Forensic Science International
108 (2000) 81–95

Forensic Science International

www.elsevier.com/locate/forsciint

Facial reconstruction using 3-D computer graphics

P. Vanezis[a,*], M. Vanezis[a], G. McCombe[a], T. Niblett[b]

[a]*Department of Forensic Medicine and Science, University of Glasgow, Glasgow G12 8QQ, UK*
[b]*Turing Institute, University of Glasgow, Glasgow G12 8QQ, UK*

Received 16 December 1998; accepted 22 February 1999

Abstract

Facial reconstruction using 3-D computer graphics is being used in our institute as a routine procedure in forensic cases as well as for skulls of historical and archaeological interest. Skull and facial data from living subjects is acquired using an optical laser scanning system. For the production of the reconstructed image, we employ facial reconstruction software which is constructed using the TCL/Tk scripting language, the latter making use of the C3D® system. The computer image may then be exported to enable the production of a solid model, employing, for example, stereolithography. The image can also be modified within an identikit system which allows the addition of facial features as appropriate.

Keywords: Forensic facial reconstruction; 3-D computer graphics; Optical laser scanner

1. Introduction

The discovery of skeletalised, decomposed or badly mutilated remains, where identity is unknown and not thought to belong to a particular person, leaves the investigator with very little to assist with personal identification. In such cases one is limited to the general aspects of identification, i.e. age, race, sex, stature and build. Initially, extensive enquiries are made and records of missing persons carefully examined. If it has not been possible to identify the remains when the usual avenues have been explored, then the possibility of reconstruction of the face from the skull is considered. The purpose of such a reconstruction is to trigger the recognition process to see whether a name can be

*Corresponding author. Tel.: +44-141-330-4573; fax: +44-141-330-3706.

0379-0738/00/$ – see front matter
PII: S0379-0738(99)00026-2

put to a face. Once this is achieved then one can proceed to a more definitive identification using comparative ante-mortem data.

It is not claimed that a reconstruction will produce an accurate likeness of the person during life but the task is successful if some aspect of the reconstruction facilitates recognition. Notwithstanding, every attempt is made to produce a face which matches the underlying skull.

A number of traditional methods of reconstruction are in present use, both three dimensional clay modelling techniques as well as two dimensional methods employing artists' impressions. More recently, three dimensional computer graphics have been employed to produce facial reconstructions.

We describe here the method employed by our institute both for forensic casework and historical and archaeological projects. In view of the rapid changes that are taking place in computer technology, the system we use at the present time continues to undergo development.

2. Methodology

In order to produce a reconstructed face from a skull the procedure we follow involves a number of stages as set out below.

- Anthropological assessment of the skull.
- Preparation of the skull.
- Acquisition of data.
- Manipulation of images to produce the reconstructed face.
    - Systems and reconstruction software.
    - Landmark placement on skull.
    - Selection of facial template from database.
    - Placement of facial landmarks.
    - Production of the reconstructed face.
- Exporting the reconstructed face.

2.1. Anthropological assessment of the skull

Before attempting reconstruction, it is necessary to make a general assessment of the skull for age, race and sex. In addition, the build of the person and stature, may be ascertained from examination of the post-cranial skeleton and other associated findings such as clothing and footwear. Furthermore, it is essential to carry out a careful examination of the skull, looking for asymmetry and any features which may be sufficiently discriminatory which will assist in the reconstruction.

2.2. Preparation of the skull

One of the advantages that the computerised system has over manual sculpting methods is that there is no need to produce a cast of the skull. The method of obtaining an image of the skull is non-invasive and non-destructive and so the original skull may be used since the only requirement is that it is rotated on a platform and a laser beam projected on to it. Once this has been completed then the skull may be stored safely away. It is necessary, however, in order that no data are lost, that all defects or natural orifices be blocked with cotton wool or similar substance so that the projected laser beam does not pass through the specimen. Placement of the skull on to the platform for rotation is achieved by fixing the base of the skull on a cylinder. We use adhesive tape as this does not interfere with the laser beam projection and can be easily removed. In most cases submitted to us the mandible requires articulation with the rest of the skull. We have found that a plastic fixer such as BLUE-TAC™ is ideal for this purpose. Plasticine, which tends to cling to bone and is difficult to remove, should be avoided.

