designing methods to support the SFO task to make it become systematic, automatic, reproducible,

14

and quantifiable [23]. Notice that most of the software packages employed for performing SFO lack of specific tools to properly handle the perspective effect.

Our automatic procedure, based on CV and SC, performs SFO in the most natural way by replicating the original scene in which the photograph was taken. Analyzing the achieved overlays, it obtains good superimpositions in a drastically low processing time. Our technical procedure for SFO automates the usual repetitive approach. The orientation of the skull and its size adjustment with the face in the photograph can be performed in an automatic fashion simplifying the work of the experts. That strongly reduces the time required to get a valid superimposition and automates the application of the method.

In addition, it also considers the inherent uncertainty sources of the problem. This automatic procedure can be thus considered as an instrument to assist forensic anthropologists to carry out SFO, in both an automatic and unbiased fashion. This way, the expert can focus on the crucial CFS task of assessing the anatomical consistency between the face and the skull.

The first source of uncertainty is the replication of the photographing scenario. There are many unknown and/or uncertain parameters involved in the replication of the photographic conditions. We model this uncertainty as a computer vision problem [44, 45, 46, 55]. The landmark location uncertainty refers to the extremely difficult task of locating landmarks in an invariable place. Several works have recently studied the error caused by identifying facial landmarks on photographs [32, 33]. That repeatability has also been a further consideration in the study of Gordon and Steyn [49] where they adjusted the size of the landmarks according to their own repeatability study. In our approach, the forensic anthropologist can draw the location of any landmarks using an ellipse. The size of the ellipse will be directly related with the uncertainty (lack of accuracy) of its location, i.e., that ellipse delimitates a region where the anthropologist can assure the anatomical location of the landmark. We have mathematically modeled those landmarks using fuzzy sets (see the complementary material for the corresponding formulation). Finally, the cranial-facial landmark matching uncertainty refers to the imprecision in the matching of two sets of landmarks that belong to two different objects, a face and a skull. The correspondence between facial and cranial landmarks is not always symmetrical and perpendicular. We have also modeled this source of uncertainty using fuzzy sets taking into account the available information concerning soft tissue depths (see complementary material for the corresponding formulation).

The SFO is independent of the CFS decision making stage and our automatic (as well as any SFO) procedure must get the best possible overlay between the skull and the face regardless whether the skull belongs to the person in the photograph or not. There is a lack of objective measurements to assess the quality of the SFO results. Even so, we can appreciate that our automatic proposal properly deals with the perspective projection issue thanks to the considered CV approach. Furthermore, it achieves, as a whole, a competitive matching between pairs of corresponding cranial and facial landmarks due to the natural modeling of the landmark correspondences using SC methods.

Beyond the described uncertainty that is present in the SFO stage, the CFS also includes some other uncertainty sources related to the expression of morphological matching as a degree of truth and the final identification decision according to several confidence levels. The latter uncertain events could be properly modeled using fuzzy sets theory and fuzzy reasoning [56] (rather than probabilistic reasoning) due to the nature of the decision process followed by anthropologists. While probability theory is interested in trying to make predictions about events from a state of partial knowledge, fuzzy logic is all about degrees of truth - about fuzziness and partial or relative truth.

Although our proposal does not focus in identification, it properly models the sources of uncertainty inherent to the SFO stage. Thus, the uncertainty can be quantified and propagated to the next CFS stage, the decision making, where other sources of uncertainty can be modeled and aggregated to the uncertainty model. The latter should be considered by the forensic practitioner evaluating the skull-face relationship as follows: the lower amount of uncertainty the higher the confidence in the evaluation result, and *vice versa*. We aim to consider this challenge in future research works.

# References

1. Burns KR (2012) The forensic anthropology training manual 3rd ed. Pearson Education, Upper Saddle River, New Jersey

2. Cattaneo C (2007) Forensic anthropology: development of a classical discipline in the new millennium. Forensic Sci Int 165(2-3):185–193

3. Yoshino M (2012) Craniofacial superimposition. In: Wilkinson C, Rynn C (eds) Craniofacial Identification, University Press, Cambridge, pp 238-253

4. Aulsebrook WA, Iscan MY, Slabbert JM, Beckert P (1995) Superimposition and reconstruction in forensic facial identification: a survey. Forensic Sci Int 75(2-3):101-120

5. Stephan CN (2009) Craniofacial identification: Techniques of facial approximation and craniofacial superimposition. In: Blau S, Ubelaker DH (eds) Handbook of Forensic Anthropology and Archaeology, Left Coast Press, Walnut Creek, 25:304-321