2.3. Data acquisition

A laser scanning system for measuring facial surfaces (Facia Optical Surface Scanner™) developed by the Medical Physics Department of University College London [1] is used for this purpose (Fig. 1). With the room in darkness, a thin beam of light is emitted from the laser and strikes a small cylindrical prism filter in front which fans it out to produce a vertical line on the skull which is 0.7 mm wide (Fig. 2). The laser used is low power (1 mW) and the intensity does not exceed 5 W/cm^2. When a live subject's face is scanned, despite the fact that there is no hazard to the person, it is recommended that the beam is not observed directly any closer than 30 cm from the laser source.

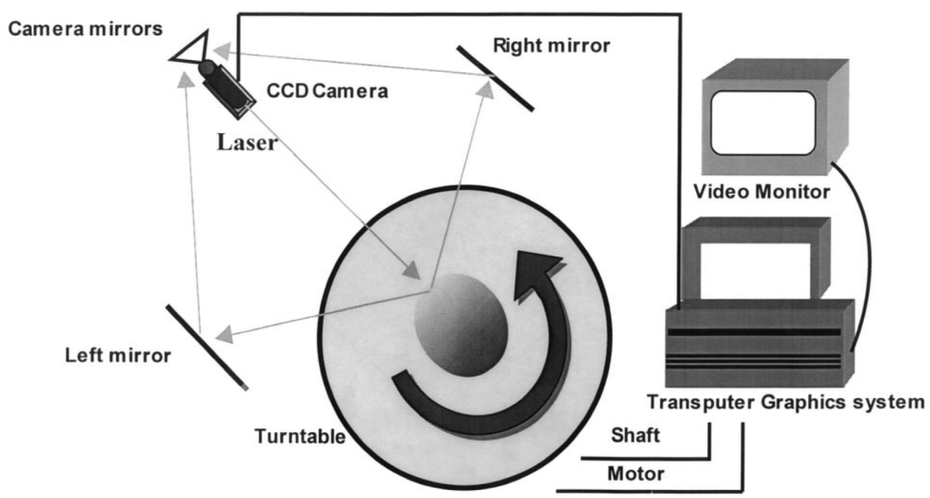


Fig. 1. The optical laser scanner system.

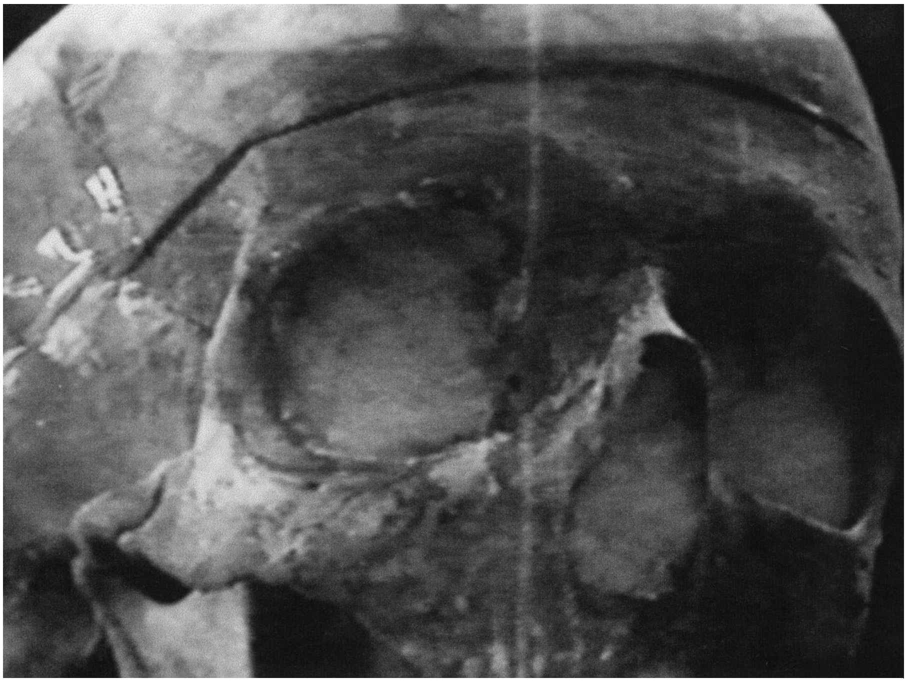


Fig. 2. Detail of skull showing vertical line from laser scanner.