6. Glaister J, Brash JC (1937) Medico-legal aspects of the Ruxton case. E and S Livingstone, Edinburgh

7. Bertillon A (1896) The Bertillon System of Identification. McClaughry RW, Chicago, IL

8. Broca P (1875) Instructions craniologiques et craniométriques de la Société d'Anthropologie de Paris [in French]. In: G Masson (ed), vii, Paris

9. Ubelaker DH, Bubniak E, Odonnell G (1992) Computer-Assisted Photographic Superimposition. J Forensic Sci 37(3):750-762

10. Damas S, Cordón O, Ibáñez O, Santamaría J, Alemán I, Botella M et al (2011) Forensic identification by computer-aided craniofacial superimposition: A survey. ACM Computing Surveys (CSUR) 43(4):27

11. Dorion RB (1983) Photographic superimposition. J Forensic Sci 28(3):724-734

12. Brocklebank LM, Holmgren CJ (1989) Development of equipment for the standardization of skull photographs in personal identifications by photographic superimposition. J Forensic Sci 34(5):1214-1221

13. Maat GJ (1989) The positioning and magnification of faces and skulls for photographic superimposition. Forensic Sci Int 41(3):225-235

14. Helmer R, Grüner O (1976) Vereinfachte Schädelidentifizierung nach dem Superprojektionsverfahren mit Hilfe einer Video-Anlage [in German]. Z für Rechtsmedizin 80(3):183-187

15. Fenton TW, Heard AN, Sauer NJ (2008) Skull-photo superimposition and border deaths: identification through exclusion and the failure to exclude. J Forensic Sci 53(1):34-40

16. Seta S, Yoshino M (1993) A combined apparatus for photographic and video superimposition. In: Iscan MY and Helmer RP (eds) Forensic Analysis of the Skull, Wiley, New York, pp 161-169

17. Lan Y, Cai D (1993) Technical advances in skull-photo superimposition. In: Iscan MY and Helmer R (eds) Forensic Analysis of the Skull, Wiley, New York, pp 119-129

18. Pesce Delfino V, Colonna M, Vacca E, Potente F, Introna F Jr (1986) Computer-aided skull/face superimposition. Am J Forensic Med Pathol 7(3):201-212

19. Ricci A, Marella GL, Apostol MA (2006) A new experimental approach to computer-aided face/skull identification in forensic anthropology. Am J Forensic Med Pathol 27(1):46-49

20. Al-Amad S, McCullough M, Graham J, Clement J, Hill A (2006) Craniofacial identification by computer-mediated superimposition. J Forensic Odontostomatol 24(2):47-52

16

21. Ghosh AK, Sinha P (2001) An economised craniofacial identification system. Forensic Sci Int 117(1-2):109-119

22. Nickerson BA, Fitzhorn PA, Koch SK, Charney M (1991) A methodology for near-optimal computational superimposition of two-dimensional digital facial photographs and three-dimensional cranial surface meshes. J Forensic Sci 36(2):480-500

23. Ubelaker DH (2000) A history of Smithsonian-FBI collaboration in forensic anthropology, especially in regard to facial imagery [Abstract]. Forensic Sci Communications 2(4)

24. Ibáñez O, Cordón O, Damas S, Santamaría J (2011) Modeling the skull–face overlay uncertainty using fuzzy sets. IEEE Trans Fuzzy Syst 16(5):946-959

25. Sonka M, Hlavac V, Boyle R (2007) Image Processing, Analysis, and Machine Vision $3^{rd}$ ed. Thomson-Engineering, Toronto, Canada

26. Zitova B, Flusser J (2003) Image registration methods: a survey. Image Vision Comput 21(11):977-1000

27. Bonissone PP (1997) Soft computing: the convergence of emerging reasoning technologies. Soft Comput 1(1):6-18

28. Zadeh LA (1994) Soft Computing and Fuzzy Logic. IEEE Softw 11(6):48-56

29. Eiben AE, Smith JE (2003) Introduction to Evolutionary Computation. Natural Computing Series. Springer, Heidelberg

30. Damas S, Cordón O, Santamaría J (2011) Medical Image Registration Using Evolutionary Computation: An Experimental Study. IEEE Comput Intell M 6(4):26-42

31. Bookstein FL (1997) Morphometric Tools for Landmark Data: Geometry and Biology. Cambridge University Press, New York

32. Cummaudo M, Guerzoni M, Marasciuolo L, Gibelli D, Cigada A, Obertovà Z, Ratnayake M, Poppa P, Gabriel P, Ritz-Timme S, Cattaneo C (2013) Pitfalls at the root of facial assessment on photographs: a quantitative study of accuracy in positioning facial landmarks. Int J Legal Med 127(3):699-706