The skull is secured on a platform (or the subject sat in a chair) which is rotated through 360° under computer control at a distance of 1 m from the laser source. The height of the platform and chair can be adjusted as required. An optical shaft encoder is attached to the platform and as the skull or subject turns, a series of profiles are collected at programmed intervals. Up to 198 profiles are read into the computer at one scan, although we can acquire up to 250 if required, memory permitting. The illuminated profile is reflected off two sets of mirrors (to the left and right of the object), producing two profile lines which are captured by a video camera. The distance between the two profile lines as seen by the camera is proportional to the distance of the profile from the centre of rotation. By measuring the distances between corresponding points on the two profile lines, we can produce a set of discrete points on the actual profile. As the object continues to rotate, further profiles are illuminated and the discrete points on them are captured. The time taken for a complete rotation is ~55 s, by the end of which, we have acquired around 50 000 discrete points on the object with a resolution of 0.5 mm, spaced ~1 mm vertically and 3 mm horizontally.

The raw data from the scanner is stored in the form of an LSM (Laser Scan Multiple). An LSM file contains each of the measurements from each profile captured by the camera. These measurements are converted into Cartesian co-ordinates by our software.

3. Manipulation of images to produce the reconstructed face

3.1. Systems and reconstruction software

An INMOS transputer system [2] hosted by an Intel 80386 personal computer is used to calibrate and drive the scanner and to view images. However, our recently developed facial reconstruction software is now implemented on a Silicon Graphics Indigo^2 workstation, running the IRIX 5.3 operating system.

The user interface to our Facial Reconstruction (FR) software is constructed using the TCL/Tk scripting language. The scripts make use of the C3D® system, developed by the Turing Institute of Glasgow University. This is a major C++ subroutine library built using OpenGL, which provides industry standard methods for viewing and manipulating objects in three dimensions. The C3D® system itself provides much more than this, including the glue that allows TCL/Tk to make use of the C3D® system.

The FR software provides facilities to view a skull and face, position corresponding landmarks on them and perform a reconstruction using a predefined set of tissue thicknesses (thin, medium or fat), possibly augmented by some user-defined thicknesses. It has been designed to make the process of performing a reconstruction as straightforward as possible, allowing the operator to refine a reconstruction based on experience and see the effects at the touch of a button. Important features include:

- being able to rotate objects in real time
- being able to zoom-in and zoom-out on objects in real time
- being able to view objects from three different vantage points at the same time (by default: left profile, anterior–posterior and right profile) to assist in the placement of landmarks
- repositioning landmarks easily using a mouse to drag them from one position to another
- identifying landmarks simply by moving the mouse pointer over them
- being able to see a skull landmark in three dimensions, including the direction in which it points
- being able to alter the direction of a skull landmark using the mouse
- alpha-blending (mixed view) to allow the operator to see where the skull landmarks are in relation to the reconstructed face
- being able to store faces with their facial landmarks so that previously marked-up faces can be reused.

Our software can be adapted for measurement with the inclusion of a third type of landmark — *a measure-mark*. These could be placed upon the skull, face or reconstructed face and the distance between two such measure-marks calculated. This would only be a direct distance as surface distances cannot easily be calculated owing to the data-hiding implementation of the C3D® subroutine library.

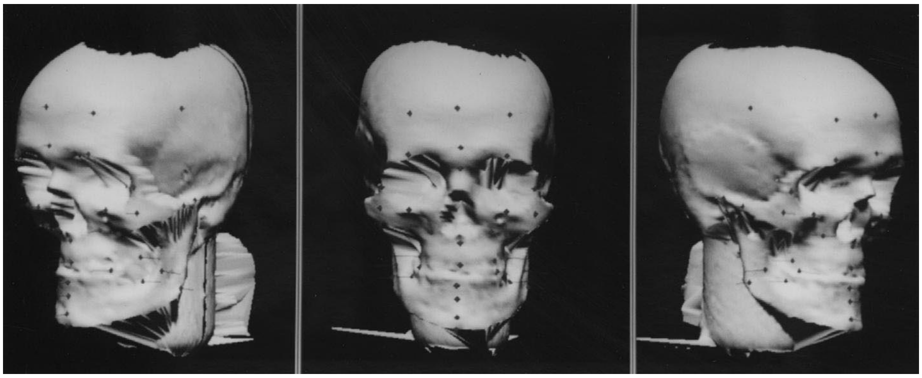


Fig. 3. Views of digitised image of skull with landmarks in position.

3.2. Landmark placement on skull

Once the digitised three-dimensional skull image has been acquired and displayed, landmarks are then located on the skull (Fig. 3). Each skull landmark is uniquely numbered and has a name which describes its anatomical location. Associated with each landmark is a set of tissue thicknesses derived from measurements taken from real subjects (our current data is from Rhine and Moore [3]). These thicknesses are classified by anthropological type (e.g. Caucasian male) and are further subdivided for thin, medium and fat tissue thicknesses. A fourth, user-defined tissue thickness can be used to replace any of these values as required. The soft tissue thicknesses are represented as lines projecting from these landmarks and the length of these lines correspond to the depth of the soft tissue at that particular location. Furthermore, the operator can alter the direction of these lines projecting from the skull landmarks to match the required direction and location of soft tissue thicknesses, very much like the pegs used in manual facial reconstruction.

The system, in addition to allowing adjustment of facial thickness data, also allows for the addition of other similar databases or replacement of existing ones. The type of landmarks used are those for which facial thickness data is available. There are 40 skull landmarks and the same number of corresponding facial landmarks available for use and more may be added if required. It is crucial that the landmarks are placed in their correct anatomical location and if the operator is not satisfied with placement of a particular mark, it can be relocated to a preferred position. Some landmarks for example are best located by rotating the skull and face laterally.

3.3. Selection of facial template from database and placement of facial landmarks

The next stage is the selection of a facial template from a database of faces which have been scanned into the system. A face is chosen which has standard average features and matches the skull anthropologically. Landmarks are then placed on the face which correspond in location and name to those of the skull (Fig. 4). The number given to each

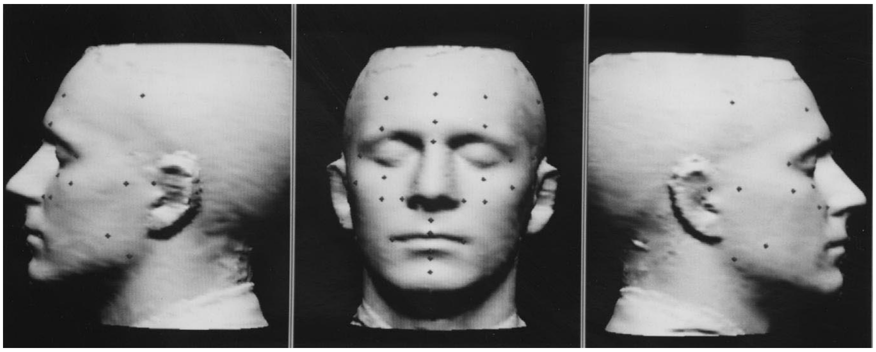


Fig. 4. Views of male facial template with landmarks in position.

facial landmark is the same as the number given to the skull landmark that will point to it after the reconstruction. This one-to-one mapping is used to calculate the mathematical transformation which will produce the reconstructed face. Since landmark placement and correspondence between facial landmarks and skull landmarks is crucial to producing a realistic reconstruction that will faithfully match the skull anatomy, detailed knowledge of craniofacial correlation is essential. In addition to soft-tissue thickness data, the operator needs to know how the corresponding points between skull and face are related. George [4,5] for example, argues that one needs to know if these points are perpendicular or angled and if they are angled, by how much and Peck and Peck [6] state that 'ultimate appreciation of the profile depends upon the manner in which these points are connected'. Thus, when the operator is satisfied that all the landmarks have been correctly placed then facial thickness data is selected to give either a fat, medium or thin appearance to the face. The distance between and relative position of these corresponding landmarks on the skull and the face after the reconstruction has been performed, will be the tissue thickness chosen.

3.4. Production of the reconstructed face

The computer is now ready to fit the face over the skull. The process involves moving every point on the original face to a new position. This is achieved using a three dimensional transformation termed a warp. First a Procrustes transform [7] is determined to provide a best-fit mapping between the before and after positions of the facial landmarks (the result of the reconstruction places each facial landmark at the position pointed to by its corresponding skull landmark). A set of radial-base functions is then derived [8] and combined with the Procrustes transform to produce the final warp. The warp is then applied to every point on the original face, producing the reconstructed face (Fig. 5).