33. Campomanes-Álvarez BR, Ibáñez O, Navarro F, Alemán I, Cordón O, Damas S (2014) Dispersion assessment in the location of facial landmarks on photographs. Int J Legal Med, in press, doi: 10.1007/s00414-014-1002-4

34. Aja-Fernández S, Luis-García R, Martín-Fernández MA, Alberola-López C (2004) A computational TW3 classifier for skeletal maturity assessment. A Computing with Words approach. J Biomed Inform 37(2):99-107

35. Santamaría J, Cordón O, Damas S, García-Torres JM, Quirin A (2009) Performance evaluation of memetic approaches in 3D reconstruction of forensic objects. Soft Comput 13(8):883-904

36. Dinh QH, Ma TC, Bui TD, Nguyen TT, Nguyen DT (2011) Facial Soft Tissue Thickness Prediction Using Anthropometric Distances. In: Nguyen NT, Trawinski B, Jung JJ (eds), 351, New Challenges for Intelligent Information and Database Systems in Computational Intelligence, Springer, Berlin Heidelberg, pp 117-126

37. De Angelis D, Sala R, Cantatore A, Grandi M, Cattaneo C (2009) A new computer-assisted technique to aid personal identification. Int J Legal Med 123(4):351–356

17

38. Franke K, Srihari SN (2008) Computational Forensics: An Overview. Lecture Notes in Computer Science (LNCS) 5158:1-10

39. http://www.face2skull.net/ [Accessed: 1st May 2014]

40. Faugeras O (1993) Three-Dimensional Computer Vision. A Geometric Viewpoint. The MIT Press, Cambridge

41. Park HK, Chung JW, Kho HS (2006) Use of hand-held laser scanning in the assessment of craniometry. Forensic Sci Int 160(2-3):200-206

42. Ibáñez O, Ballerini L, Cordón O, Damas S, Santamaría J (2009) An experimental study on the applicability of evolutionary algorithms to craniofacial superimposition in forensic identification. Inf Sci 179(23):3998-4028

43. Ibáñez O, Cordón O, Damas S (2012) A cooperative coevolutionary approach dealing with the skull–face overlay uncertainty in forensic identification by craniofacial superimposition. Soft Comput 18(5):797-808

44. Chatterjee C, Roychowdhury VP (2000) Algorithms for coplanar camera calibration. Machine Vision and Applications 12:84–97

45. Abdel YI, Karara HM (1971) Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry. In: Proceedings of the Symposium on Close-Range Photogrammetry, 1:1-18

46. Santamaría J, Cordón O, Damas S, Ibáñez O (2009) Tackling the coplanarity problem in 3D camera calibration by means of fuzzy landmarks: a performance study in forensic craniofacial superimposition. In: 3DIM Workshop, IEEE International Conference on Computer Vision, Kyoto, Japan, pp 1686–1693

47. Abbott P (2004) In and Out: Coplanarity. Mathematica J 9:300-302

48. Gordon GM, Steyn M (2012) An investigation into the accuracy and reliability of skull-photo superimposition in a South African sample. Forensic Sci Int 216(1–3):198.e1–6

49. Stephan CN, Simpson EK (2008) Facial soft tissue depths in craniofacial identification (Part I): an analytical review of the published adult data. J Forensic Sci 53(6): 1257-1272

50. Stephan CN, Simpson EK (2008) Facial soft tissue depths in craniofacial identification (Part II): an analytical review of the published sub-adult data. J Forensic Sci 53(6):1273-1279

51. Ferrario VF, Sforza C (1997) Size and shape of soft tissue facial profile: effects of age, gender, and skeletal class. Clef Palate Cranifac J 34(6):498-504

52. Rhine JS, Campbell HR (1980) Thickness of facial tissues in American blacks. J Forensic Sci 25(4):847-858

53. Valencia-Caballero L (2007) Metodología para elaborar reconstrucciones faciales empleando gráficos computarizados tridimensionales [in Spanish]. PhD Dissertation. University of Granada, Spain

54. Navarro-Merino FJ (2011) Superposición Craneofacial para Identificación Humana. Un Estudio en Población Mediterránea [in Spanish]. PhD Dissertation. University of Granada, Spain

55. Taylor KT (2001) Forensic Art and Illustration, CRC Press, New York

56. Zadeh LA (1965) Fuzzy sets, Information Control 8 (3): 338–353