The warp produces the reconstructed face in a point wise fashion. The advantage of this, as opposed for example, to deformation of a triangular mesh as described by Waters and Terzopoulos [9], is that it is independent of the representation of the face. The corresponding disadvantage is that detailed information about how the deformation

Fig. 5. Views of reconstructed male face.

should proceed based on particular facial properties cannot be used. It should be noted that mesh-based procedures will not work for the reconstruction of faces from skulls, as there is no skull surface from which to work.

Superimposition of the skull and the reconstructed face (alpha blending) allows the operator to check soft tissue to skull alignment and to see if there are any obvious errors (Fig. 6).

3.5. Exporting the reconstructed face

One of the major problems with any reconstruction from a skull is the uncertainty of the individual characteristics of soft tissue structures such as eyes, ears, lips and nose. In addition, with the laser scanning system, the faces within the database all have closed eyes, as described earlier. Thus it is necessary to add opened eyes, facial and head hair to give a realistic appearance to the face. The software provides the facility to export a two-dimensional view from the three-dimensional image in a TIFF or JPEG format. The file can then be imported into a police identikit system such as CD-fit™ or E-fit™, which allow the addition of features. In a forensic case, if there is no information available, the

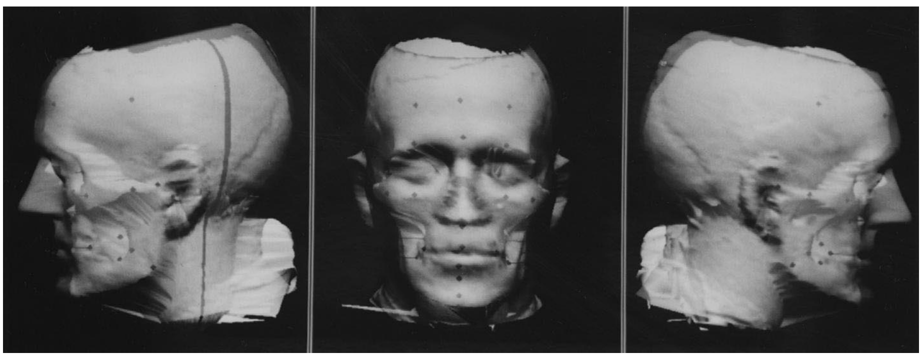


Fig. 6. Superimposition views of the skull with the reconstructed face to check soft tissue alignment.

style and length of hair which is added to the head should be kept as neutral as possible and be appropriate for the age group in question. Head hair characteristics such as curls, waves, length and colour and facial hair such as moustache or beard should only be added where such information might be available from the site of discovery of the remains. When dealing with a historical reconstruction it is appropriate to add a hair style of the period in question. When opened eyes are added, they are selected so that they match the dimensions of the closed eyes of the reconstructed face (Fig. 7a and b).

Images can also be exported as VRML file format via the internet to authorised distant sites such as police stations and may be used for the production of a solid model such as a stereolithograph [10]. This may then be refined by an artist, if required, to give a more ‘humanised’ appearance. An artist may also produce a bust of the reconstructed image working directly from the image on the computer monitor.

4. Examples of reconstructions carried out

4.1. Identification of a murder victim

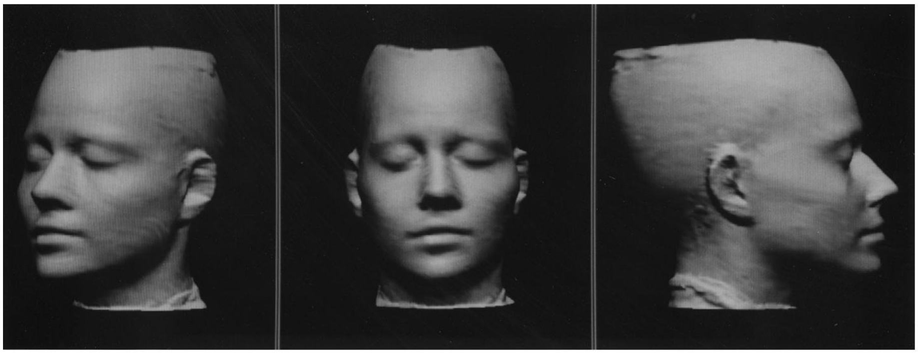
This case was described briefly by us [11], and is now presented in detail here.

In 1991 an exhumation was carried out on a woman who had 2 years previously had a post-mortem carried out when death was thought to be due to natural causes. The reason for the exhumation was that further information had come to light that she had in fact been strangled. This was confirmed at the exhumation. However, although she was a homeless person, suffering from chronic alcoholism, and known to a circle of similar persons in west London, no one knew her true identity. Furthermore, because of the nature of her acquaintances, no one was able to give a helpful description of her facial appearance before death, other than to inform us that she wore glasses. Her face was mummified and details of fine features unrecognisable. She was edentulous and from the alveolar surfaces of the maxilla and mandible, it was clear that she did not wear dentures. Her hair was present, therefore it was appropriate to use this in our reconstructed image. The results of the reconstructed image and its treatment using CD-fit™ is shown in Fig. 8. Within a few days of publication of the images we were informed of a possible person who might be the victim. We were sent photographs (Fig. 9) which we matched to the skull using video-superimposition and confirmed the identity with mitochondrial DNA from her skull compared with her mother and sister.

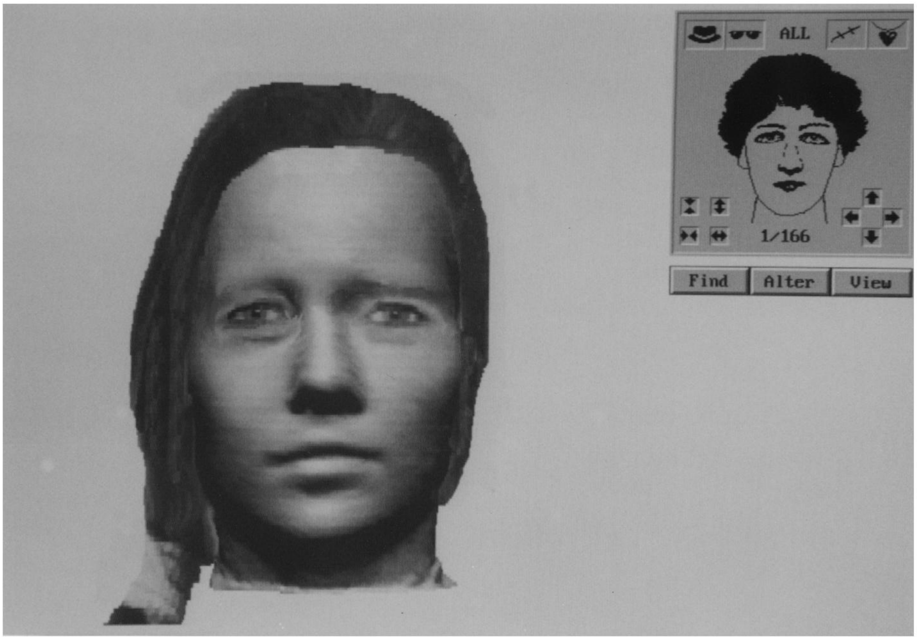
4.2. Reconstruction of historical/archaeological skulls

From time to time reconstructions are also carried out which are of historical or archaeological interest. One example of such a reconstruction was based on a stereolithograph of a skull of an Egyptian mummy dating back to the first century AD which was housed in the Carlsberg Glyptotek Museum in Copenhagen and was originally from the Roman cemetery of Hawara in El-Faiyum [12].

A further example involves reconstruction of the face of the Iceman, a 5300-year-old early copper age mummified male corpse found in the Otzaler Alps of the Southern



(a)



(b)

Fig. 7. (a) Views of a female reconstructed face prior to the addition of further facial features. (b) Frontal view after the addition of hair and matching opened eyes.

Tyrol. A stereolithograph of the skull derived from a CT scan was used for the reconstruction. The final image was produced using CD-fit™ with the importation of facial hair. A full size model has since been produced, based on our reconstruction, and is exhibited in Bolzano, Italy.

Fig. 8. Reconstructed image of murder victim.

4.3. Mass grave identifications

Computerised facial reconstruction using the earlier version of our system has been employed in the identification of victims murdered by the Pinochet regime in Santiago, Chile in 1973 [13]. Fourteen skulls from a mass grave containing 129 victims were reconstructed from plaster casts. The reconstructed images were successfully compared with photographs of suspected victims and results confirmed by superimposing skull casts with the photographs independently by another laboratory. The author relied on the face shape, dominated by the underlying skull, to carry out the matches. No reliance was placed on the detail of individual facial features such as eyebrows, opened eyes, lips and ears as these could not be predicted from the available information from the grave site.

5. Discussion

Three dimensional computer imaging of human anatomy for diagnostic, therapeutic and educational purposes has been in existence for a number of years with the

Fig. 9. Photograph sent to us by family for skull-photo superimposition.

introduction of magnetic resonance imaging, computerised axial tomography and a number of other imaging techniques. With regard to facial visualisation, this field has been principally developed and successfully employed in craniofacial surgical planning [14–19].

The application of such technology for facial reconstruction from skulls for the purpose of identification was developed in the late 1980s [20]. In essence, the principle of the technique is to 'fit' a three-dimensional facial image, selected from a database, over a skull image in order to produce the reconstructed face.

Other methods of computer reconstruction, such as the technique described by Tyrell et al. [21], are in the process of development. They employ Open Inventor software, developed by Silicon Graphics.

Some promising preliminary work has been produced by another group [22] who base their reconstructions on the principle of deformable models. They scanned two pairs of skulls with a CT scanner and computed three dimensional models of both skulls and their facial tissue. One set of skull/facial data was used as a reference and the second set to validate their method. They applied a global parametric transformation that turned the reference skull into the skull to be reconstructed. Their algorithm was based on salient lines of the skull called crest lines. Thus the crest lines of the reference skull were matched to the crest lines of the skull to be reconstructed. The algorithm was then applied to the reference face to obtain the reconstructed unknown face. The authors acknowledge that their work could be greatly improved by the use of larger datasets to cover different categories of individuals and by more accurate registration of the skull and facial model.

Facial reconstruction utilising three dimensional computer graphics was an inevitable development from the manual sculpting methods with the arrival of computer technology. Yet do computerised techniques provide us with more accurate results? In our original publication [20], we demonstrated the feasibility of using this method of reconstruction and hinted at future possibilities. Despite the clearly prototypic nature of the early reconstructed images, the principle behind the method of reconstruction remains a sound one.

Our present system allows more precise placement of the facial template on to the skull so that the underlying skull shape determines more accurately the facial shape of the reconstructed image. We are able to place skull and facial landmarks with greater ease, make adjustments where necessary and correct errors more rapidly and effectively than with our earlier version.

Whatever method of reconstruction is used, the central issue is whether the face is of sufficient likeness to the original face and thus facilitates recognition. At the present time, the reasoning which governs the forensic investigating authority's request for a reconstruction, is simply that there is no other method of identifying the person and therefore, despite the recognised limitations, it is worth trying. The reconstruction produced should be employed as an aid to recognition and not be regarded, under any circumstances, as a definitive means of identification. However, if the reconstructed image is recognised as being that of a particular person, then positive identification can then be achieved using comparative information such as dental records or DNA profiling.

There are several factors that influence whether or not a reconstruction will lead to an identification and thus be classed as a 'success'.

- Publication of the images needs to reach those who know the deceased. Clearly, wider dissemination of the reconstructed image through the various mass media, will increase the chances of identification.
- Relatives or others who know the deceased may, for various reasons, not wish to come forward.
- The size of the population of missing persons is relevant to the success of recognition. If there are only a few missing persons in a small community, then the

chances of success are much greater than where there is a large number of missing persons to choose from in a large metropolis.

- Knowledge of the dead person in the community. Occasionally, someone disappears, who has no friends or relatives and consequently the community may not be aware that he/she is missing. Furthermore, the person may have resided a long way from the area of discovery.
- The person may have disappeared as a child and is not found dead until later adult life.
- The accuracy of the reconstruction. If the reconstruction is inexpertly produced, then this may not only diminish the chances of a recognition, but may lead to a misidentification.

Undoubtedly, the problem of assessing and improving the reliability of facial reconstructions needs to be addressed and further research carried out. It has to be conceded, however, that because of the complexity and diversity inherent in the morphology and spatial relationships of facial features, it is likely that, despite our best efforts, the prediction of the true morphology of soft tissue features such as ears, nose, lips and eyes, will remain largely speculative — at least for the foreseeable future.

References

[1] J.P. Moss, A.D. Linney, S.R. Grindrod, C.A. Mosse, A laser scanning system for the measurement of facial surface morphology, Optics Lasers Eng. 10 (1989) 179–190.
[2] A.C. Tan, R. Richards, A.D. Linney, 3-D medical graphics — using the T800 transputer, in: Proceedings of the 8th OCCAM User Group Technical Meeting, 1988, pp. 83–89.
[3] J.S. Rhine, C.E. Moore, Facial reproduction tables of facial tissue thickness of American caucasoids in forensic anthropology, in: Maxwell Museum Technical Series 1, Maxwell Museum, Albuquerque, New Mexico, 1982.
[4] R.M. George, The lateral craniographic method of facial reconstruction, J. Forensic Sci. 32 (1987) 1305–1330.
[5] R.M. George, Anatomical and artistic guidelines for forensic facial reconstruction, in: M.H. Iscan, R.P. Helmer (Eds.), Forensic Analysis of the Skull, Wiley-Liss, New York, 1993, pp. 215–227, Chapter 16.
[6] H. Peck, S. Peck, A concept of facial aesthetics, Angle Orthodont. 40 (1970) 284–318.
[7] C.R. Goodall, Procrustes methods in the statistical analysis of shape (with discussion), J. R. Stat. Soc. Series B 53 (1991) 285–339.
[8] R.L. Hardy, Multiquadric equations of topography and other irregular surfaces, J. Geophys. Res. 76 (1971) 1906–1915.
[9] K. Waters, D. Terzopoulos, Modelling and animating faces using scanned data, J. Visual. Graphics Image Process. 24 (1991) 52–96.
[10] H. Hjalgrim, N. Lynnerup, M. Liversage, A. Rosenklint, Stereolithography: potential applications in anthropological studies, Am. J. Phys. Anthropol. 97 (1995) 329–333.
[11] A.W. Sharom, P. Vanezis, R.C. Chapman, A. Gonzales, C. Blenkinsop, M.L. Rossi, Techniques in facial identification: computer-aided facial reconstruction using a laser scanner and video superimposition, Int. J. Legal Med. 108 (1996) 194–200.
[12] N. Lynnerup, R. Neave, M. Vanezis, P. Vanezis, H. Hjalgrim, Skull reconstruction by stereolithography, in: J.G. Clement, D.L. Thomas (Eds.), Let's Face It! Proceedings of the 7th Scientific Meeting of the International Association For Cranofacial Identification, Local Organising Committee of the IACI, Melbourne, 1997, pp. 11–14.

[13] Gonzalez-Figueroa, An Evaluation of the Optical Laser Scanning System for Facial Reconstruction, Ph.D. thesis, University of Glasgow, 1998.
[14] D.C. Hemmy, D.J. David, G.T. Herman, Three-dimensional of craniofacial deformity using computed tomography, Neurosurgery 13 (1983) 534–541.
[15] M.W. Vannier, J.L. Marsh, J.O. Warren, Three dimensional CT reconstruction images for craniofacial surgical planning and evaluation, Radiology 150 (1984) 179–184.
[16] S. Arridge, J.P. Moss, A.D. Linney, D.R. James, Three-dimensional digitisation of the face skull, J. Max.-fac. Surg. 13 (1985) 136–143.
[17] S.R. Arridge, Manipulation of volume data for surgical simulation, in: K.H. Höhne, H. Fuchs, S.M. Pizer (Eds.), 3D Imaging in Medicine, NATO ASI Series F 60, Springer-Verlag, Berlin, 1990, pp. 289–300.
[18] J.P. Moss, A.D. Linney, S.R. Grinrod, S.R. Arridge, J.S. Clifton, Three dimensional visualization of the face and skull using computerized tomography and laser scanning techniques, Eur. J. Orthodont. 9 (1987) 247–253.
[19] J.P. Moss, A.D. Linney, S.R. Grinrod, S.R. Arridge, D. James, A computer system for the interactive planning and prediction of maxillo-facial surgery, Am. J. Orthodont. Dental-facial Orthopaed. 94 (1988) 469–474.
[20] P. Vanezis, R.W. Blowes, A.D. Linney, A.C. Tan, R. Richards, R. Neave, Application of 3-D computer graphics for facial reconstruction and comparison with sculpting techniques, Forensic Sci. Int. 42 (1989) 69–84.
[21] A.J. Tyrell, M.P. Evison, A.T. Chamberlain, M.A. Green, Forensic three-dimensional facial reconstruction: historical review and contemporary developments, J. Forensic Sci. 42 (1997) 653–661.
[22] G. Quatrehomme, S. Cotin, G. Subsol, H. Delingette, Y. Garidel, G. Grévin, M. Fidrich, P. Bailet, A. Ollier, A fully three-dimensional method for facial reconstruction based on deformable models, J. Forensic Sci. 42 (1997) 649–652.